A Novel Sensor Network Architecture

by

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To my loving parents and inspiring grandfather

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Abstract

Wireless sensor devices are becoming an integral part of the human environment and their seamless integration has created a range of new Wireless Sensor Network (WSN) architectures. The Medium Access Control (MAC) protocol is a key component of WSN's, as it critically affects important characteristics like lifetime of the network, throughput guarantees and cost effectiveness. In this thesis we attempt to design new MAC protocols for emerging WSN architectures and applications.

A sensor network can be functionally described as *a heterogeneous collection of devices that collect and exchange data.* Based on this functional distinction we propose to classify the network into two tiers- i) a class of resource constrained devices that collect data and ii) a class a devices whose main function is to exchange and propagate the collected data through the network.

First, we consider data collection using resource constrained nodes and study the problem of providing a *guaranteed delivery probability and differentiated QoS* to nodes that do not have the capability to receive any signals. We develop a new MAC protocol based on stochastic methods to solve this problem and show that we can achieve good performance for densely deployed networks. We also study extensions of the protocol that use multiple channels and rudimentary BPSK receivers to improve the system capacity.

Secondly, we study data intensive networks in which the nodes require *guaranteed QoS in terms of throughput and delay.* Although there exist many protocols that meet these requirements, all of them require some form of centralized control. Specifically, we study the problem

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of high data rate communication in a completely distributed manner, with *no* form of centralized control. To solve this problem we develop a TDMA based protocol and algorithms that can provide distributed contention free channel access.

Finally, we apply these MAC protocols to practical applications and study their performance in field deployments. This provides a significant insight into the performance, benefits and drawbacks of these protocols. We hope the lessons learnt will be a valuable input to the design of protocols for next generation networks.

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Chapter 1

Introduction

The ubiquitous use of wireless networks has been consistently growing and the trend is set to continue. One of its important applications are sensor networks, which in the future will be an integral part of the human environment. Wireless sensor networks present a more difficult set of challenges as compared to other applications of wireless networks as they require a distributed architecture and are resource constrained. These features create many interesting problems in the design of distributed and efficient protocols.

We observe that a generic functional description of any sensor network can be given as - *A heterogeneous collection of devices that collect and exchange data.* The data collected by these networks can be used in wide gamut of combinations to achieve many application goals. In this thesis, we propose that a hierarchical network structure is better suited to accommodate the needs of different applications and explore a network structure consisting of two tiers. The major function of the *Tier* 1 network is to collect data while that of the *Tier* 2 nodes is to process this data and exchange/propagate this data through the network. We focus on designing MAC layer protocols and data collection methods that are completely distributed, topology independent and meet the other requirements, like energy efficiency, minimal overhead etc., of such networks.

A considerable amount of research has been done in the field of MAC protocols for sensor networks and many new protocols have been proposed. In general these protocols belong to the spectrum in which the extremes are pure TDMA and pure CSMA. The most popular MAC protocol for sensor networks today is the IEEE

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802.15.3 ZigBee protocol and it uses a hybrid access strategy in which TDMA is used for one part of the frame and CSMA for the rest of the frame. Although the ZigBee standard successfully addresses the energy efficiency aspect of the problem, it has a critical disadvantage of centralized control. Further, for sensor networks which periodically collect data, the efficiency of CSMA based protocols like ZigBee is low.

It is clear that using a single MAC protocol for such a heterogeneous network will be inefficient as the main functions of the different nodes will demand characteristics of a MAC protocol that include both ends of the spectrum. Although a hybrid protocol is a good compromise, it is still inefficient. To address these problems we present new MAC protocols that are designed for use with *Tier* 1 and *Tier* 2 nodes. A brief introduction of the ideas and concepts used in the design of these protocols are presented in the following sections.

Tier 1 and *Tier* 2 networks together provide the necessary infrastructure to sense and collect many different types of information for a wide variety of applications. To achieve the overall goal of distributed information exchange and propagation we need effective data collection and dissemination techniques that can operate in a completely decentralized manner. Without such a mechanism we cannot tap the potential of the powerful sensing and communication platform provided by *Tier* 1 and *Tier* 2 networks completely.

In many real world applications the data from the sensor nodes needs to be collected as a globally consistent snapshot. Some application may calculate a function over the data provided by individual nodes, in which case, collecting data from each node data is not very significant. However, in other situations the data provided by each node may be critical. Hence a robust and generic solution to this problem will be applicable to many practical sensor network deployments. In the latter part of the thesis, we study this problem and design a distributed and topology independent data collection and dissemination protocol called Hear-Hear that addresses these problems.

In the final part of the thesis we present a practical application that uses the protocols developed in this work to show their viability and use in real world scenarios. We develop a practical WSN based parking lot monitoring and occupancy information system called iGate that is designed to be robust, distributed

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and cost effective and we have demonstrated its use in an inexpensive and non-intrusive deployment that can be effectively used to monitor existing parking lots.

1.1 Protocols for *Tier* 1 Networks - Data Collection

The *Tier* 1 network can be described as a low complexity, low power and low cost wireless network. Such a network typically consists of a large number of source nodes that collect data, which are within one-hop communication range to one (or a few) sink node(s). Each source node is equipped with only a transmitter module in order to eliminate the cost due to the hardware complexity and energy consumption of the receiver module. As a result, they are not capable of receiving any signals (e.g. ACK/NAK, time synchronization beacon). The source nodes transmit a relatively small data frame to the sink node(s) periodically and have low throughput requirements. The sink node(s) are the only nodes in the network that are equipped with receiver modules and are capable of receiving the transmissions of the source nodes.

In such a low cost network, the nodes may be divided into different classes and the data generated by each class may have varying degrees of significance to the system as a whole. For example, in an intra-vehicular network, the data generated by a brake sensor is more important to ensure passenger safety than that generated by a tail light sensor and hence needs to be provided a high delivery probability and lower latency. Hence, providing differentiated QoS in terms of guaranteed data delivery probability and low latency is a critical requirement that needs to be met by an efficient MAC design. Further, the nodes in such networks are typically battery powered and hence the MAC should be designed to minimize the energy consumption.

This configuration is applicable to many active and passive wireless sensor networks, each having numerous applications like Smart Homes [Das *et al.* 2002], Green House Monitoring [Jacobson *et al.* 1989, Stipanicev & Marasovic 2003], Intelligent Transportation [Andrisano *et al.* 2003], Smart Kindergarten [Chen *et al.*

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2002], Medical Monitoring [Anliker *et al.* 2004] and Intra-Vehicular Networks [Elbatt *et al.* 2006].

Another application that is gaining significant importance in the construction field is the use of building sensors. With the advent of the concept of *Green/Smart Buildings*, engineers have the need to sense different parameters like temperature, humidity, light quality, smoke etc. at a large number of points within the building. These sensors need not communicate among themselves and their duty cycle depends on the sampling rate of the data which is inherently low. Hence equipping these sensors with complex radios like 802.11 which provide two way communication capability is an unnecessary cost both in terms of energy and capital.

Another widely used application is RFID-based passive sensor networks in inventory management. Some of the largest consumers of this technology are the US Armed Forces and Walmart. The RFID tags are passive devices that have the capability to transmit data only when excited by a suitable reader[1]. Since these RFID's cannot receive any information from the reader (e.g time synchronization beacon, ACK/NAK), they respond by transmitting a data frame as soon as they are excited by the reader. There is no time synchronization between the RFID-tagged nodes, or any form of coordinated transmissions. In a typical scenario, a few hundred items that are placed on a rack or container will have to be scanned. In this case, a single scan by the reader will not return any valid readings as there will be a significant number of collisions between the responses generated by the different nodes.

Current methods used in the industry for developing/managing inventory are based on scanning each item individually or by spacing them sufficiently apart from each other, so that the responses generated by the different nodes (items) do not collide. Certain advances in technology allow the scanning of multiple items that are closely spaced by performing multiple scans in an adhoc fashion. However, these methods are still inefficient because they either involve manual labor in the form of a person scanning each individual item or large infrastructure costs in developing an automated system to accomplish the task. The MAC

[1] Although active RFID's, that are capable of receiving data are available, their use is limited.

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scheme proposed in this work is capable of guaranteeing delivery of data frames with a predetermined probability and can be efficiently used to scan all the items in a single pass.

1.2 Protocols for *Tier* 2 Networks - Information Exchange and Propagation

Tier 2 networks mainly consist of aggregator nodes and sensor nodes that perform computationally intensive sensing tasks (like video monitoring), complex functions (like data aggregation, filtering, mining), event detection etc. The *Tier* 2 nodes are data-oriented and sometimes bandwidth intensive. These nodes have a unique set of requirements that differentiate them from exiting devices. They typically require high data rates to transfer significantly larger amounts of data as compared to tier1 nodes. Since they are battery powered devices they also demand high energy efficiency and optimized use of resources. They need to be able to communicate effectively in adhoc, topologically diverse network conditions without being administered or controlled by a central entity.

Although the IEEE 802.11 [IEEE 1999] and the IEEE 802.15.3 [IEEE 2003] are widely used, recent studies show that the many amendments and enhancements to these protocols that provide energy efficiency, QoS [IEEE 2005] are yet to be adopted on a significant scale since they considerably increase the complexity of the MAC protocol. This makes it inefficient for implementation on battery driven devices in sensor networks.

We explore TDMA based protocols which have the inherent advantage of bandwidth and energy efficiency as compared to CSMA based protocols. However, TDMA based protocols suffer from the fact that current designs need some form of centralized control. This leaves us with the question - *Can we design TDMA based wireless MAC protocols capable of similar or better performance as compared to today's popular CSMA based protocols in a completely distributed manner?*

We try to answer this question in the context of emerging Physical Layer technologies like UWB and also using new spectrum like 60GhZ. We present the

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design a protocol called DT-MAC that can operate in a completely decentralized manner while still using a TDMA frame structure.

The potential applications of such a TDMA based protocol can extend to all forms of wireless networks that are bandwidth intensive, require distributed control and strict QoS guarantees. Home Networking is one such application that involves various types of traffic from rich multimedia streaming to voice, which will benefit considerably from using such protocols.

A distributed TDMA protocol could also potentially replace the popular 802.11 technology for wireless networking applications as it will be capable of delivering similar or better performance on all services that is currently supported by the 802.11 protocol with the added advantage of improved bandwidth and energy efficiency.

1.3 Distributed Data Collection

In this part of the thesis we study the problem of distributed data collection in sensor networks. The problem is to *reliably collect a globally consistent snapshot of data at each node in a multihop network in a relatively small duration of time*. The data collection problem has been studied from the point of view of data aggregation in which the data from a group of nodes is collected by an aggregator node and a function of all this data (like MIN, MAX or AVG) is then propagated through the network [Krishnamachari *et al.* 2002, Heinzelman *et al.* 1999]. However, in this work we focus on applications in which the data at each node is critical to the calculation or estimation of a global system state.

The challenge is to design a completely distributed algorithm that is capable of achieving this goal effectively. Our design also aims to develop the capability to disseminate the global data to all the nodes in the network so that any node in the network can respond to a query regarding the system state.

We develop a distributed algorithm that collects and disseminates a globally consistent snapshot of data in a multihop network using a novel, controlled broadcast mechanism. Our design *does not require any infrastructure in the form of centralized control or topology management*. In our algorithm a node does not need to maintain routes to the sink or remember its neighbors. It is capable of

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operating in any dynamic adhoc environment in which the nodes are arbitrarily connected and also ensures that every node in the network has the global data. We can use this feature to design systems in which the whole network acts as a unified entity so that any node can provide the global information.

We study this problem in the context of a parking lot monitoring applications. The application requires that the data collected from all the motes in the network is a globally consistent snapshot. Collecting the snapshot reliably is also crucial requirement of our deployment as the parking lot occupancy cannot be determined even if the data from one mote is not received at the basestation. To make things more challenging, we also need to collect data in a relatively short duration as real-time data is required during peak hours

To collect and disseminate the occupancy information of multiple parking lots, we design a protocol called Hear-Hear. It uses a novel strategy of simultaneous collection and dissemination to minimize the cumulative delays of first collecting and then disseminating the information. A key feature of Hear-Hear is that its operation is independent of the topology and it can operate with similar efficiency irrespective of the size of the network. We evaluate the performance of Hear-Hear analytically, through simulations and using a practical wireless sensor network deployment.

In general, this concept can be applied to any multihop sensor network deployment in which data needs to be collected periodically from every node. A few examples of such applications are i) Building Monitoring, ii) Environment monitoring in a wine cellar/vineyard, iii) Monitoring the occupancy of a building.

1.4 iGate

We present a practical application that uses the DT-MAC and Hear-Hear protocols developed in this work to show their viability and use in real world scenarios. We we present *i*Gate, a multi parking lot monitoring and occupancy information system. At the core of *i*Gate are a distributed detection and classification algorithm, a distributed MAC protocol (DT-MAC) and a decentralized data collection/dissemination protocol (Hear-Hear).

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The design of *iGate* allows for easy, non-intrusive deployments while also allowing it to be tuned to the various operating conditions. At the core of the system is a decentralized, detection and classification algorithm, that can consistently detect the movement of a car and is yet able to differentiate between different objects moving through the entry/exit points of a parking lot. We also use the self-synchronizing, energy efficient design of the DT-MAC that helps the sensor motes to sleep for 100% of the time when there is no activity but still allows them to quickly synchronize and communicate when movement is detected. To collect and disseminate the occupancy information of multiple parking lots, we use the Hear-Hear protocol.

We present results from a real world deployment in which *i*Gate is used to monitor the occupancy of 5 parking lots with a total capacity of more than 1000 cars. We study the viability of our solution as a feasible practical application by presenting data and trends collected by this deployment.

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Chapter 2

Background

Existing MAC protocols that are used widely in wireless sensor networks are 802.11 [IEEE 1999], 802.15.3 [IEEE 2003], S-MAC [Ye *et al.* 2002], B-MAC [Polastre *et al.* 2004] and their derivatives. These protocols are part of the spectrum, one end of which is pure TDMA while the other end is pure CSMA. Figure 2.1 presents a graphical classification and taxonomy of the popularly used protocols within this spectrum. In the following we study the applications of these protocols to the sensor network architectures described in Chapter 1.

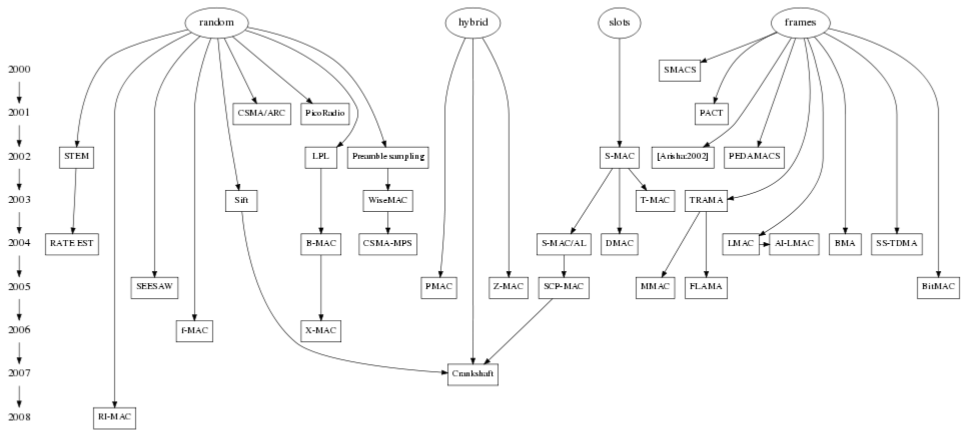

Figure 2.1: Taxonomy of MAC protocols for Sensor Networks

Figure 2.1 courtesy http://www.st.ewi.tudelft.nl/ koen/MACsoup/taxonomy.php

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2.1 *Tier* 1 Networks

All the existing protocols rely heavily on the channel sensing capability of the transceiver and the existence of symmetric physical communication channels. Channel sensing is a critical requirement without which these protocols cannot operate. However, in the future, low cost networks (Tier 1) might use asymmetric transceivers that will have very limited or no receiving capability. This will immediately rule out the use of existing protocols.

We must also note that the existing protocols, excepting pure CSMA based protocols, require some form of synchronization between the sink and the sensor nodes. This is achieved by either using synchronization beacons from a controller or time synchronization protocols like FTSP [Marti *et al.* 2004]. Both these approaches require the transceiver to have the capability to receive and techniques like FTSP generate significant traffic on the downlink channel. Considering the limited downlink channel bandwidth and capabilities of the receiver module, it might not be feasible to perform any form of time synchronization. Further, it is desirable that the MAC protocol does not require any form of global synchronization in order to minimize the complexity of the sensor nodes and the network.

The operation of *Tier* 1 networks will typically involve periodic transmission of small data packets from the sensor devices to a sink node. In some applications, the number of nodes may be large (a few hundred) and the interval between the transmissions may be small. This results in a high contention for the shared wireless channel. It is known that the performance of CSMA based protocols, in terms of packet delivery probability and latency, deteriorates considerably when there is a significant amount of contention for the wireless channel.

Another important feature of such networks is that they may consist of various types of sensor nodes and the significance of data generated by each type might be different. For example, in a medical sensing application, the data generated by the heart rate sensor is considerably more important than that generated by the body temperature sensor. In other words, the heart rate sensor requires a higher Quality of Service (QoS) in terms of the packet delivery probability as compared to the body temperature sensor. Although the 802.11e [IEEE 2005] protocol provides differentiated QoS, its complexity and high energy requirements make

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it difficult to implement it on low complexity, low cost, low power sensor nodes. The other existing protocols do not offer the capability of providing differentiated QoS at the MAC layer.

[Blaszczyszyn & Radunovic 2008] discuss a similar network setup in which transmit-only nodes collect data and transmit it to a sink node. However, they do not consider the problem of providing guaranteed delivery probability and differentiated QoS. To our best knowledge there is no other related work.

The unique set of requirements of such networks thus eliminates the possibility of using existing protocols and we have to turn to the legacy ALOHA protocol [Kuo 1974] for solutions. ALOHA is capable of operating under the given requirements and is robust for *Tier* 1 networks. However, it can neither provide guaranteed delivery probability nor is it capable of providing differentiated QoS. We propose a MAC scheme that is similar to ALOHA in its transmission policy but is still capable of delivering QoS guarantees.

2.2 *Tier* 2 Networks

2.2.1 Drawbacks of existing CSMA based Protocols

Contention - It is known that CSMA-based protocols have good performance at light traffic loads, but as the load offered to the network increases, their performance deteriorates due to the increased contention for the shared medium. In 802.11, the back-off algorithm is inefficient [Razafindralambo & Valois 2006] in terms of channel utilization. Especially when the contention for the channel is high, the aggregate throughput at the application layer that the CSMA-based protocols achieve is considerably lesser than the raw channel bandwidth. This means that they can support only a lesser number of devices in the network.

In future it will be common place for many devices (up to 50 at hot spots) to access high data rate (DVD quality) video streams from an access point. Even at the projected physical layer bandwidths of up to 1Gbps, the aggregate bandwidth requirement will be close to the raw channel bandwidth.

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Saturation of the shared medium is a realistic possibility in future networks. The MAC protocol design should ensure that the aggregate throughput at the application layer is maximized, irrespective of the network size.

Architecture - The 802.11 and 802.15.3 protocols, in their current state, create a hierarchical structure of nodes in order to implement all the functionalities. For example, the 802.11 protocol can implement the power saving and QoS features only in an infrastructure based setup. The 802.15.3 protocol requires a coordinator node which transmits beacons and schedules the transmission and sleep cycles of all the nodes in the network. The functionality of these protocols in ad-hoc mode is limited.

It is well known that an ad-hoc setup of communicating devices has considerable advantages over an infrastructure based setup. Thus the MAC protocol should be designed to provide all features in an ad-hoc setup.

Quality of Service - Although there have been many works that propose methods to provide QoS guarantees as specified by the 802.1p standard, they are not widely used due to the considerable increase in complexity. The standardized approach used to providing QoS in both 802.11 and the 802.15.3 is to use a hybrid frame structure in which access to the channel is divided into separate periods employing TDMA and CSMA. The idea is to support all traffic types - CSMA can support the bursty data well while TDMA can meet the bandwidth guarantees for multimedia and other similar traffic.

However, this approach suffers from one fundamental drawback. Partitioning the frame and allowing only certain traffic types (based on the channel access mode) in each partition, inherently induces delays in another traffic types when a node is servicing multiple traffic types. For example, if multimedia traffic arrives during the CSMA period of the frame it will have to wait until the reserved slot in the TDMA period to be transmitted. The same holds for, say, HTTP traffic arriving during the TDMA period.

Overhead - A study by [Chatzimisios *et al.* 2004] shows that 802.11 consumes one third of the total bandwidth for control messages and achieves an aggregate throughput of about one third the total bandwidth, which results in an *Overhead Ratio* of approximately 1. Roughly, there is an equivalent of one byte of control overhead for every payload byte that is transmitted.

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The existing CSMA-based protocols are inefficient in terms of Overhead Ratio. There is a need for a redesign of the MAC strategy to provide all the existing functionality with a significantly lesser Overhead Ratio.

2.2.2 Limitations of existing TDMA based protocols

TDMA based protocols rely of reservation in order to ensure collision free transmissions and the reservation procedure is the key component that determines the efficiency of the protocol. [Tanenbaum 2003] describes a bit-map reservation protocol in which the nodes send a bit during the slots alloted to them to reserve a data slot. The scalability of this protocol is limited as the number of nodes that it can support is fixed. Although the idea of this protocol form the basis of our work we solve many significant problems in the path towards a practically implementable protocol for multi hop sensor networks.

Existing protocols like PEDAMACS [Ergen & Varaiya 2006] and SS-TDMA [Kulkarni & Arumugam 2006] provide a centralized solution in which an access point coordinates collision free transmissions between all the nodes in the network. These protocols attempt to solve the scheduling problem using the standard approach of transforming it into a distance-2 graph coloring problem. The critical problem with this approach is that complete topology information is assumed and its applicability to a dynamically changing topology is limited.

DRAND [Rhee *et al.* 2006] provides a distributed solution to solve the scheduling problem as a distance-2 graph coloring. It develops a strategy in which each node reserves a slot by exchanging control information with its first and second hop neighbors. The main assumption in this method is that the slot reservations will be constant for an amount of time that justifies the control overhead. However, when we consider practical scenarios the traffic types that are generated by the nodes might vary and this will lead to inefficient bandwidth usage. In general, the protocol is unsuitable for random traffic patterns as encountered in a LAN.

The WiMedia specification [ECMA 2008, Pavon *et al.* 2006] is TDMA-based and uses beacons to exchange information between the nodes in the network. However, the protocol uses a slotted frame structure which suffers from the in-

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herent disadvantage of bandwidth wastage. If the node does not have enough data to transmit during the entire slot it reserved, bandwidth is wasted.

The reservation process is complex with slots being reserved over multiple frames. In dynamic conditions this will create an unfair sharing of bandwidth between the nodes. The protocol also specifies that other nodes can transmit in certain reserved slots by using a CSMA mechanism. This forces all nodes to be awake all the times which in turn leads to a higher energy consumption. *It is thus evident that slotted TDMA does not work well due to the problem of bandwidth wastage and complexity of slot reservation.*

2.3 Distributed Data Collection

Flooding and gossiping [Hedetniemi & Liestman 1988] are two classical mechanisms to relay data in sensor networks without the need for any routing algorithms and topology maintenance. In flooding, each node broadcasts its data to its neighbors, who in turn also do the same and this continues until the data arrives at the destination. Gossiping is an enhanced version of flooding where a node sends the packet to a randomly selected neighbor, which in turn picks another random neighbor of its, to forward the packet to and so on. Although these methods are easy to implement, they have their own set of problems [Heinzelman *et al.* 1999] which include *implosion*, which is the duplication of messages sent to a same node and *overlap*, which is caused when two nodes sensing the same region send similar packets to the same neighbor. They also suffer from energy inefficiency as they consume a large amount of energy. Gossiping avoids the problem of implosion by selecting a random node to send the packet rather than broadcasting. However, this causes delays in propagation of data through the network. While flooding and gossiping have their explicit set of drawbacks, they provide robustness and fault tolerance by using redundancy.

Data Centric Protocols - Data centric protocols are a class of protocols where the data is the focus of attention rather than the nodes it self. SPIN [Heinzelman *et al.* 1999] was the first data-centric protocol, which considered data negotiation between nodes. Nodes that have data use meta-data as advertisements to neighbors and the nodes interested in this data use request messages

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to obtain this data. While SPIN addresses problems of data acquisition such as overlap and energy inefficiency it does not help if data changes frequently as meta-data flooding occurs. Directed Diffusion [Intanagonwiwat *et al.* 2003] was developed on the concepts of SPIN and has become a breakthrough in data-centric routing. Directed diffusion removes the drawbacks of SPIN by having a query based data dissemination. Although this improves energy efficiency, it is dependent on the attribute naming of data which has significant overheads. Many other protocols have also been proposed either based on Directed Diffusion [Braginsky & Estrin 2002, Schurgers & Srivastava 2001, Chu *et al.* 2002] or following a similar concept [Manjeshwar & Agrawal 2001, Yao & Gehrke 2002, Shah & Rabaey 2002, Sadagopan *et al.* 2003].

Other Data Collection Algorithms - ASAP[Gedik *et al.* 2007] dynamically selects a subset of nodes to sense and report data values. Probabilistic models that exploit the spatial and temporal correlation of data are used to predict the data at the other nodes. For our application, we need the raw data at every node and probabilistic methods will be unsuitable.

Propagation of Information Via Feedback (PIF) - [Segall 1983] is the first concept of *distributed network protocol* that has been used in many distributed systems to obtain a global snapshot. In [Segall 1983] information is sent to each node by its *parent*, who then forwards it to their *children* and this process is continued, spreading information to every node in the network. On receiving feedback from its children, a node reports it to its parent, thus collecting information from all the nodes in the system and relaying it to the root node. Though this algorithm is very robust and reliable, the protocol incurs the overhead of topology maintenance, either at the node or at a central location. Further, only the root node obtains the global snapshot of the network.

More generally, data acquisition is classified into Event based and Periodic models. Event based models are used when the events of interest have different rates of occurrence and hence the nodes are given the responsibility of reporting data to the basestation. To reduce the frequency of reports, nodes perform local filtering, as a result of which raw data is not made available to the basestation.

Periodic data acquisition usually employs query based schemes to obtain a snapshot of the data of *all* the nodes in the network using some aggregation

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function[Krishnamachari *et al.* 2002]. An important observation is that aggregation is efficient in suppressing redundant data [Intanagonwiwat *et al.* 2003, Heinzelman *et al.* 2000, Lindsey & Raghavendra 2002, Yao & Gehrke 2002] but it is more suited for heterogeneous networks where the aggregation functions can be assigned to specialized nodes [Subramanian & Katz 2000]. Its performance will suffer in homogeneous networks. Further it is unsuitable for applications requiring raw data and a high frequency of sampling.

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Chapter 3

Protocols for *Tier* 1 Networks

3.1 Overview

Wireless Sensor Networks (WSNs) have a pervasive impact on a broad spectrum ranging from consumer electronics to academic research. The most recent applications that have created the path for a wave of new services has been the introduction of sensors in mobile phones. Other customized applications have lead to the development of devices that improve security in homes [Das *et al.* 2002] and enable parents to track the whereabouts of their children [Chen *et al.* 2002]. On the other hand, academics are leveraging the uses of sensor networks in their research on the growth patterns in greenhouses [Jacobson *et al.* 1989]. Advanced health care systems also use sensor devices to offer better monitoring capabilities with minimal intrusion and discomfort to the patient [Anliker *et al.* 2004].

As a special class of sensors, RFID tags are gaining popularity in applications like inventory management. A recent study claims that WalMart is the second largest consumer of RFID tags after the US defense services [Weinstein 2005, Goth 2005]. Recently, the postal services are also using RFID tags to improve sorting speeds and delivery times.

A common characteristic of these popular data collection and monitoring applications is a large number of densely deployed sensor devices or nodes, each of which has to send only a small amount of data to a control unit or base station. All the nodes are usually within one hop transmission range of the base station and

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the flow of information is unidirectional - from the nodes to the base station. Existing WSN architectures in conjunction with commercial off-the-shelf hardware are feature rich and support sophisticated applications requiring high throughput and many sensors in a multi-hop network. Accordingly, they can easily handle these popular applications. However, the specific nature of the applications would leave many components of the existing WSN architecture underutilized, resulting in low system efficiency.

To reduce system cost and energy consumption of the nodes, we propose the Asymmetric Transceiver Network (ATN) architecture in which the nodes are equipped either with a fully functional transmitter or a fully functional transmitter and a rudimentary receiver. The rudimentary receiver is only capable of receiving fixed radio pulses and cannot receive any signals or perform any auxiliary functions like channel sensing that a node equipped with a fully functional transceiver can do. We call the nodes equipped with only transmitters as *transmit-only nodes* and the nodes equipped with an additional rudimentary receiver as *asymmetric nodes*. In an ATN, the base station is the only network element that is equipped with a fully functional transceiver module.

Eliminating the fully functional receiver module from the sensor nodes in conjunction with efficient non-CSMA based MAC protocols can result in considerable cost and energy savings due to the reduction of the hardware that needs to be constructed and powered. This enables us to design and deploy networks with longer lifetimes and lower capital costs. However, such a choice raises questions about the transmission reliability that can be achieved with only the capability to send minimal feedback from base station.

One of the problems we address in this chapter is that of providing guaranteed delivery probability to the nodes in an ATN. It is true that we cannot guarantee 100% delivery probability, but, data collection and monitoring applications are tolerant to packet loss and only require a high packet delivery probability from each node to the base station. Also, once new data is generated, the older data might not be useful or relevant to the system state. Hence, delivery probability is a more meaningful performance metric as compared to throughput and 100% reliability in such applications. In RFID based networks, where 100% reliability in identifying tags is desirable, the tags are read over multiple passes to improve

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reliability. In other words, the delivery probability translates directly affects the total time required (or the number of passes) to read all the information from a given set of tags.

Another problem we address is that of providing differentiated QoS in terms of different delivery probabilities to different sub-groups or classes of nodes within the same network. This problem arises from the fact that many applications tend to monitor different parameters of a larger entity, and the importance of each of these parameters to the state of the entity has a definite priority. This results in different nodes requiring different delivery probabilities for their data.

These problems are relevant to data collection and monitoring applications mentioned earlier that benefit by using ATNs. As another example, consider an Intra-vehicular wireless sensor network [Elbatt *et al.* 2006] that typically consist of hundreds of nodes falling into different priority classes in terms of delivery probability. The data generated by a node that senses the status of the brakes is more important than that generated by a node sensing the status of the tail lights. Also, due to the criticality of the brake sensor data, it requires a high delivery probability of, say 0.99 or higher.

3.2 System Definition

In general, an ATN consists of a large number of nodes partitioned into many different QoS classes with each class of nodes requiring different minimum delivery probabilities. Formally, we can describe the system as a set of N (> 1) nodes that are partitioned into m QoS classes, $\{Q_1, \cdots, Q_m\}$, with each class containing $\{n_1, \cdots, n_m\}$ nodes $(N = \sum_{i=1}^{m} n_i)$ respectively. The packet arrival rates of the nodes in each class are $\{T_1, \cdots, T_m\}$ respectively. The frame transmission duration, t_f, of all the nodes is assumed to be the same and $t_f \ll T_i$ for all i. Each node in Q_i requires a minimum frame delivery probability of p_i $(1 \leq i \leq m)$. For simplicity, the groups are ordered such that, if $i < j$, then $p_i \geq p_j$. Due to the nature of the applications, delivering an older data packet after a new data packet has been generated is useless and hence it is required that the packet be delivered to the sink within T_i or it is considered to be lost.

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The problem is to find the optimal number of retransmissions x_i for each Q_i, such that, if every node in Q_i retransmits each of its data frames x_i times in every T_i units of time, it can achieve a delivery probability of P_i such that $P_i \geq p_i$. It is critical to note that solution of x_i for each i is not independent. For example, if we increase x_1 in order to allow the nodes in Q_1 to achieve a higher p_1 it will reduce the p_i of the nodes in the QoS classes $\{Q_2, \cdots, Q_m\}$.

Since we consider transmit only and asymmetric nodes which either have no receiver module or a receiver module with limited capability, the design of the MAC protocol assumes that the following standard features/mechanisms that can otherwise be used with standard receiver modules are unavailable

1. Channel Sensing
2. Global time synchronization
3. Centralized scheduling mechanisms

Existing MAC protocols that are based on polling, scheduled transmissions [Ye *et al.* 2004], carrier sensing [IEEE 2005] [Zheng *et al.* 2005] [Lin *et al.* 2004], collision avoidance/detection [Jamieson *et al.* 2003] and MAC layer Automatic Repeat Request (ARQ) cannot be used in such networks as they require the nodes to have the capability to receive control signals. In the following we propose MAC protocols that can provide a guaranteed minimum delivery probability and a deterministic upper bound on latency under the above mentioned conditions.

3.3 QoMoR : QoS-Aware MAC Scheme Using Optimal Retransmissions

We propose an asynchronous MAC scheme, which allows each node to transmit each of its data frames multiple times and at random instants, thus increasing the probability of delivery. Since the transmission duration of the data frames are relatively very small when compared to the data generation rate, retransmitting each data frame multiple times is meaningful. In addition, if a frame cannot be successfully delivered within T units of time, the frame is simply discarded thus

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bounding the latency of successfully delivered frames. Accordingly, the latency is randomly distributed in the interval $(0, T)$ and is bounded by T.

The challenge, however, is that, if all the nodes follow a greedy approach and try to transmit their data a large number of times, the maximum delivery probability that can be achieved by each individual node will eventually be decreased due to an increase in the number of collisions. Hence, the focus of this work is to address the challenge of finding an *optimal solution for the number of retransmission that each node should attempt for each of its data frames, so that all the nodes in the network achieve their required QoS (in terms of data delivery probability)*. One should note that the solution to this problem also addresses the problem of energy efficiency, as the number of transmissions and hence the usage of the radio module are optimized. Although the proposed scheme uses random transmissions as in ALOHA, the novelty of our scheme is in finding the optimal number of retransmissions to achieve a guaranteed QoS instead of relying on a receiver module to detect collisions.

We can optimize the solution to this problem based on some practical design considerations. For instance, the nodes in the wireless sensor network are usually powered by batteries and hence need to conserve energy. Therefore they need to minimize their number of transmissions as much as possible. Based on this consideration we can find the minimum value of the number of retransmissions that achieves the required delivery probabilities of the nodes. In certain conditions, the main criteria might be to provide the highest priority nodes the highest possible delivery probability that can be achieved while also satisfying the minimum delivery probability required by nodes in all the other classes.

Based on the above discussion, the optimization criteria can be summarized as

1. Minimize the total network traffic. Alternatively, minimize x_i for every Q_i, subject to $P_i \geq p_i, \forall i$

2. Maximize the delivery probability of the highest priority class, subject to $P_i \geq p_i, i = 2, \cdots, m$

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3.3.1 Single QoS Class

We first consider a network in which all the N nodes require the same minimum delivery probability. Formally, it is a system in which $m = 1$, $p_i = p$, $n_i = N$ and $T_i = T$ for some values of p, N and T. Given these parameters and t_f, we need to determine x. The following analysis examines the problem of maximizing the delivery probability of each node and develops a closed form expression for the same.

3.3.1.1 Analysis

We consider the case where all the N nodes belong to the same QoS class, and each node transmits x copies of a frame at random instants in every interval T. The arrival of packets to the channel (from all the nodes, whether they are new or retransmitted packets) are independent of each other, since each node randomly and independently decides when to transmit a packet. Further, it is assumed that the frame transmission duration $t_f \ll T$. Hence the distribution of the arrival of packets to the channel within any given period of time can be closely approximated to follow a Poisson distribution [Papoulis & Pillai 2002]. Accordingly, the probability of k frames being transmitted during some time period t is given by $P_{t,n} = e^{-\lambda t}\frac{(\lambda t)^n}{n!}$, where, $\lambda = \frac{(N-1)x}{T}$ represents the rate of background traffic generated by the other $N-1$ nodes in the interval T.

We are interested in finding the probability that a transmission by, say, *node* j is received successfully at the sink. Let us suppose that *node* j transmits its k^{th} frame at time t_0 and the frame ends at time $t_0 + t_f$. Also, assume that the signal propagation delay from the node to the sink is the same for all nodes and is negligible as compared to the frame duration. In order that the k^{th} transmission of *node* j does not collide with the transmissions of any of the other nodes, it is required that none of the other $N-1$ nodes start transmitting during the interval $[t_0 - t_f, t_0 + t_f]$. The probability, p_s^k, that the k^{th} transmission of *node* j is successful, can be calculated by evaluating $P_{t,n}$ at $n = 0$ and $t = 2t_f$.

Since each transmission of *node* j can be regarded as an independent event, the probability of success for each transmission is the same and hence, $p_s^k = p_s = e^{\frac{-2x(N-1)t_f}{T}}$ for all k. Assuming that the probability of transmission errors due to

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reasons other than collision (fading, interference etc.) to be α, we can calculate the probability that a transmission by *node j* will be successful as

$$p_s = e^{\frac{-2x(N-1)t_f}{T}}(1-\alpha) \tag{3.1}$$

The frame delivery probability, $P(x)$, achieved by *node j* is the probability that at least one of the x copies sent by the node during interval T is successfully received by the sink. To calculate this probability, we first evaluate $P_e(x)$, which is the probability that none of the transmissions were successful and it is given by

$$P_e(x) = \prod_{k=1}^{x}(1-p_s^k) = (1-p_s)^x \tag{3.2}$$

Accordingly, the probability that at least one of 'x' transmissions will be successfully received at the sink is

$$P(x) = 1 - P_e(x) = 1 - [1 - e^{\frac{-2x(N-1)t_f}{T}}(1-\alpha)]^x \tag{3.3}$$

Although a closed form solution for the maximum value of $P(x)$ does not exist, we can use numerical methods to determine the value of x that maximizes $P(x)$.

3.3.1.2 Numerical Results

The simulation was performed using the $ns-2$ simulator package. The proposed protocol was implemented at the MAC layer of the $ns-2$ framework. For the simulation, the Physical Layer bandwidth was set to $11Mbps$ and two-ray propagation characteristics were used. These parameters (which are the standard operational parameters of the 802.11b protocol) were chosen so that all aspects of the performance of the proposed protocol can be accurately compared to the 802.11b protocol. Further, to simulate the fact that the nodes have only a transmitter and no receiver, the receive power of the simulated radio module was set to zero while the transmit power was set to $660mW$. A random flat-grid topology was chosen for the placement of the nodes within a $50m \times 50m$ region.

Fig. 3.1 presents the results for a Single QoS Class system consisting of 100 nodes. The ratio of the transmission time to the data generation interval, $\frac{t_f}{T}$, was

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chosen to be $6.4 \times 10^{-4} ms$, which corresponds to each node transmitting a 50 byte packet at a rate of 25 packets per second using a $11 Mbps$ channel. It should be noted that the delivery probability depends on the ratio $\frac{t_f}{T}$, while the actual values of t_f and T are not significant. The results for different values of the ratio $\frac{t_f}{T}$ have not been presented due to lack of space. However, in general, the delivery probability decreases exponentially with an increase in the ratio.

Fig. 3.1 plots $P(x)$ from the numerical analysis (3.3) and the simulation. The first curve from the simulation results presents the case when all the nodes are randomly distributed in a $50m \times 50m$ area. It can be seen that the mean delivery probability from the simulation closely agrees with that from the analysis with $\alpha = 0.001$, which is a nominal error rate for a wireless medium. The second curve from the simulation presents the case when the nodes are randomly distributed in a $230m \times 230m$ area. The reason behind considering such a large area is to study the performance of the system under conditions that are more prone to channel errors. Again, the simulation results agree with the analysis for the case when $\alpha = 0.15$, suggesting that by varying α, our analytical model can be used to predict the delivery probability under various wireless channel conditions.

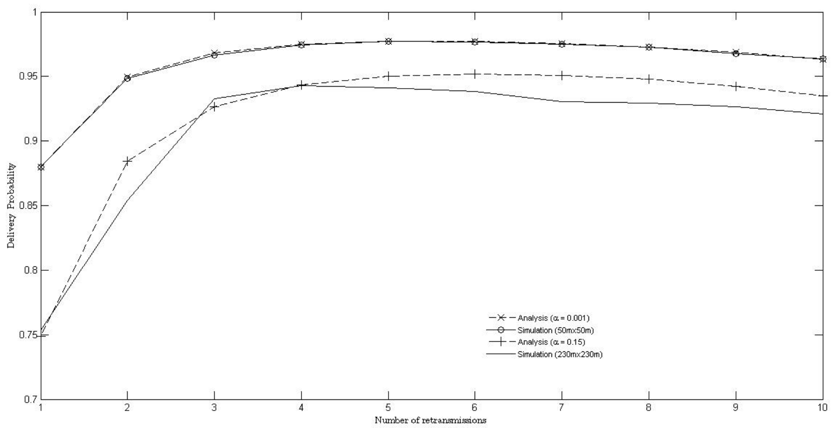

Figure 3.1: Analysis and simulation results for the Single QoS class case

We also observe that in either case, $P(x)$ initially increases with the number of retransmissions, reaches a peak and then decreases and the maximum value of $P(x)$ (which is about 0.97 for the $50m \times 50m$ scenario) is reached when $x = 5$ or

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$x = 6$. Based on these results, one can choose the value of x to be 5 or 6 to achieve maximum delivery probability or a smaller value to minimize network traffic and hence improve node lifetime while still satisfying the required minimum delivery probability.

3.3.2 Multiple QoS Classes

In this section, we extend the discussion to the case where the nodes in the network require different minimum delivery probabilities. In general, the nodes can be divided into m (≥ 1) QoS classes $\{Q_1, \cdots, Q_m\}$ with each group of nodes requiring minimum delivery probability of $\{p_1, \cdots, p_m\}$. Also, each group can have a different packet arrival rate T_i depending on the requirements of the nodes.

3.3.2.1 Analysis

The following analysis proceeds in a manner similar to that of the single QoS class case and the frame delivery probability for each node in Q_i can then be expressed as

$$P_i(x_i) = 1 - (1 - e^{-2\lambda_i t_f}(1 - \alpha))^{x_i} \tag{3.4}$$

where $\lambda_i = \frac{n_1 x_1}{T_1} + \cdots + \frac{n_m x_m}{T_m} - \frac{x_i}{T_i}$ is the rate of background traffic generated by all the other nodes.

We can now formulate the first optimization problem, which is to minimize the total network traffic, as a non-linear programming problem (due to non-linear constraints). That is, given $n_1, \cdots, n_m$ and $p_1, \cdots, p_m$, we are required to find $x_1, \cdots, x_m$, such that

$$\min \sum_{i=1}^{m} n_i \times x_i \tag{3.5}$$

subject to

$$1 - e^{-2\lambda_i t_f}(1 - \alpha) - (1 - p_i)^{\frac{1}{x_i}} \leq 0 \quad , \quad i = 1 \cdots m \tag{3.6}$$

$$1 \leq x_i \leq \frac{T_i}{t_f} \quad , \quad i = 1 \cdots m \tag{3.7}$$

In the objective, (3.5), $\sum_{i=1}^{m} n_i \times x_i$ is the total number of transmissions by all source nodes within time T_m. The constraint (3.6) guarantees that every node

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in *Group* i $(1 \leq i \leq m)$ has the delivery probability of at least p_i. The constraint (3.7) states that the maximum number of retransmissions can not exceed $\frac{T_i}{t_f}$ due to hardware limitation.

The second optimization problem can be formulated similarly with the objective being that given $n_1, \cdots, n_m$ and $p_2, \cdots, p_m$, find the maximum value of $P_1(x_1)$ (and $x_1, \cdots, x_m$) subject to the constraints in (3.6) and (3.7).

3.3.2.2 Algorithm

In this section, we describe an efficient algorithm to find the solution to the first optimization problem. The objective of the algorithm is to find the optimal values of $\{x_1, \cdots, x_m\}$ that meet the above requirements while minimizing the total network traffic, $\sum_{i=1}^{m} n_i x_i$. The motivation behind the algorithm is to utilize the fact that the background traffic governs the maximum achievable delivery probability for any node in the network. The algorithm starts by considering the whole system as a single QoS class containing $N = \sum_{i=1}^{m} n_i$ nodes requiring a minimum delivery probability of p_m, the delivery probability of the lowest priority group. Using the closed form expressions derived for the Single QoS Class case, we can now find the minimum and maximum values of the number of transmissions, x_{min} and x_{max}, that satisfy the above condition.

Now, we split that N nodes into two groups, Q' and Q_m, containing $n'(= \sum_{i=1}^{m-1} n_i)$ and n_m nodes respectively, and requiring delivery probabilities p_{m-1} and p_m respectively. Since our aim is to minimize the total network traffic we need to find the minimum number of retransmissions for each QoS class that achieves the required delivery probability for that class. Hence we set the number of retransmissions for Q_m as $x_m = x_{min}$. It follows that, since $p_{m-1} > p_m$, we require $x' > x_m$.

In addition, we also require that certain traffic constraints be met so that the nodes in Q_m always achieve a probability of at least p_m. The background traffic for a node in Q_m must be bounded by

$$n'x' + (n_m - 1)x_m \leq [n' + (n_m - 1)]x_{max} \tag{3.8}$$

$$\implies \quad x' \leq x_{max} + \tfrac{n_m - 1}{n'}(x_{max} - x_m) \tag{3.9}$$

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In the following discussion, we denote $\frac{n_m-1}{n'}(x_{max} - x_m)$ by x'_{max}. Given the bounds on x' and x_m, it seems that we need to loop through all combinations of values of x' and x_m to find a suitable combination that satisfies p_{m-1} and p_m. However, upon closer examination, we note that there is no need to loop through all possible values of x_m. Specifically, for the problem of network traffic minimization, if no appropriate x' can be found such that the nodes in Q' can achieve a minimal delivery probability of p_{m-1} when $x_m = x_{min}$, then there does not exist any feasible solution. This is due to the fact that any increase in x_m will not only reduce x'_{max} and thus limit the possible values of x', but will also increase the amount of background traffic for the nodes in Q' and negatively affect their maximum achievable delivery probability. Hence, to find the solution we set $x_m = x_{min}$ and find x' as the the minimum number of retransmissions in the interval $[x_m, x_{max} + x'_{max}]$ that guarantees a delivery probability of p_{m-1} to the nodes in Q'.

Next, we further split the group Q', in a recursive fashion, into two groups, Q'' and Q_{m-1}, containing $n''(= \sum_{i=1}^{m-2} n_i)$ and n_{m-1} nodes and requiring delivery probabilities p_{m-2} and p_{m-1} respectively. Now, the system consists of three QoS classes, Q'', Q_{m-1}, Q_m. The nodes in Q_{m-1} have to transmit x' times to achieve a delivery probability of p_{m-1}. Hence x_{m-1} is set to x'. Now, we need to calculate the number of retransmissions for the group Q'' (i.e. x'') such that the nodes achieve a probability of at least p_{m-2}. As in the above discussion, we have, $x'' \geq x_{m-1}$ and the bounds are given by

$$n''x'' + n_{m-1}x_{m-1} + (n_m - 1)x_m \leq [n'' + n_{m-1} + (n_m - 1)]x_{max} \quad (3.10)$$

$$\implies \quad x'' \leq x_{max} + \frac{n_{m-1}}{n''}[(x_{max} - x_{m-1}) + x'_{max}] \quad (3.11)$$

The above process is repeated recursively until the bounds for the highest priority class and hence the optimal number of retransmissions are determined. If the optimal number of retransmissions cannot be determined in any one of the recursions the system is declared infeasible. Algorithm 1 illustrates the procedure (*Note:* The discussion above uses different variables for the sake of clarity, how-

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ever, the algorithm uses the same variables to improve its efficiency with respect to time and space complexity).

Algorithm 1 : The total traffic minimization problem

Initialize x_{lb}, x_i $(\forall i)$, $x'_{max} \leftarrow 0$, $x_{ub} \leftarrow 20$ and $n' \leftarrow \sum_{i=1}^{m} n_i$
for $j \leftarrow m$ to 1 **do**
    Find x_{min} and x_{max}, *within the limits* x_{lb} and x_{ub}, such that n' nodes can achieve a delivery probability of at least p_j using the formula $P_i(x) = 1 - (1 - e^{\frac{-2x(n-1)t_f}{T_i}}(1-\alpha))^x$
    if *not found* **then**
        No feasible solution exists; Goto End
    end if
    $n' \leftarrow \sum_{i=1}^{j-1} n_i$
    $x_j \leftarrow x_{min}$, $x'_{max} \leftarrow \frac{n_j - 1}{n'}[(x_{max} - x_j) + x'_{max}]$
    $x_{lb} \leftarrow x_j$, $x_{ub} \leftarrow x_{max} + x'_{max}$
end for
Output the values of $x_1, \cdots, x_m$
End

3.3.2.3 Numerical Results

To simplify the presentation of results, we assume that there are only two QoS classes, Q_1 and Q_2 requiring minimum delivery probabilities of $p_1 = 0.95$ and $p_2 = 0.9$. Fig. 3.2 illustrates the simulation results of the variation of $P_1(x_1)$ with x_1 and x_2 for a network consisting of $n_1 = 20$ and $n_2 = 50$ nodes and having a packet arrival rate of $T_1 = T_2 = 1ms$. The frame transmission duration, t_f is $6.4 \times 10^{-4} ms$.

The plot demonstrates that for a fixed value of x_2, $P_1(x_1)$ initially increases, reaches a peak and then decreases with x_1 as in the single QoS class case. For a fixed value of x_1, $P_1(x_1)$ decreases monotonically with x_2. This is due to the fact that the increased traffic from Q_2 increases the probability of collision for the frames transmitted by the nodes in Q_1, hence reducing the delivery probability of the nodes in Q_1. Also, Fig. 3.2 shows that there exist many pairs of x_1 and

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x_2 satisfying the required p_1 (and p_2). The values of x_1 and x_2 can be selected depending on the design objective. For example, the solution to the problem of minimizing network traffic will be $x_1 = 2$ and $x_2 = 2$.

The jagged edges of the plot for $P_1(x_1)$ are due to the facts that x_1 and x_2 can take only integer values and that only values of $P_1(x_1)$ above the required threshold of 0.95 are shown. Also, note that in the numerical analysis, x_1 and x_2 are real numbers while in simulations they are integers. This explains the differences in the results from the numerical analysis and simulations, especially when x_1 and x_2 are large.

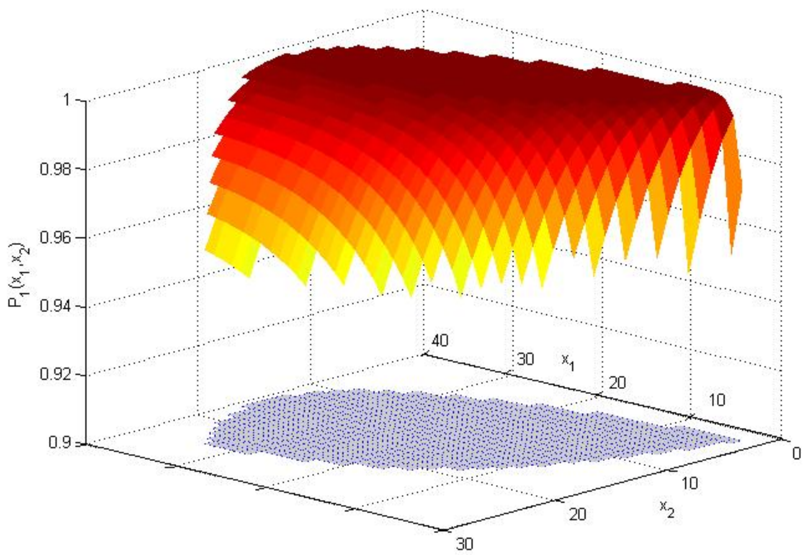

Figure 3.2: Simulation results of P_1 as a function of x_1 and x_2

Fig. 3.3 shows the solutions to the second optimization problem of maximizing the delivery probability of the highest priority nodes. When the total number of nodes is small, the achievable $P_1(x_1)$ is high for a given n_1, n_2 (and $p_2 = 0.9$). For example, when $n_2 = 30$ and $n_1 = 30$, it is possible to achieve $P_1(x_1) = 0.9997$. However, with large n_1 and n_2 (*e.g.* $n_1 = 80, n_2 = 80$), the achievable $P_1(x_1)$ drops to nearly 0.9. This indicates that $P_1(x_1)$ is more sensitive to the number of nodes in a higher priority group, because more transmissions are required (and thus more network traffic) to increase the delivery probability which is already high.

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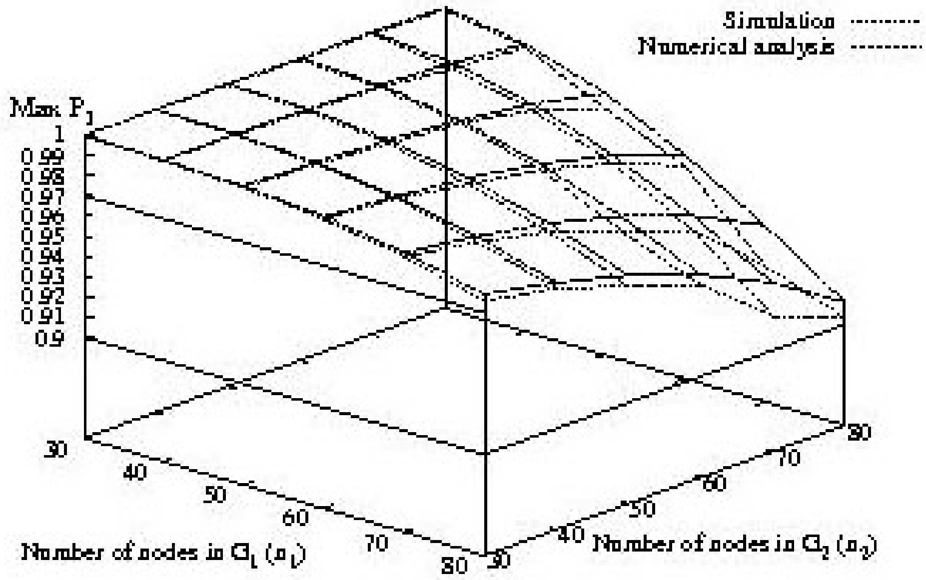

Figure 3.3: Analysis and simulation results for the multiple QoS class case

3.3.3 Energy Consumption

In this section, we simulate and study the performance of the proposed scheme with respect to energy consumption and compare the average power consumption and the delivery probability achieved using the proposed protocol and 802.11b. The simulations were performed using the $ns - 2$ simulator package and all the parameters are the same as in 3.3.1.2.

Fig. 3.4 shows the average energy consumption of the proposed protocol for different number of retransmissions and also the energy consumed when using the 802.11b protocol for transmitting about 2000 data packets when the aggregated data rate generated by all the nodes is about 11$Mbps$, which is equal to the available bandwidth. For ease of presenting the results and a better comparison, the plot shows the energy consumption of 802.11b only due to transmissions. We can clearly see that the energy consumed by the proposed protocol for a high number of retransmissions, say 10, is lesser than that consumed by the 802.11b protocol. This is attributed to the fact that the 802.11b protocol requires the use of many control packets like RTS and CTS, which unnecessarily consume

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energy and bandwidth. Further the 802.11*b* protocol also implements MAC ARQ mechanisms which retransmit packets a number of times to ensure successful delivery. These repeated transmissions also contribute to the increased power consumption.

Although not shown in this paper due to space limit, simulation results also indicate that the actual average energy consumed by the 802.11*b* protocol was about $71 Joules$. This is about 250 times the energy consumed by the proposed protocol, and is due to the fact that in 802.11*b* packets that are not destined to a particular node are also received by it, and these unnecessary receptions consume a considerable amount of energy.

To put the benefits of the proposed protocol into perspective, the plot also shows the corresponding delivery probabilities achieved by it for the number of retransmissions ranging from 1 to 10 and the 802.11*b* protocol under the same conditions. The results show that the delivery probability achieved by the proposed protocol is significantly higher than that achieved by the 802.11*b* protocol. This can be attributed to the following facts which indicate that the 802.11*b* protocol does not use the available bandwidth as efficiently as the proposed protocol. Firstly, the proposed does not have any control packet overheads like RTS and CTS. Secondly, it does not use any exponential back-off mechanisms which causes the channel to be unused for certain periods of time.

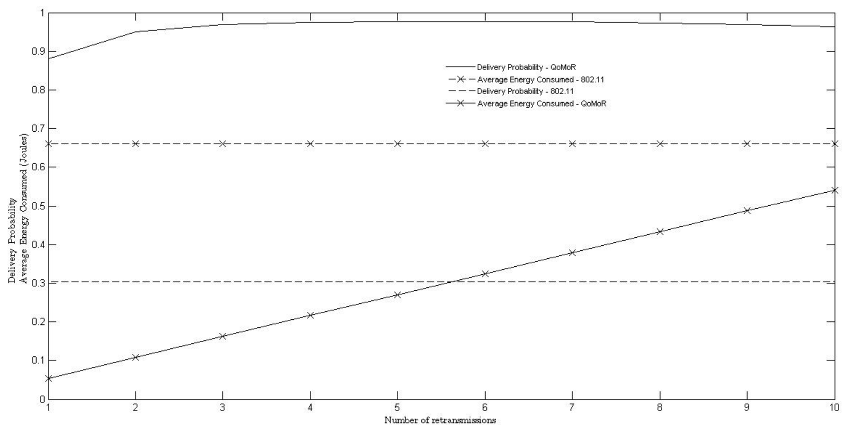

Figure 3.4: Energy Consumption and Comparison

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The most important observation from these results is that when the number of nodes is large and the aggregate data rate is close to the available channel bandwidth, the performance of the proposed protocol is significantly better than 802.11*b* both in terms of QoS and energy consumption for the applications under consideration. The results also strongly suggest that, for most sensing applications for which a single-hop wireless network setup suffices, the proposed protocol performs better that the standard 802.11*b* protocol.

3.3.4 Motivating Technologies

It is important to note that the concept of multiple retransmissions is meaningful only when the transmission duration of each packet is significantly smaller than the rate of generation of packets. Consequently, a wireless transmission technology that can support a high bit rate and thus reduce the transmission duration of the packets will be needed. One such technology is Ultra-Wide Band (UWB).

In this section we discuss a few potential applications where our MAC scheme will be extremely effective and provide considerable performance improvements over existing state of the art technology. We also describe the Ultra-Wideband (UWB) physical layer technology, which is potentially best suited to such applications. Finally, we present a study on the cost and energy savings that motivate the design of our MAC scheme.

UWB is a promising technology as it has valuable features such as high transmission rate, low power consumption and super resolution of multipath [Li & Talty 2006] [Gresham *et al.* 2004], that are currently not provided by any of the existing wireless physical layer technologies. Further, the design of UWB transmitters is also simple [Orndorff 2004] and the power levels used by UWB devices are very low (specified by the standard to be -41.3 dBm/Mhz) which allows for a cost and energy efficient design of the nodes. A study on UWB transceiver architectures in [Orndorff 2004] shows that the receiver circuitry is much more complicated and hence consumes more power than the transmitter. As a result, by removing the receiver module, we can save a significant amount of energy, which translates into a considerable improvement in node lifetime. Thus UWB

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provides a set of features that are very useful for designing nodes used in the class of networks considered in this work.

3.4 Beyond QoMoR

The performance analysis and results suggest that QoMoR performs well when the sum traffic generated by all the nodes in the network is significantly lower than total channel capacity. The performance of QoMoR in terms of the delivery probability it can achieve deteriorates with the number of nodes in the network. Even for a network consisting of 100 nodes QoMoR can only provide a delivery probability of 0.975 which may not be viable for certain applications.

With the ubiquitous use of sensor devices future applications may deploy many hundreds of sensors within one hop range of each other. There is a need for solutions better than QoMoR that will be able to provide high delivery probabilities of say 0.9999, even at such high node densities. Other applications like body sensor networks, although requiring only a small number of nodes, pose an interesting problem of significantly high channel error rate, due to the fact that the human body considerably attenuates the RF signal. In such cases, the performance of the single channel scheme described in [Sudhaakar *et al.* 2009] will not be able to provide a sufficiently high delivery probability even for a small number of nodes.

To address these challenges, we study two mechanisms that improve the performance of QoMoR in terms of delivery probability, QoS differentiation and energy consumption. First, we study a scheme with a multiple channel ATN with transmit only nodes and propose a MAC scheme called MC-QoMoR that provides effective QoS differentiation. In order to provide differentiated QoS, one approach is to assign dedicated channels to different classes of nodes. Another approach is to divide each class of nodes into k subgroups and assign channel i to the i^{th} subgroup of each class.

In [Shi 2007], a model was developed to study the energy consumption of sensor nodes. In general, the power consumed by the receiver module is equal to or greater than that consumed by the transmitter module depending on the coding and modulation schemes used.

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As an alternative to trading increased complexity for better QoS differentiation using two channels, we study another scheme which uses a single-channel ATN where high priority nodes have asymmetric transceivers, and low priority nodes use transmitters only. We propose a new MAC scheme called A-QoMoR which is motivated by the fact that, in QoMoR, most of the packets were successfully delivered within the first few transmission attempts. If each node transmits a fixed number of times as in QoMoR, the transmissions after the packet have been successfully delivered are useless. Moreover, they can collide with the transmissions of other nodes thereby reducing the delivery probability that can be achieved by them.

Based on this observation we explored the use of a rudimentary receiver module by high priority nodes to receive only acknowledgments (ACK's) from the base station in the form of a fixed radio pulse. The receiver module is not capable of performing any other functions of a standard receiver like channel sensing, packet reception etc. Using the proposed A-QoMoR scheme, high priority nodes will keep retransmitting a packet either until it receives an ACK or in a less likely case, until the maximum number of retransmissions are attempted. This results in fewer transmissions by the high priority nodes which in turn will boost the QoS performance of all the nodes in the system.

Although such devices do not currently exist in the market, it is easy to construct such devices from existing technology. For example RFID tags can incorporate a rudimentary receiver that can still function from the energy harvested from the beacon transmitted by the reader. Existing sensor devices can also be modified to fall into this category by disconnecting parts of the receiver circuitry.

3.5 MC-QoMoR : Multiple Channel QoMoR Scheme

In QoMoR, all the nodes used the same channel to transmit their data and hence the maximum capacity of the system in terms of the number of nodes it can support and the maximum delivery probability that it can achieve was limited. In order improve the capacity of the system we propose the Multiple Channel QoMoR (MC-QoMoR) scheme that uses multiple channels for the transmissions.

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The basic idea is to assign a different channel to each priority class in order to reduce the contention for the shared medium and increase the maximum delivery probability that can be achieved for each node. This assumes that the sink is capable of simultaneously receiving signals transmitted using any channel. However, we consider the use of only two channels as shown in Fig.3.6, as it is practically too complex to design a receiver that can simultaneously receive transmissions from more than two channels. Moreover we show that the performance improvements achieved with two channels provide a delivery probability of close to 100% and hence the use of more channels will not offer significant gains compared to the increase in costs.

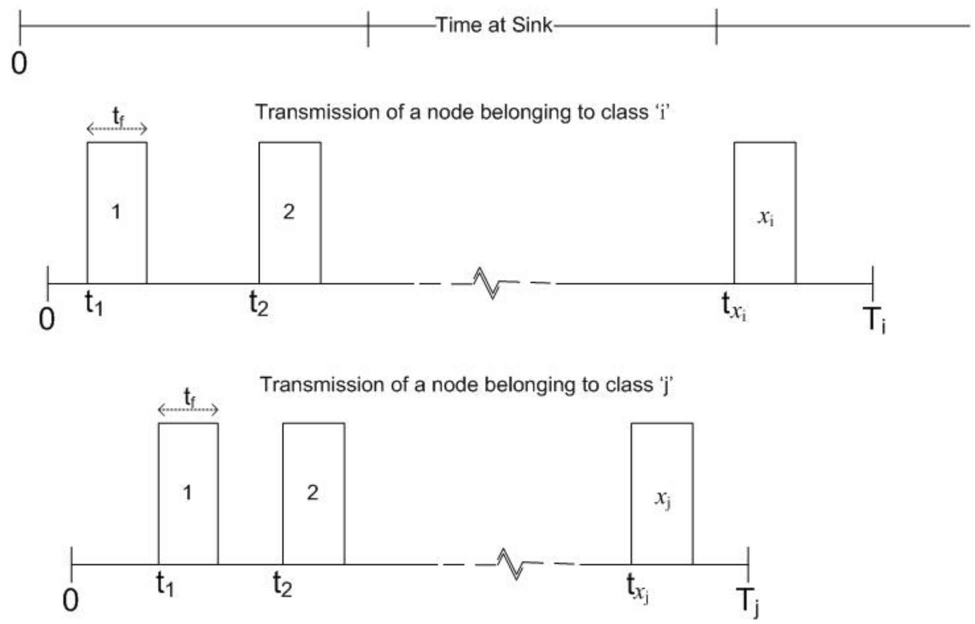

Figure 3.5: Transmissions of two nodes belonging to different classes

The following sections address some fundamental problems for such a system.

1. What are the Physical Layer technologies that make implementing such a system viable?

2. How does the structure of the Physical Layer affect the design of the transmission schemes?

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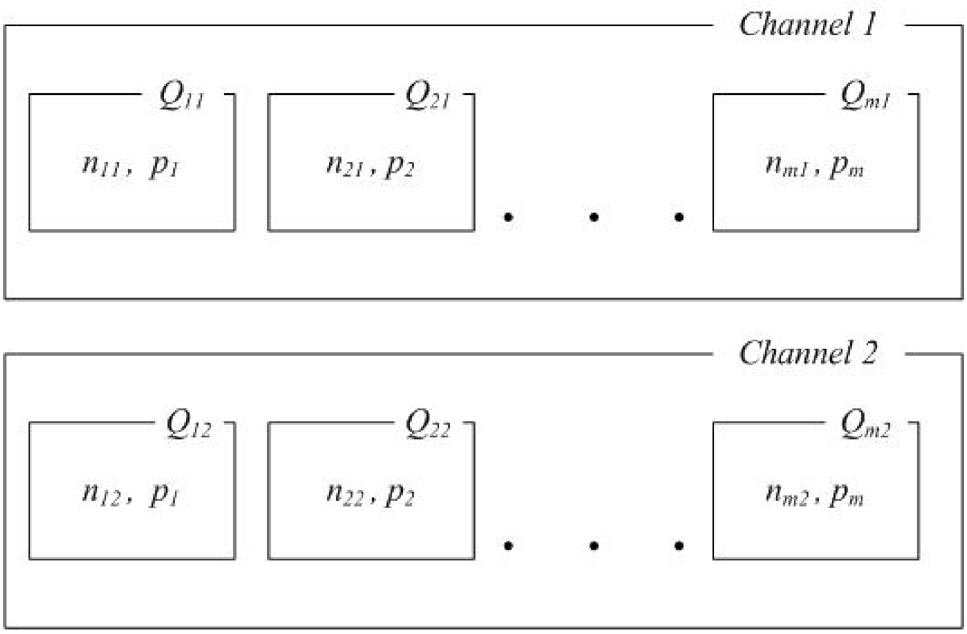

Figure 3.6: System using '2' channels with 'm' classes

3. How do we calculate the optimal number of transmissions for each class of nodes for each channel in order to achieve the global delivery probability requirements?

4. How do we assign channels to the nodes in order to maximize the delivery probability that can be achieved by each class?

3.5.1 Enabling Technologies

The design of the MAC scheme described above relies on using multiple channels that can be realized by various Physical Layer technologies. In this section we present Code Division Multiple Access (CDMA) and Frequency Division Multiple Access (FDMA) based physical layer technologies that can be used to provide the multiple channels of communication for the different classes of nodes in the network. We also discuss the features of each technology and address their consequent effects on the design of the MAC scheme.

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3.5.1.1 Multiple Channels using CDMA in combination with UWB

Although Direct Sequence CDMA is the most widely used form of CDMA, closer examination indicates that it might not a viable solution to the problem at hand. This is because, if a code of length n chips is used, then the packet length as compared to the case where CDMA is not used correspondingly increases by a factor of n (assuming that the symbol rate remains the same). This causes an increase in the transmission duration which will result in a higher collision probability of each packet and thus a lower delivery probability.

However, by using Pulse Position Modulation(PPM) as described in [Orndorff 2004] we can achieve the multiple access feature of CDMA without increasing the symbol rate or the packet length. The scheme modulates the UWB pulses with the code sequences using the PPM technique. The data is then modulated on this new train of pulses using any traditional scheme viz. bi-phase modulation, on-off keying(OOK) etc. This enables us to maintain the same symbol rate and hence the same packet transmission duration as in QoMoR.

Although this scheme offers multiple access without decreasing the effective symbol rate of the transmissions, it poses another interesting problem. Since we assume no global time synchronization between the nodes in the network, the transmissions can start at random instants of time. The PPM technique described in [Orndorff 2004] satisfies the condition of orthogonality only if all the transmission are synchronized with respect to time. Hence we need to take into consideration the effects of interference from transmissions using a different code. Although the errors due to this interference may be far lesser than that caused by direct contention, it is still important to consider them to accurately model the system.

3.5.1.2 Multiple Channels using FDMA

Another possibility is the use of different frequency channels for simultaneous transmissions. The 802.11 Physical Layer, for example, provides multiple frequency channels that can be used for the different classes of nodes. The idea is to assign nodes of different priorities to transmit on different frequencies so that

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the background traffic generated by one class of nodes does not directly affect the other nodes.

Although the frequencies used by the different nodes are separated we must note that the nodes are inexpensive and do not use complex radios that employ advanced filtering techniques. Hence the possibility that the transmission on a given frequency band interferes with a transmission on a another frequency band cannot be ruled out.

3.5.2 Effect of Physical Layer Structure on the efficiency of the MAC protocol

From hereon in the chapter, without loss of generality, we will refer to a code or frequency (depending on the physical layer technology used) as a channel. As detailed in the above discussion we need to consider the effect of interference due to transmissions on other channels on a given channel. For this purpose we define a new parameter called the maximum overlap tolerance, 'd'.

The maximum overlap tolerance signifies the maximum number of packets transmitted using a different channel that can overlap *concurrently* (as illustrated in Fig.3.7) with the packet of interest, without causing an error during detection. Alternately, this means that, if '$d + 1$' or more packets that use a different channel, overlap *concurrently* with the packet of interest, then it cannot be correctly detected at the receiver. The rationale behind such an assumption is that, when '$d + 1$' or more packets using a different channel overlap concurrently with the packet of interest, the combined energy of the '$d + 1$' packets decreases the received Signal to Interference plus Noise Ratio (SINR) for the packet of interest and consequently results in errors during detection. The actual value of 'd' varies from one system to another and our model applies to any system where '$d \geq 1$'.

In short, in such a multiple channel system, a packet will be in error not only when it collides with a packet that uses the same channel, but also when it collides with more than 'd' packets that use a different channel. This observation forms the basis for the theoretical analysis.

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3.5.3 Theoretical Analysis

For ease of presentation, we consider a specific case when there are two QoS classes - a high priority class Q_h and a low priority class Q_l. They contain n_h and n_l nodes respectively, and their minimum delivery probability requirements are p_h and p_l ($p_h > p_l$) respectively. For the analysis we consider a specific channel assignment strategy in which the nodes in Q_h are assigned channel C_1 and the nodes in Q_l are assigned channel C_2.

As explained in 3.5.2 it is important to note that, the transmissions of the two classes are not completely independent as the transmissions generated by the high priority nodes (using C_1) interfere with, and hence cause errors in the transmissions of the low priority nodes(using C_2) and vice-versa.

We proceed as follows to calculate the delivery probability achieved by a node in Q_h which is denoted by P_h. From the analysis in Section 3.3.1.1 we have p_s to be the probability that a given transmission will be successful, only considering collision and physical channel errors. In this case however, we also need to consider the probability I that interference due to transmissions on the other channel causes errors in the transmission. Hence, the probability that a given transmission will be successful will be $p'_s = p_s I$, and the probability that all the x_h transmissions by a node in Q_h are in error is $(1 - p'_s)^{x_1}$.

Thus the delivery probability of a node in Q_h, which is the probability that at least one of x_h transmission are successful is given by

$$P_h = 1 - (1 - p'_s)^{x_h} \qquad (3.12)$$

Using the same approach we can calculate the delivery probability for a node in Q_l.

3.5.3.1 Bounds on the delivery probability

In the following analysis we attempt to find bounds on the probability that interference causes errors, I, and subsequently on the delivery probability of a high priority node.

First we calculate the interfering traffic is defined as the traffic generated by all the nodes using a *different channel* from that used by the node. For the nodes

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in Q_h, this is the traffic generated by all the nodes in Q_l and its rate is given by

$$\lambda'_h = \frac{n_l x_l}{T_l} \tag{3.13}$$

By definition, if a packet arrives at 't_0', and the number of packets using a different channel that arrive in the interval $[t_0 - t_h, t_0 + t_h]$, which is denoted by 'k', is such that, $0 \leq k \leq d$, then interference does not cause an error. For a high priority node, this probability is given by

$$L = \sum_{k=0}^{d} e^{(-2\lambda'_h t_l)} \frac{(-2\lambda'_h t_l)^k}{k!} \tag{3.14}$$

Now, we need to consider the case when $d+1 \leq k \leq 2d$. Specifically, consider the case when $k = d{+}1$. Fig.3.7(a) illustrates a scenario when all the '$d{+}1$' packets overlap with the packet of interest and cause an error. However, there is also the possibility that these '$d+1$' packets are disjoint in the interval $[t_0 - t_h, t_0 + t_h]$ (i.e.) all of them do not *overlap* with the packet under consideration as shown in Fig.3.7(b). In this case, although '$d+1$' packets using a different channel arrive in the interval $(t_0 - t_h, t_0 + t_h)$ they do not cause an error because not *all* the packets overlap with the packet of interest. Using similar arguments we can prove that this is true for all values of 'k' satisfying the condition $d+1 \leq k \leq 2d$.

Next, consider the case when 'k' is equal to '$2d{+}1$'. As illustrated in Fig.3.7(c), in the worst case, these 'k' packets can arrive as two disjoint (not overlapping with each other) sets containing 'd' and '$d+1$' packets. However, by definition, only '$d+1$' packets need to overlap with the packet of interest to cause an error. Hence, if '$2d{+}1$' packets of a different channel arrive in the interval $[t_0{-}t_h, t_0{+}t_h]$, then it definitely causes a packet error. By induction we can prove that this is true for $k \geq 2d+1$. In summary, if a packet arrives at t_0 and $k \geq 2d+1$ packets, using a different channel, arrive in the interval $[t_0 - t_h, t_0 + t_h]$, then it definitely causes an error in the packet of interest. Thus we need not consider this case for the calculation of the probability that interference does not cause an error.

From the above arguments it is evident that (3.14) gives a lower bound on I which is the probability that the interference is insufficient to cause error in the detection of the packet of interest. On the other hand, if we replace the upper

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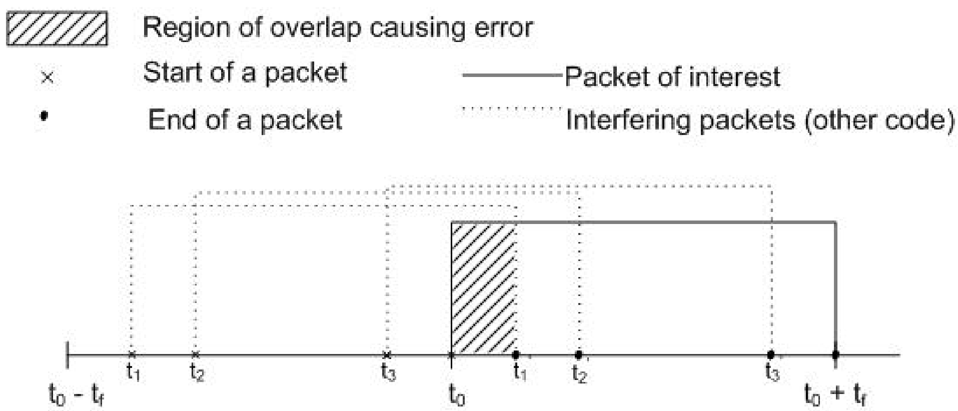
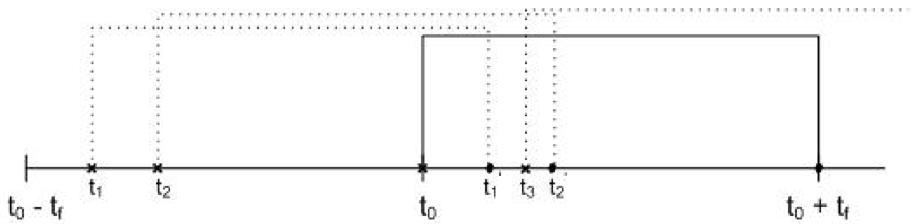
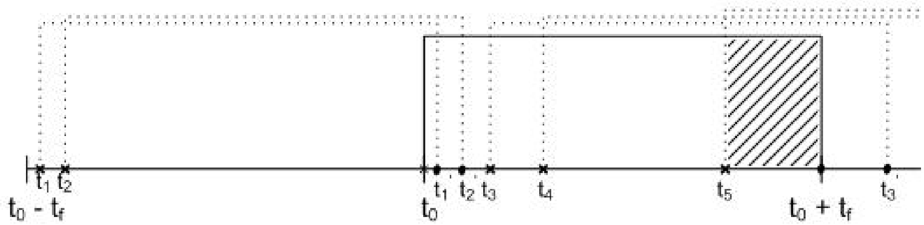


(a) '$d+1$' packets overlap with the packet of interest causing an error



(b) '$d+1$' packets arrive in the interval $t_0 - t_h, t_0 + t_h$ but do not cause a packet error as all of them do not overlap *concurrently* with the packet of interest at the same time



(c) '$2d+1$' packets arrive in the interval $t_0 - t_h, t_0 + t_h$ as two disjoint sets of 'd' and '$d+1$'

Figure 3.7: Different possibilities when interference causes errors ($d = 2$)

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limit of the summation in (3.14) with '$2d$', we will obtain a corresponding upper bound which is given by

$$U = \sum_{k=0}^{2d} e^{(-2\lambda'_h t_l)} \frac{(-2\lambda'_h t_l)^l}{k!} \tag{3.15}$$

Substituting these bounds on I in (3.12) gives the corresponding bounds on the delivery probability. Using this analysis we can find the bounds on the delivery probability for any class of nodes in the network.

3.5.4 Channel Assignment

In this section we study the problem of allocating the channels to the nodes and the corresponding effect on the system performance. For ease of representation, we divide the nodes in class Q_1 into two subgroups Q_{h1} and Q_{h2} which contain n_{h1} and n_{h2} nodes respectively, such that, $n_{h1} + n_{h2} = n_1$. The nodes in Q_{h1} are assigned channel C_1 and those in Q_{h2} are assigned channel C_2. Note that both the subgroups Q_{h1} and Q_{h2} require a minimum delivery probability of p_1. Similarly the nodes in class Q_2 are divided into two subgroups Q_{l1} and Q_{l2} and assigned channels C_1 and C_2 respectively.

The theoretical analysis in Sec. 3.5.3 assumed that the nodes in Q_h are assigned channel C_1 and the nodes in Q_l are assigned channel C_2. Let us call this channel assignment strategy *Approach A*. Formally, we set $n_{h1} = n_h$, $n_{h2} = 0$, $n_{l1} = 0$, $n_{l2} = n_l$ and assign C_1 to Q_{h1} and C_2 to Q_{l2}.

In this approach we assign channel C_1 to the high priority nodes and channel C_2 to the low priority nodes. In *Approach A* the background traffic for the nodes in each group is reduced to that generated by the nodes in the same QoS class as compared to a single channel system. Such a reduction has a much more dominant effect on the performance than the effect of interference from the traffic using a different channel. Accordingly the nodes in each QoS class are able to individually achieve a higher delivery probability as compared to the case where only a single channel is used. In particular, when the background traffic of Q_{h1} and Q_{l2} (i.e. λ_{h1} and λ_{l2} respectively) are comparable, the performance of this approach is optimum. However, in cases where the background traffic of the

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two groups differs by a large value then this approach may not provide the best solution.

For example, if $\lambda_{h1} \gg \lambda_{l2}$ then the reduction in background traffic for the nodes in Q_{h1} is relatively small. But, for the nodes in Q_{l2} there will be a large reduction in background traffic and they will be able to achieve a much higher delivery probability than the case where multiple channels are not used.

An alternate method is to divide the nodes in the high and low priority nodes among the two groups and assign C_1 to a few nodes and C_2 to the rest of the nodes for each QoS class. Let us call this strategy *Approach B*. To describe the node distribution between the channels, we define two parameters α and β which govern the distribution of the nodes between the two channels. The node distribution can be described using the equations $n_{h1} = \alpha n_1$, $n_{h2} = (1-\alpha)n_1$, $n_{l1} = (1-\beta)n_2$, $n_{l2} = \beta n_2$.

It must be noted that the theoretical analysis still applies to this channel assignment strategy. All that is required is to calculate the rate of the background traffic and interfering traffic, and the delivery probabilities P_1 and P_2 as $\min(P_{h1}, P_{h2})$ and $\min(P_{l1}, P_{l2})$ respectively.

An interesting problem in this approach is to find the optimum value of α and β that will give the maximum P_h satisfying the condition that $P_l \geq p_l$. The complexity of this problem is accentuated by the fact that the number of retransmissions of the four groups are independent of each other. In other words it is not necessary that $x_{h1} = x_{h2}$ and $x_{l1} = x_{l2}$.

However, the equations describing the nodes distribution and the delivery probability form a linearly constrained system and can be solved numerically. Fig.3.8 illustrates the variation of P_h for different values of α and β. The delivery probability is directly affected by the background traffic perceived by a node. Hence, P_{h1} monotonically decreases with α and increases with β. P_{h2}, however, monotonically increases with α and decreases with β. From this it is evident that highest delivery probability is indeed achieved when $\alpha = 0.5$ and $\beta = 0.5$.

Fig.3.9 shows the Packet Error Probability $(1 - P_h)$ versus the ratio of the nodes in Q_h to Q_l. The graph is generated by assuming that $n_1 = 25$ and finding the Packet Error Probability for *Approach A* and *Approach B* (at $\alpha = \beta = 0.5$) for different values of n_2. The performance of *Approach B* is better than

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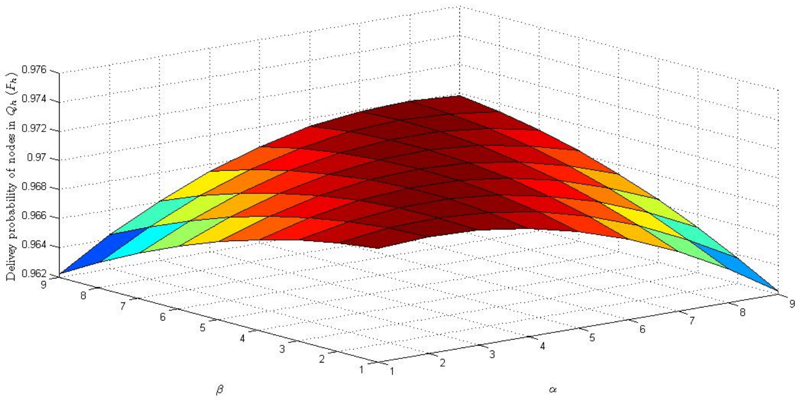

Figure 3.8: Variation of P_h with α and β in *ApproachB*

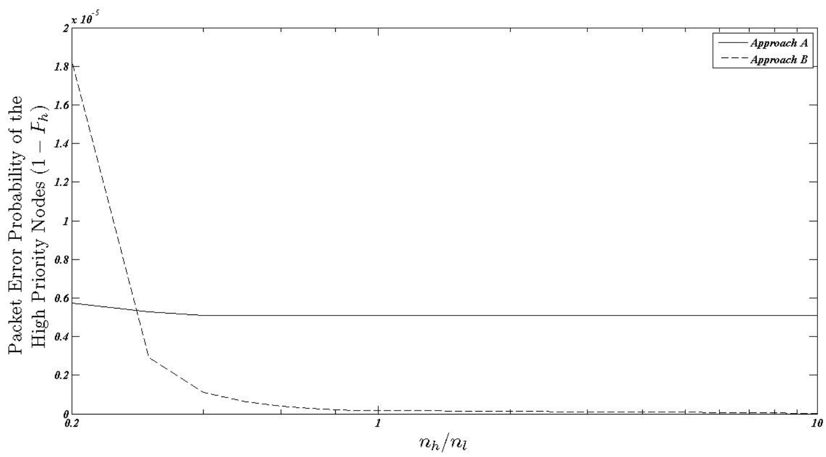

Figure 3.9: Packet Error Probability for *Approach A* and *Approach B*

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Approach A for all cases where the ratio $\frac{n_1}{n_2}$ is greater than 0.3. However, for $\frac{n_1}{n_2} < 0.3$, *Approach B* does not provide a solution better than *Approach A*. This behavior suggests that *Approach A* performs better when there are a large number of nodes in the lower priority group and consequently the total traffic generated by the low priority nodes is greater than that generated by the high priority nodes. For all other cases *Approach B* performs better.

3.5.5 Energy Consumption

The simplicity of the MC-QoMoR MAC scheme allows us to analytically calculate the energy consumed by the sensor nodes. This is an important tool in accurately determining the lifetime of the network.

Let E_{tx} be the energy consumed by the sensor node per unit time for transmitting. Let E_s be the energy consumed by the sensor node when it is sleeping. The energy consumed for each transmission attempted by a sensor node is thus $E = E_{tx}t_i$. In each data generation interval the sensor node attempts an average of x_i transmissions and sleeps for the rest of the time. Thus the energy consumes per data generation interval is given by

$$E_{avg} = E_{tx} \times t_i \times x_i + E_s(T_i - t_i \times x_i) + E_{dev} \times T_i \tag{3.16}$$

where E_{dev} is the average energy consumed for the operation of the other circuits in the device, for example, the microprocessor, memory etc.

3.6 A-QoMoR : Asymmetric QoMoR Scheme

In QoMoR, depending on the size of the network and other parameters, we have shown that the value of x_{opt} can vary between 1 and 10. An analysis of this scheme, however, also shows that, in most cases, the packet is successfully delivered to the sink after the first few, say x', transmission attempts, where $x' < x$. In each case, the additional $x - x'$ transmission attempts that occur after the packet has been successfully delivered to the sink, contribute not only to wasted energy, but also to an unnecessary increase in the background traffic and hence contention for the shared wireless channel.

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The idea behind the proposed MAC protocol is to take advantage of the (rudimentary) receiver at each sensor node in order to eliminate these unnecessary transmissions and hence improve the overall delivery probability that can be achieved by the system. In order to accomplish this, there is a need for some form of feedback from the sink to the sensor nodes. Hence, in the proposed protocol we use a very short ACK packet that is transmitted by the sink immediately after it receives a successful transmission from a sensor node.

The following describes a simple medium access scheme called *Asymmetric QoMoR (A-QoMoR)*. The A-QoMoR MAC, upon receiving a packet generated by the higher layers, randomly picks x_{max} instants, $t_1, t_2, \cdots, t_{x_{max}}$, within the data generation interval T. As illustrated in Fig. 3.10, it *may* attempt to transmit the packet at each of these instants.

To conserve energy, the sensor node is initially in a sleep state, during which both the transmitter and receiver modules are turned off. At the first chosen transmission instant, t_1, the sensor node turns on its transmitter and transmits the packet as shown in Fig. 3.10. The sink is expected to send a short acknowledgement (ACK) packet as soon as it successfully receives the packet from a sensor node. We note that there is a small duration between the time the sink completes receiving a packet successfully and the time it starts to transmit the ACK. This is known as the turnaround time, t_{ta}, and is the sum of the processing delays at the sink and the time taken by the sink to switch its transceiver from receiving to transmitting mode.

On completion of the transmission, whose duration is denoted by t_{tx}, the sensor node turns off the transmitter module and turns on the receiver module. In order to minimize the energy consumed by the receiver module, the sensor node turns off the receiver module, *irrespective of whether an ACK was received or not*, after a fixed duration of time called the receiver-on-time, which is denoted by t_{ro}. The receiver-on-time is calculated taking into account the turnaround time of the sink node, t_{ta}, and the transmission of duration of the ACK packet, t_{ack}. Assuming that the propagation durations are negligible, it is given by $t_{ro} = t_{ta} + t_{ack}$. The total channel access duration, t, for each transmission attempt of a sensor node is thus

$$t = t_{tx} + t_{ta} + t_{ack} \tag{3.17}$$

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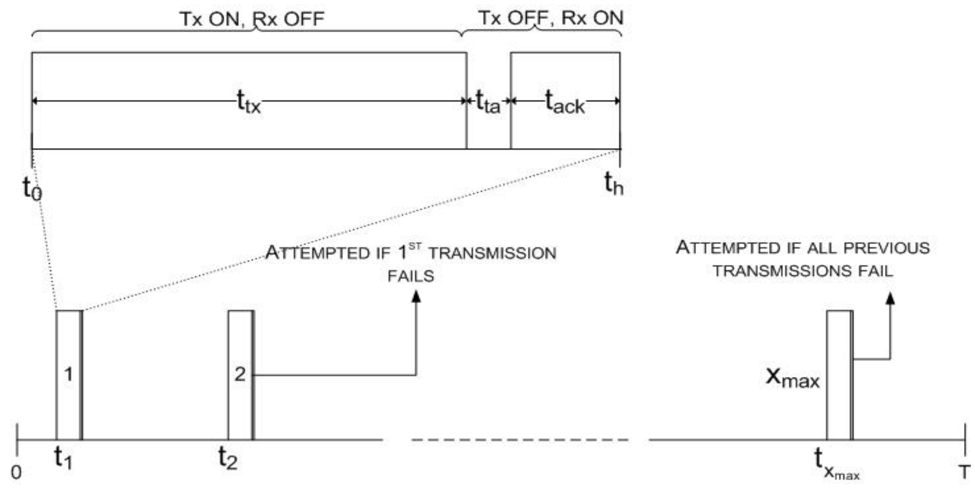

Figure 3.10: The A-QoMoR MAC channel access strategy

If an ACK was received during the receiver-on-time, the sensor node goes into the sleep state until the next packet is generated by the higher layers and *does not* transmit at any of the remaining transmission instants it had chosen. Otherwise, it will go through the process of waking up and transmitting the packet at the next chosen transmission instant. This process repeats until either an ACK is received or x_{max} transmissions are completed.

If no ACK is received after x_{max} transmissions, the packet is considered to be lost and will be discarded. *Thus a successfully delivered packet has a maximum delay of* T. Thus, we are able to guarantee a deterministic upper bound on the latency of successfully delivered packets which is currently not guaranteed by any of the CSMA based protocols.

When a new packet is generated, the process repeats by picking x_{max} random transmission instants within the data generation interval and performing the transmissions.

3.6.1 Frame Formats

The A-QoMoR MAC protocol uses only two types of packets viz. 1) Data Packet and 2) ACK packet. The data packet is transmitted by the sensor nodes to the sink and the ACK packet is transmitted by the sink to the sensor nodes. In the

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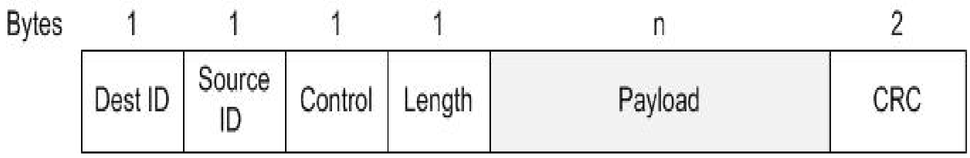
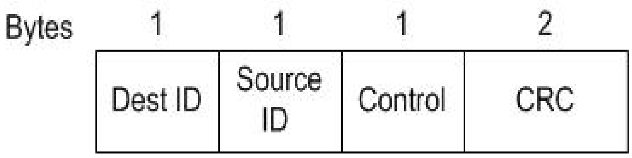
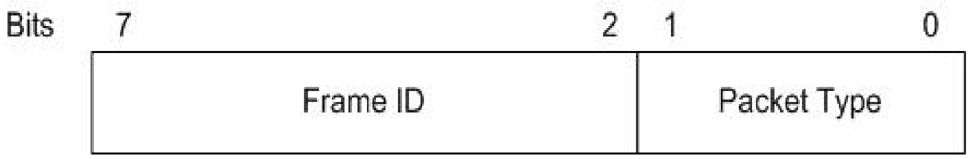


(a) Frame format for data packets



(b) Frame format of the ACK packets



(c) Format of the Control Field

Figure 3.11: Packet Formats used by the A-QoMoR protocol

following we present the headers used by the protocol.

The A-QoMoR MAC protocol adds a total of 6 bytes of overhead to each payload packet received from the higher layers before transmitting it. As shown in Fig.3.11(a), the headers consist of four fields, Destination ID, Source ID, Control Field and Length. The Destination and Source ID fields contain the device ID of the device to which the packet is intended and the device that transmitted the packet. Each of these fields is one byte long and hence a maximum of 256 different devices can be addressed. The Length field indicates the length of the payload and is also one byte long allowing a maximum payload size of 256 bytes. Considering the nature of packets generated by the class of networks we study in this work this is acceptable. A standard 16-bit Cyclic Redundancy Check (CRC) is added to the end of the payload in order to detect bit-errors in the packet at the receiver.

The Control Field is further subdivided into two sub-fields that represent the Packet ID and the Packet Type. As shown in Fig.3.11(c) the most significant 6 bits are allocated for the Packet ID. The Packet ID field is incremented (modulo-

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64) each time a new packet arrives from the higher layers. It is also used in the ACK packet to identify the packet that is being acknowledged. The least significant 2 bits are used to indicate the Packet Type, namely, Data or ACK packet.

Whenever the sink successfully receives a data packet with a particular Packet ID, it sends an ACK packet acknowledging the reception. The size of the ACK packet is kept to a minimum in order to reduce t_{ack}. As shown in Fig.3.11(b), it consists of a Destination ID, Source ID, Control Field and CRC. The Destination ID, Source ID and CRC fields perform the same function as in the data packet. The Packet ID sub-field is set to the same value as the Packet ID of the data packet that was successfully received and the Packet Type sub-field is set to the ACK packet type.

3.6.2 Theoretical Analysis

In the A-QoMoR protocol, the sensor nodes will stop retransmitting the packet once they receive an ACK from the sink, the number of transmission attempts that each sensor node will make for each packet will be different. The major challenge in the analysis of A-QoMoR is the modeling of the traffic generated by the sensor nodes, as the number of transmissions they attempt for each packet is different. Although x_{max} might be set to a high value, the average number of transmissions attempted by a sensor node to successfully deliver a packet is typically much lesser. We denote this parameter by x_{avg}. Since the energy consumed by each sensor node is directly proportional to x_{avg}, it is an important metric that quantifies the performance of A-QoMoR.

Before proceeding with the analysis, we define the variables used - n, T, t are the total number of sensor nodes, the data generation interval and the channel access duration of the sensor nodes. It is assumed that the size of the packets generated by all the nodes and the ACK packet generated by the sink is a constant and hence the transmission duration, t, is also a constant. Further, it is also assumed that $t \ll T$.

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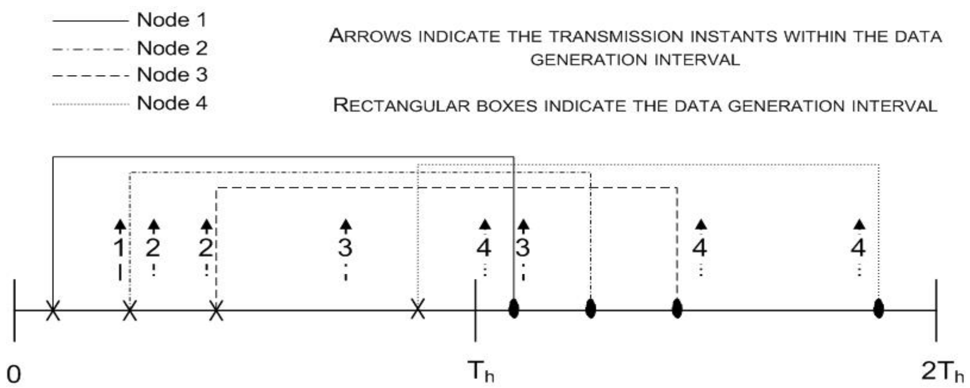
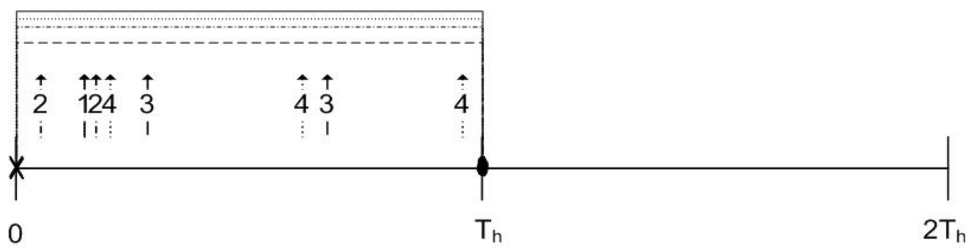


(a) Random starting points for the data generation intervals



(b) Same starting points for the data generation intervals

Figure 3.12: Variation of Traffic for Asynchronous and Synchronous Data Generation Intervals

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3.6.3 Preliminaries

Since the transmissions from all the sensor nodes are independent and asynchronous events, we observe that the data generation intervals of the sensor nodes are not "synchronized" in that, they have different starting times for their data generation intervals. Alternately, the arrival of packets to the MAC layer of each sensor node is not synchronized.

Since all the sensor nodes in the network have the same data generation interval T, the start of these intervals can be assumed to be uniformly distributed within the interval T. Further, each sensor node transmits at random instants of time within *its* data generation interval. A closer inspection reveals that, although each sensor node might transmit a different number of times (until its packet is successfully delivered to the sink) within each of its data generation intervals, the transmissions from all the sensor nodes in the network tend to be uniformly distributed over time.

Fig. 3.12(a) illustrates this phenomenon. The figure depicts the transmissions of four sensor nodes in the network where *Node 1* successfully delivers its packet on the first transmission attempt, *Nodes 2* and *3* succeed on the second transmission attempt while *Node 4* succeeds on the third attempt. As we can see, the start of the data generation intervals of the four sensor nodes are uniformly distributed in the interval $[0, T]$ and the transmissions of all the sensor nodes are uniformly distributed in the interval $[0, 2T]$. *Consequently, we can deduce that the average number of transmissions, x_{avg}, is always constant with respect to time.*

3.6.3.1 Analysis of the General Case

Since the transmissions from all the sensor nodes are independent, asynchronous events and the packet transmission durations are very small compared to the data generation interval, the arrival of packets to the channel can be modeled as a Poisson process [Papoulis & Pillai 2002]. Consequently, the probability of k frames being transmitted during some time period t is given by

$$P_{t,k} = e^{-\lambda t} \frac{(\lambda t)^k}{k!} \tag{3.18}$$

where λ is the rate of background traffic.

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The background traffic, is defined as the traffic generated by all the *other* sensor nodes in the network. More specifically, the rate of background traffic, λ, can be expressed as

$$\lambda = \frac{(n-1)x_{avg}}{T} \tag{3.19}$$

For a transmission by a sensor node to be successful, we need that $k = 0$ frames be transmitted by all the other sensor nodes during the interval $[t_0 - t, t_0 + t]$, where t_0 is the start of the packet transmission. Accordingly, the probability of a transmission by a sensor node being successful is

$$p_s = e^{\frac{-2(n-1)x_{avg}t}{T}} \tag{3.20}$$

Since the sensor nodes use the wireless medium that is inherently unreliable for communications, excluding the packet errors caused due to the nature of the wireless medium will result in a significant error in the calculation of this probability. In order to account for packet loss due to the wireless medium we introduce a factor L, which is defined as the probability that there are no bit errors in the packet. We can calculate L as

$$L = (1 - BER_{tx})^{b_{tx}}) \times (1 - BER_{ack})^{b_{ack}} \tag{3.21}$$

where BER_{tx} is the Bit Error Rate of the wireless medium for the modulation used by the transmitter, b_{tx} is the length of the transmitted packet in bits, BER_{ack} is the Bit Error Rate of the wireless medium for the modulation used by the receiver and b_{ack} is the length of the ACK packet in bits. This model is able to capture the errors caused by the physical medium and hence the average packet loss, with sufficient accuracy.

Thus the probability that a transmission by a sensor node is successful can be modified as

$$p_s = e^{\frac{-2(n-1)x_{avg}t}{T}} \times L \tag{3.22}$$

The achieved delivery probability, P, is the probability that at least one of the transmissions of the sensor node results in the successful delivery of the packet to the sink. It is thus given by

$$P = 1 - (1 - p_s)^{x_{max}} \tag{3.23}$$

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We now proceed to calculate the average number of transmissions attempted by each sensor node, x_{avg}, to successfully deliver a packet to the sink. First, it should be noted that number of transmissions attempted by a sensor node is a random variable. Next, we observe that, irrespective of any other event, every sensor node will attempt at least one transmission in each data generation interval. So, the transmission attempts by the sensor nodes can be categorized as, one transmission (the first transmission attempt for a packet within each data generation interval) followed by, at most, $x_{max} - 1$ retransmissions. A critical observation here is that, these are two dissimilar events as the first transmission is *always* attempted while each of the retransmissions *may or may not* be attempted.

Hence, we calculate $x_{avg} = 1 + x_{retx}$, where, x_{retx} is the average number of retransmissions attempted to successfully deliver a packet to the sink.

Since the number of retransmissions attempted by each sensor node is also a random variable, by the definition of the mean of a random variable, it is given by

$$x_{retx} = \sum_{i=1}^{x_{max}-1} i \times (1-p)^i \tag{3.24}$$

and hence

$$x_{avg} = 1 + \sum_{i=1}^{x_{max}-1} i \times (1-p)^i \tag{3.25}$$

Eq. (3.22) and (3.25) form a system of non-linear equations involving two variables. These equations can be solved under the constraint $P \geq p$ and the corresponding value of x_{max} can be calculated. We note that there may be many solutions for x_{max}, however, in order to minimize the energy consumption, we would like to choose the minimum of all the possible solutions.

3.6.3.2 Calculation of the Lower Bound

In the analysis of the general case, we assumed that the start of the data generation intervals and hence the transmissions were uniformly distributed over time. We however note that, if the start of the data generation intervals is *non-uniformly*

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distributed, the distribution of the transmissions over time is also non-uniform. As illustrated in Fig. 3.12(b), if we assume that the data generation intervals of all the sensor nodes start at the same time, the background traffic in the channel will initially be high and gradually reduce as more and more sensor nodes successfully deliver their packets and stop further retransmissions. This is because each sensor node randomly chooses x_{max} instants to transmit within its data generation interval, but will stop their remaining transmissions after receiving an ACK.

Thus, if the start of the data generation intervals are non-uniformly distributed, the average number of transmissions, x_{avg} is no longer a constant over time.

Since the x_{max} transmission instants chosen by each sensor node are still uniformly distributed in the interval T, we can approximate that all the sensor nodes will attempt their first transmission during the same sub-interval $[0, \frac{T}{x_{max}})$. Subsequently, all the sensor nodes whose first transmission failed will attempt their second transmission (or first retransmission) during the second sub-interval $[\frac{T}{x_{max}}, \frac{2T}{x_{max}})$ and so on. This clearly is an over estimation of the contention for each transmission and hence gives us an upper bound on the background traffic in the channel. Since the delivery probability and the background traffic in the channel are inversely proportional to each other, this also gives us the lower bound on the delivery probability.

To calculate λ_1, the rate of background traffic for the first transmission of a sensor node, we consider the worst case scenario, where all the n sensor nodes in the network contend for the channel with their first (mandatory) transmission during the first sub-interval $[0, \frac{T}{x_{max}})$. Thus, we have $\lambda_1 = \frac{(n-1)x_{max}}{T}$.

The probability that the first transmission of a sensor node will be successful is denoted by p_1. On an average, $p_1 \times n$ sensor nodes will successfully deliver the packet on the first attempt. Consequently, only $(1 - p_1) \times n$ sensor nodes will attempt a second transmission. Further, the nodes only have $x_{max} - 1$ remaining transmission attempts. Accordingly, the rate of background traffic for a sensor node attempting its second transmission, λ_2, will be $\frac{((1-p_1)n-1)(x_{max}-1)}{T}$.

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In general, the rate of background traffic for the j^{th} transmission of a node, λ_j, is given by

$$\lambda_j = \frac{((\prod_{k=1}^{j} 1 - p_{k-1})n - 1)(x_{max} - (j-1))}{T} \tag{3.26}$$

where the delivery probability of the j^{th} transmissions is given by

$$p_j = e^{-2\lambda_j t} \times L \tag{3.27}$$

It should be noted that the above analysis has been done considering the worst case scenario for the rate of the background traffic. Since the rate of background traffic is inversely proportional to the delivery probability and directly proportional the average number of transmission attempts, the following expressions for the delivery probability and the average number of transmission attempts provide the corresponding lower and upper bounds.

The lower bound on the delivery probability, P_s^l, can then be calculated as the probability that at least one of the transmissions attempted by a sensor node results in the successful delivery of a packet to the sink. It is thus given by

$$P_s^l = 1 - \prod_{j=1}^{x_{max}} (1 - p_j) \tag{3.28}$$

Proceeding in a manner similar to the calculation of the average number of transmissions in Sec. 3.6.3.1, we can calculate the upper bound on the average number of transmissions that will attempted by each sensor node as

$$x_{avg}^u = 1 + \sum_{j=1}^{x_{max}-1} (\prod_{k=1}^{j} 1 - p_k) \times j \tag{3.29}$$

3.6.3.3 Energy Consumption

The simplicity of the A-QoMoR MAC protocol also allows us to analytically calculate the average energy consumed by the sensor nodes. This is an important tool in accurately determining the lifetime of the network.

Let E_{tx}, E_{rx} be the energy consumed by the sensor node per unit time for transmitting and receiving respectively. Let E_s be the energy consumed by the sensor node when it is sleeping.

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The energy consumed for each transmission attempted by a sensor node is thus

$$E = E_{tx}t_{tx} + E_{rx}t_{ro} \tag{3.30}$$

In each data generation interval the sensor node attempts an average of x_{avg} transmissions and sleeps for the rest of the time. Thus the average energy consumes per data generation interval is given by

$$E_{avg} = E \times x_{avg} + E_s(T - t \times x_{avg}) + E_{dev} \times T \tag{3.31}$$

where E_{dev} is the average energy consumed for the operation of the other circuits in the device, for example, the microprocessor, memory etc.

3.6.4 Performance Study

To study the performance of A-QoMoR, we perform simulations using the $NS-2$ simulator. The protocol was implemented at the MAC layer of the $NS-2$ framework. First, we present the results from the analysis and simulation of the A-QoMoR protocol. Next, we present results from the practical implementation of the A-QoMoR protocol on a network consisting of XSM motes deployed and compare them to the analytical and simulations results.

The A-QoMoR protocol is designed for sensor nodes that are equipped with asymmetrical transceivers. Hence, we compare the A-QoMoR MAC protocol to the QoMoR scheme that is also capable of operating using the same hardware.

The performance study would however be incomplete without comparisons to existing MAC protocols. Hence, we setup a network consisting of sensor nodes equipped with asymmetric transceivers running the A-QoMoR MAC protocol and another network consisting of sensor nodes equipped with fully functional transceivers running the 802.11 protocol. We study and compare the delivery probability and energy consumption of the sensor nodes in both networks under the same traffic conditions.

3.6.4.1 Simulation Setup

To establish a common base for the comparison of the protocols, we fixed the rate of data generated by the higher layers and the physical layer parameters like

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channel bandwidth, transmit power and receiver sensitivity. The following are the parameters used in the simulations.

A total of a 100 nodes were placed in a random flat-grid topology within a $50m \times 50m$ region. The uplink channel datarate was set to $2Mbps$ and the downlink channel datarate was set to $250Kbps$. The transmit power of the radio module used was set to $200mW$ while the receive power was set to $100mW$. The physical layer propagation model was chosen to incorporate the shadowing and multipath characteristics of the typical operating environment of these networks. The size of the MAC payload was set to $64bytes$ and the data generation interval T was set to $250msec$. These parameters were chosen from the typical requirements of the applications described in [Stipanicev & Marasovic 2003] [Andrisano *et al.* 2003] [Chen *et al.* 2002] [Anliker *et al.* 2004] [Elbatt *et al.* 2006] and standard device specifications.

The frame formats described in Sec. 3.6.1 were used to construct the packets in the simulations. Thus, the total data packet size, including the MAC overhead, is 70 bytes resulting in a transmission duration of $t_{tx} = 284\mu sec$. For A-QoMoR, the total ACK packet size is 5 bytes. Consequently, the transmission duration of the ACK packet is $t_{ack} = 160\mu sec$. The turnaround time t_{ta} was set to $10\mu sec$, resulting in a channel access duration of $t = 454\mu sec$ per transmission. These values were used in calculating the performance of A-QoMoR analytically.

3.6.5 Analysis and Simulation results of A-QoMoR

The analysis and simulation results of A-QoMoR for the setup described above are presented here.

Fig.3.13 shows the variation of the delivery probability, P_s, achieved by the nodes for different values of x_{max}. The delivery probability monotonically increases with x_{max}. This follows from the fact that a higher number of transmission attempts improves the delivery probability. Further, the results indicate that the theoretical model and the simulation results concur with each other.

Fig. 3.14 shows the simulation and analysis results of the average number of transmissions (x_{avg}) attempted by A-QoMoR for different values of x_{max}. The results show that x_{avg} initially increases relatively slowly as compared to x_{max}.

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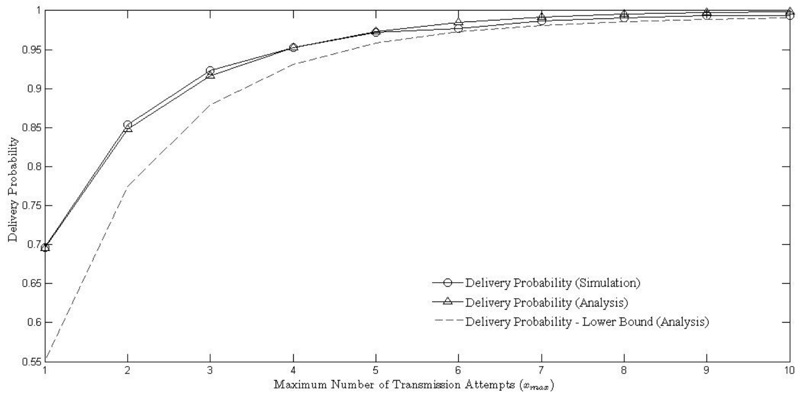

Figure 3.13: Analysis and simulation results for Delivery Probability

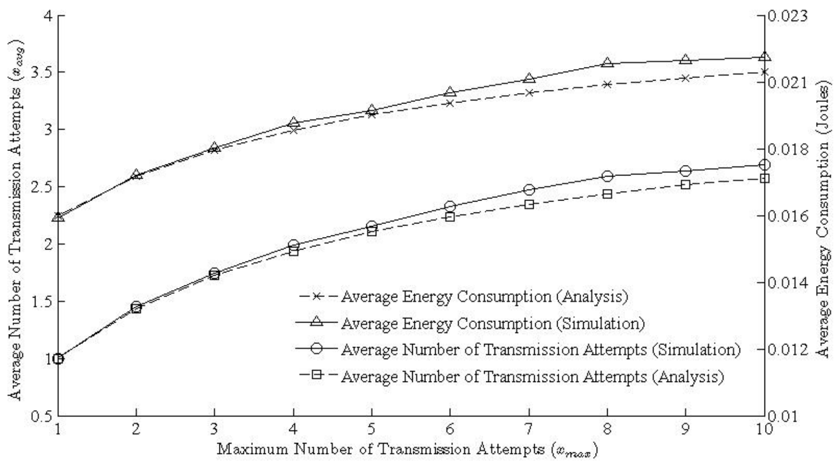

Figure 3.14: Analysis and simulation results for Energy Consumption and Average Number of Transmission Attempts

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This result concurs with our initial prediction that, although x_{max} may be set to a high value, most packets are successfully delivered in the first few transmission attempts. Fig. 3.14 also shows the energy consumption of the nodes in the network and we can see that it is proportional to the average number of transmission attempts.

3.6.6 Implementation of A-QoMoR on XSM motes

The A-QoMoR protocol was implemented on a test bed consisting of 15 XSM motes. The XSM motes were chosen as they have a CC1000 radio module that is typical of a low cost sensor node and has a data rate of 19.2Kbps. Due to the unavailability of off-the-shelf hardware with asymmetric transceivers, we used the fully functional transceiver of the XSM motes, albeit, without using its capability to sense the channel. To simulate a lower data rate downlink channel the length of the ACK packet was increased 8 fold to ensure that the ratio of the uplink to downlink datarate remains the same as in the simulation setup.

From the analysis in Sec. 3.6.2, we note that the delivery probability of the nodes is proportional to the factor $\frac{t_f \times n}{T}$. Since only 15 XSM motes were available we setup the parameters t_f and T such that the factor remains the same as in the simulation setup. Hence, we can compare the results in Fig.3.15 and Figs.3.13 and 3.14.

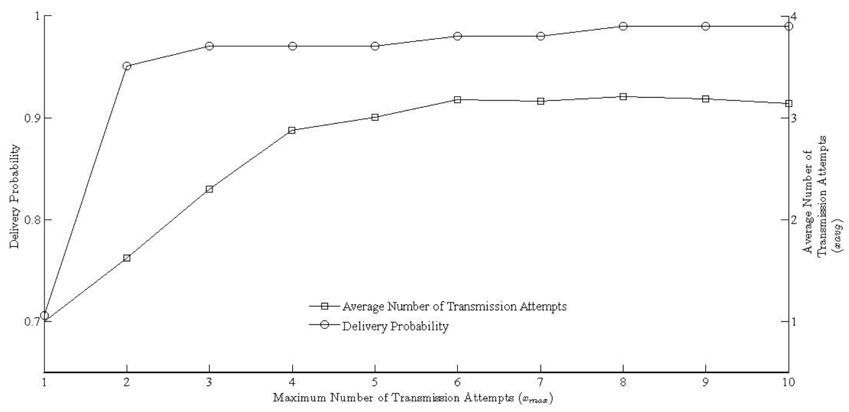

Figure 3.15: Performance of A-QoMoR on a Practical Test-Bed

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The test was setup with the motes placed randomly in an office room that had a lot of obstructions in the form of furniture. Further, there was interference from other wireless devices like an 802.11 access point and cellular devices. This environment was chosen in order to study the performance of the protocol in a setup that is close to a realistic deployment of such networks.

The results from the test bed have the same general trend as the simulation results. We do however, observe that the average number of transmissions are slightly higher than that from the simulation results. This can be attributed to the fact that the simulation does not take into account interference from other sources like wireless LAN and cellular devices. However, the results do indicate the same trend further corroborating the theoretical model of the protocol.

3.6.6.1 Comparison of A-QoMoR and QoMoR

In order to provide a common base for comparing A-QoMoR and QoMoR, the same MAC headers were used for the data packet. The receiver module was completely switched off while simulating QoMoR.

A comparison with the delivery probability achieved when the sensor nodes use QoMoR shows that A-QoMoR outperforms QoMoR significantly. Note that even the lower bound on the delivery probability for A-QoMoR is higher than the achieved delivery probability of QoMoR. When QoMoR achieves its highest delivery probability of $P = 0.86$, at $x = 4$, A-QoMoR achieves a much higher delivery probability of $P = 0.95$ for a corresponding value of $x_{max} = 4$.

In terms of energy consumption, A-QoMoR consumes a significantly lower energy than QoMoR in most cases, as seen in Fig. 3.16. This is due to the fact that, even though x_{max} is high, the average number of transmissions, which directly affects the energy consumption in A-QoMoR, is low. Hence the extra energy consumed by the receiver module is offset by the smaller number of transmissions attempted. Fig. 3.16 shows that, at $x_{max} = 4$, when QoMoR achieves its maximum delivery probability, A-QoMoR achieves a much higher delivery probability while consuming about 10% lesser energy.

A-QoMoR achieves significant performance gains over QoMoR because they make use of their capability to receive. However, this also makes them more

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complex than the sensor nodes required for the operation of QoMoR. Hence, there is a definite cost-performance trade off introduced by A-QoMoR.

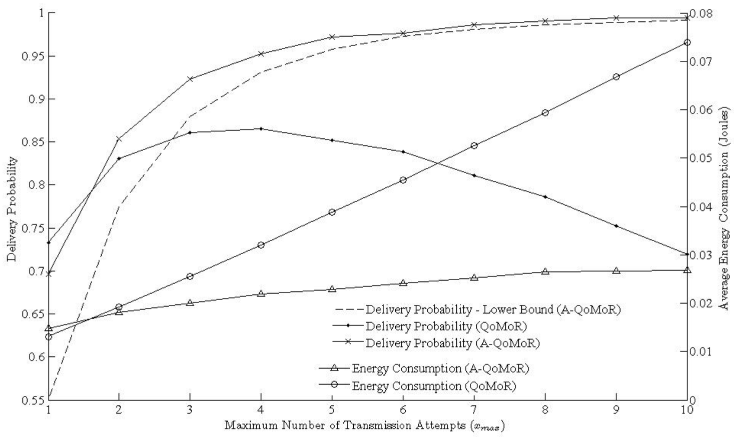

Figure 3.16: Comparison between A-QoMoR and QoMoR

3.6.6.2 Comparison of A-QoMoR and 802.11

In this section, we study the performance of the 802.11 MAC protocol in terms of packet delivery probability and energy consumption and compare it to A-QoMoR. As mentioned earlier, the same rate of data generated by the higher layers and the same physical layer parameters were used to establish a common base for comparison. Two independent simulations were set up - one consisting of nodes equipped with fully functional transceivers to study the performance of 802.11 and another consisting of nodes equipped with asymmetrical transceivers to study the performance of A-QoMoR. The following presents the results for delivery probability and energy consumption obtained from these setups.

Fig.3.17 shows that A-QoMoR is able to achieve a higher delivery probability than 802.11 for values of x_{max} greater than one. As the value of x_{max} is increased A-QoMoR performs significantly better than 802.11.

It is worth noting that given the simulation settings, the aggregate traffic is about $200Kbps$, which is much smaller than the channel bandwidth. Further, the size of each packet is relatively small (64bytes) and the number of contending sensor nodes is high (100). Since the 802.11x protocol has a significant overhead

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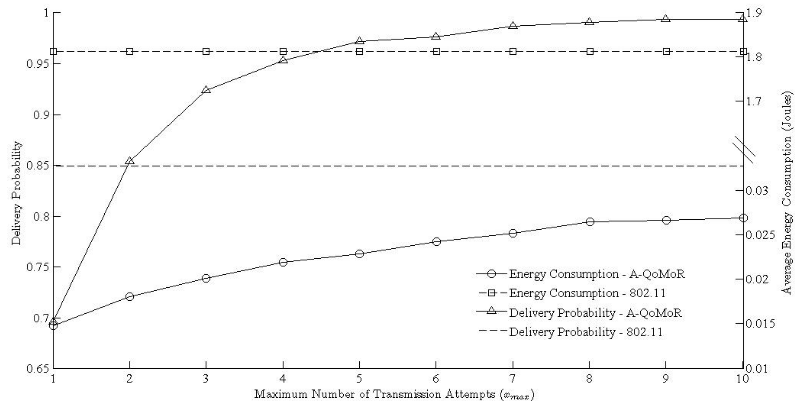

Figure 3.17: Comparison between A-QoMoR and 802.11

in terms of control packets and the exponential back off mechanisms lead to bandwidth wastage, it performs poorly. This also implies that for the many applications described in [Stipanicev & Marasovic 2003] [Andrisano *et al.* 2003] [Chen *et al.* 2002] [Anliker *et al.* 2004] [Elbatt *et al.* 2006], where there are many sensor nodes and small data packets are generated at short, periodic intervals, 802.11 is not a suitable protocol. Instead, new protocols such as A-QoMoR will be needed.

In terms of energy consumption per node, the 802.11 protocol consumes $1.8 Joules$ as compared to $0.015 - 0.028 Joules$ (depending on the value of x_{max}) consumed by A-QoMoR for the same simulation duration. This is due to the fact that, in 802.11, all the sensor nodes keep their receivers ON all the time and consequently receive packets that are not intended for them. This wasteful energy consumption is the reason for the significantly high energy consumption of the 802.11 protocol.

3.6.7 QoS Provisioning in A-QoMoR

In this section we describe a method to provide differentiated QoS to the sensor nodes, in terms of packet delivery probability, using the A-QoMoR MAC protocol. We study a system consisting of two QoS classes, a high priority class Q_h and a low priority class Q_l. The total number of sensor nodes n are divided into n_h

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high priority sensor nodes and n_l low priority sensor nodes requiring a minimum delivery probability of p_h and p_l respectively, where $p_h > p_l$. The data generation intervals and the channel access durations of the sensor nodes in the two classes are T_h, T_l and t_h, t_l respectively.

The results presented in Sec. 3.6.4 show that the delivery probability achieved by the sensor nodes increases with the maximum number of transmission attempts x_{max}. Therefore an intuitive way to provide differentiated QoS to the sensor nodes is to program them with different values of x_{max}. Alternately, we can program all the sensor nodes in class Q_h with a maximum number of transmissions equal to $x_{h_{max}}$ and the sensor nodes in class Q_l with $x_{l_{max}}$, where $x_{h_{max}} > x_{l_{max}}$. The following analysis develops expressions to calculate the optimum value of $x_{h_{max}}$ and $x_{l_{max}}$ in order to achieve the required minimum delivery probabilities of p_h and p_l for the two classes.

As observed in Sec. 3.6.2, the rate of background traffic affects the delivery probability that can be achieved by each class. The rate of background traffic for a high priority sensor node is given by

$$\lambda_h = \frac{(n_h - 1)x_{h_{avg}}}{T_h} + \frac{n_l x_{l_{max}}}{T_l} \tag{3.32}$$

Similarly, the total background traffic for a low priority sensor node is given by

$$\lambda_l = \frac{(n_l - 1)x_{l_{avg}}}{T_l} + \frac{n_h x_{h_{max}}}{T_h} \tag{3.33}$$

Let the delivery probabilities achieved by the two classes Q_h and Q_l be P_h and P_l respectively. Following the same steps used to derive Eq. (3.23) in Sec. 3.6.2 we have

$$p_{h_s} = e^{-2\lambda_h t_h} \times (1 - L) \tag{3.34}$$

$$p_{l_s} = e^{-2\lambda_l t_l} \times (1 - L) \tag{3.35}$$

$$P_h = 1 - (1 - p_{h_s})^{x_{h_{max}}} \tag{3.36}$$

$$P_l = 1 - (1 - p_{l_s})^{x_{l_{max}}} \tag{3.37}$$

We can calculate the average number of transmissions that each sensor node

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in Q_h and Q_l as below

$$x_{h_{avg}} = 1 + \sum_{i=1}^{x_{h_{max}}-1} i \times (1 - p_{h_s})^i \quad (3.38)$$

$$x_{l_{avg}} = 1 + \sum_{i=1}^{x_{l_{max}}-1} i \times (1 - p_{l_s})^i \quad (3.39)$$

Eqs. (3.34) (3.35) (3.38) (3.39) form a system of four equations in four variables that can be solved under the constraints $P_h \geq p_h$ and $P_l > p_l$ to obtain the values of $x_{h_{max}}$ and $x_{l_{max}}$. There may be many solutions for $x_{h_{max}}$ and $x_{l_{max}}$, however, we would like to choose the pair-wise minimum of the all the possible solutions in order to minimize the energy consumption.

3.7 Summary

In this section, we proposed a new architecture called Asymmetric Transceiver Networks (ATN) for transmit-only and asymmetric nodes. The ATN architecture is applicable to many practical wireless sensor applications like Intra-Vehicular networks. We presented three distributed MAC schemes that are contention based but can provide differentiated QoS (in terms of guaranteed frame delivery probabilities) without using any of the conventional ARQ or scheduling schemes.

In QoMoR, each node simply retransmits each of its frames an optimal number of times within a given period to ensure its frame delivery probability is above a required threshold. Accordingly, the scheme is useful for any network where asynchronous transmission is desired and the nodes have a low throughput requirement. Since no form of acknowledgment schemes are employed there is no need for a receiving module at the sensor nodes. The QoMoR scheme is simple and achieves a considerable reduction in the cost of the infrastructure and sensor nodes.

However, for certain applications in which the network size is large or the delivery probability requirement of certain mission critical sensors is very high, the performance of QoMoR cannot meet the QoS requirements. To meet the requirements of such applications we proposed two schemes called MC-QoMoR

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and A-QoMoR that provide an improvement in delivery probability over QoMoR with different tradeoffs.

MC-QoMoR uses multiple channels and provides efficient channel allocation schemes to considreably improve the delivery probability achieved by the nodes. Further, MC-QoMoR does not increase the system cost significantly as the complexity of being able to receive simultaneous transmissions is restricted to the sink nodes. Hence it still offers a practical and cost effective solution to satisfy the more demanding system requirements.

A-QoMoR, on the other hand, uses a rudimentary receiver module to receive only acknowledgments (ACK's) from the base station in the form of a fixed radio pulse. The receiver module is not capable of performing any other functions of a standard receiver like channel sensing, packet reception etc. Using the proposed A-QoMoR scheme, the nodes will keep retransmitting a packet either until it receives an ACK or in a less likely case, until the maximum number of retransmissions are attempted. This results in fewer transmissions by the nodes as compared to QoMoR, which in turn will boost the QoS performance of all the nodes in the system.

The proposed schemes are particularly suitable and cost-effective when UWB radios are used, since UWB can provide high bit rates and hence allow for multiple retransmission of a data frame within the frame generation interval. Further, UWB receiving circuits can be much more expensive than UWB transmitting circuits. Hence a significant saving in cost and energy consumption can be achieved by using transmit-only and asymmetric nodes.

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Chapter 4

Protocols for *Tier* 2 Networks

4.1 Overview

Tier 2 networks mainly consist of aggregator nodes and sensor nodes that perform computationally intensive sensing tasks (like video monitoring), complex functions (like data aggregation, filtering, mining), event detection etc. The *Tier* 2 nodes are data-oriented and sometimes bandwidth intensive. These nodes have a unique set of requirements that differentiate them from exiting devices. They typically require high data rates to transfer significantly larger amounts of data as compared to *Tier* 1 nodes. Since they are battery powered devices they also demand high energy efficiency and optmized use of resources. They need to be able to communicate effectively in adhoc, topologically diverse network conditions without being administered or controlled by a central entity.

Although CSMA based protocols are easier to deploy in adhoc, topologically diverse networks their use in such scenarios has been limited. Studies show that the IEEE 802.11 [IEEE 1999] and the IEEE 802.15.3 [IEEE 2003], which widely used, are deployed only in their basic configurations. The many amendments and enhancements that provide energy efficiency, QoS [IEEE 2005] are yet to be adopted on a significant scale since they considerably increase the complexity of the MAC protocol. One of the other drawbacks of CSMA based protocols is that the radio module has to be ON all the time in order to sense the channel and receive any information destined to the node. In the context of sensor networks

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this is a significant drain on battery resources and a node might lose all it energy before sensing any events it is meant to detect.

In this chapter we study a distributed TDMA based MAC protocol called DT-MAC that meets the requirements and supplements future needs of *Tier* 2 networks. TDMA based protocols are suitable for tier2 networks as they have the inherent advantage of energy efficiency as compared to CSMA based protocols. There has been a lot of work on how TDMA based protocols can optimize the use of resources particularly for sensor networks.

However, TDMA based protocols suffer from the fact that current designs need some form of centralized control to perform functions like conflict resolution, scheduling. This leaves us with the question - *Can we design TDMA based wireless MAC rotocols that can function in a completely distributed manner and be capable of similar or better performance as compared to today's popular CSMA and TDMA based protocols?* We try to answer this question in the context of emerging Physical Layer technologies like UWB and also using new spectrum like 60GhZ.

UWB is a promising technology as it has valuable features such as high transmission rate, low power consumption and super resolution of multipath [Li & Talty 2006] [Gresham *et al.* 2004], that are currently not provided by any of the existing wireless physical layer technologies. Further, the design of UWB transmitters is also simple [Orndorff 2004] and the power levels used by UWB devices are very low (specified by the standard to be -41.3 dBm/Mhz) which allows for a cost and energy efficient design of the nodes. Thus UWB provides a set of features that are very useful for designing nodes used in the tier2 networks.

The WiMedia Alliance has proposed and standardized a distributed TDMA MAC protocols, called the WiMedia MAC (or the ECMA-368 standard) [ECMA 2008, Pavon *et al.* 2006], that is designed for high-speed data-oriented networks. It facilitates a distributed network architecture where all the nodes are peers and do not require a centralized control in the form of a piconet coordinator. This eliminates the overheads when nodes join and leave the network. The WiMedia MAC uses a fixed length slotted frame structure to allow TDM access to the channel. However, it is does not meet the energy efficiency demanded by tier 2 nodes and is not optmized for for high-bandwidth data exchange between devices.

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4.1.1 Other motivating applications

Currently there is a wide spectrum of network based services available to consumers which are significantly more data-oriented and bandwidth intensive than in the past. With the ubiquitous availability of *Smart Devices*, most consumers access these services using wireless communication technologies. The next 5-10 years will probably see widespread usage of these Smart Devices that will demand better wireless technologies to communicate with each other and with the Internet.

Recently, Home Networking has become a popular application which has significant potential in the consumer market. It can broadly be classified under the category of high data rate wireless personal area networks (HR-WPANs) where many Smart Devices within the home communicate with each other. The work presented in this chapter is motivated by this class of applications that focuses on enabling wireless communication between commonly found devices in a home to create a clutter free and completely wireless environment. There are proposals for high speed wireless links between set-top boxes, DVD players and other video sources to HDTVs, LCD screens and similar video display devices within a home [Merabti *et al.* 2008] [Oguchi *et al.* 2006].

The advent of UWB technology [Barrett 2000] has provided a viable physical layer to provide high-speed wireless and rich multimedia capable personal-area connectivity. The WiMedia Alliance has proposed and standardized the ECMA-368 MAC protocol [ECMA 2008] [Pavon *et al.* 2006] that has been designed for such high-speed and multimedia rich networks. The opening of the 60GhZ or MilliMeter (MM) wave band for unlicensed communication has also provided opportunities for very high speed wireless communication in personal and local area networks [Smulders 2002].

As an example, consider applications like streaming High Definition (HD) video from a DVD player to a TV. An application or driver on the DVD player generates each frame and directly passes it onto the MAC layer to be transmitted to the TV. The signals are received by the MAC at the TV and passed onto the application/driver that renders the picture.

The TV may be a dumb terminal and can receive only raw video format (like a VGA data

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In such a scenario, the bandwidth requirements are very high because a high definition video stream between a source and a display requires a constant bandwidth of 150 to 200 Mbps [Meir Feder, Chief Technology Officer, AMIMON Ltd. 2008] depending on the characteristics of the video. Even two such streams can easily saturate the bandwidth even at channel rates of 480Mbps which is the maximum data rate possible with the MB-OFDM physical layer. Such inter device communications also require constant bandwidth over long durations of time and significantly lower delay bounds as compared to a device communicating with the Internet.

4.2 Requirements of a MAC Protocol for *Tier* 2 Networks

The MAC protocol's main function is to provide access to multiple devices using a common shared channel. Apart from achieving this necessary goal, it is important that a MAC protocol also provide good QoS and minimize energy consumption. The following explains key design consideration and metrics used for the design and evaluation of a MAC protocol.

4.2.1 Channel Sensing

The specification of the UWB physical layer requires that the transmit power is below the noise floor in the 2-10Ghz band [FCC Report and Order 2002] in order to avoid interference with existing technologies in the 2.4Ghz and 5Ghz unlicensed bands. In this scenario, sensing the channel will require devices to actively decode all transmissions to find out if the channel is occupied by another device using the same PHY and MAC. This will consume a considerable amount of energy and is inefficient for battery driven devices [Shi 2007]. Although the MM-wave physical layer does not suffer from the limitation of the transmit power

stream) or it may have the capability to receive MPEG-4/ H.323 encoded video signals. In the latter case, there is the added complexity of decoding the video signal before rendering it at the TV.

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having to be below the noise floor, the advantages of minimizing channel sensing are still significant.

In commercially available devices today, the energy consumed for channel sensing is greater than 75% of the energy consumed for reception [Marcelo M. Carvalho *et al.* 2004]. Channel sensing also takes a specific amount of time during which the device does not transmit or receive. This leads to unnecessary overhead and bandwidth under-utilization. *Thus, minimizing the need for channel sensing can provide significant gains in terms of energy consumption as well as improved bandwidth utilization.*

4.2.2 Energy Consumption

Energy is a critical resource in battery driven devices and it is important that the MAC protocol should be designed to minimize it.

In any communication, a significant amount of the energy is consumed by the transceiver and the MAC protocol controls its usage. Thus the most evident technique to minimize energy consumption is to ensure that the design of the MAC protocol reduces the usage of the transceiver. Apart from the duration for which the transceiver is ON, it is also necessary to consider the number of times the transceiver transitions from SLEEP state to TRANSMIT or RECEIVE states and vice versa. This is because the transition energies, although much lower than the energy consumed during the TRANSMIT or RECEIVE state, are quite significant.

The optimal method would be to group all the transmissions of a device into a single block. However, this method has a negative impact on the delay/jitter performance of the protocol as grouping the transmissions into one block involves queueing packets [Paul J.M. Havinga & Gerard J.M. Smit 2000]. *Thus, there exists a tradeoff between energy consumption and the delay/jitter performance of the MAC protocol.*

4.2.3 MAC Protocol Overhead

All protocols in the OSI stack have overheads of operation. *It is not possible to eliminate this overhead. Thus we need to minimize it while keeping the function-*

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ality of the protocol intact.

The two kinds of overheads incurred in the operation of a MAC protocol are the MAC header and the exchange of control packets. While the former is essential and cannot be minimized, the latter, which is used for collision resolution, bandwidth reservations, polling, other negotiations can be minimized. This provides us with a new parameter to evaluate the efficiency of the MAC protocol. We call this parameter as the *Overhead Ratio* which is defined as

$$OR = \frac{Bandwidth\ Consumed\ by\ Control\ Packets}{Bandwidth\ Available\ for\ Transmitting\ Payload} \tag{4.1}$$

4.2.4 Control and Data Transfer Mechanisms

Existing MAC protocols are generally use centralized control mechanisms for synchronization between nodes, exchange of control information, resolution of bandwidth reservation conflicts. Protocols capable of completely adhoc operation, like the 802.11 adhoc mode specification, make use of CSMA to avoid collisions. However, they do not have efficient mechanisms to perform bandwidth reservation based on parameters like QoS, delay guarantees etc.

In the design of the completely distributed TDMA based MAC protocol we need to solve the problem of reserving bandwidth in a completely distributed manner. This requires that every node in the network has information on the bandwidth requirements of all the other nodes in the network. A naive method to achieve this will create a large amount of control traffic and deteriorate overall performance. We need new techniques for nodes to synchronize with each other and achieve prioritized, conflict free data transmissions to address these issues.

4.2.5 Quality of Service (QoS)

The 802.1p standard describes the classification of traffic types based on the throughput and delay/jitter requirements. FTP traffic usually requires a higher throughput but has relaxed delay requirements. On the other hand, real-time traffic like that generated by VoIP and Video Conferencing applications are delay sensitive and require guaranteed bandwidth as they generate data periodically.

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The 802.1p standard recommends seven traffic classes with each class providing a particular guaranteed end-to-end throughput and delay from the application layer of the source to the application layer of the destination. The MAC protocol design must incorporate features to efficiently handle all traffic types and meet their QoS requirements.

Finer points on providing QoS guarantees :
While designing a MAC protocol the question that arises is - What is the throughput and delay that must be guaranteed from the MAC layer of the source to the MAC layer of the destination? We must note that most applications directly hook into the transport layer. Hence the layers typically involved are the Application, Transport, Network, MAC and Physical layers.

Let us first take a look at the delays introduced. In a LAN setup, congestion occurs only when the network is overloaded. We do not consider this scenario and hence assume that congestion related queuing and delays in TCP do not occur. UDP does not introduce any significant delays. Thus, for our discussion, we can say that there is practically no delay introduced by the Transport layer other than negligible processing delays.

At the Network layer, packets may be delayed until a route is discovered. Once a route is discovered the processing delay at the Network layer is negligible. The physical layer does not introduce any significant delay except the transmission delay. At current physical layer data rates, the transmission delay does not exceed a few microseconds. The delay between the instant a packet enters the MAC layer queues at the source to the instant it is delivered to the network layer at the destination is thus the most significant delay. We can thus say that the QoS guarantees are met if this delay is less than the requirement of the highest priority traffic type.

An important point to note is that the MAC protocol need not provide the minimum possible delay. It only needs to keep the delay within the limits specified for each traffic type, under all network conditions. Although counter intuitive, this means that QoS guarantees can be effectively met even if the MAC protocol introduces delays before transmitting packets.

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The bandwidth guarantees specified by 802.1p for each traffic class is the minimum bandwidth that the particular class of traffic will need, so that, the Application Layer service generating it can function optimally. When the network is lightly loaded (that is, when the aggregate bandwidth required by all the devices accessing the network is significantly less than the channel bandwidth) it is possible to guarantee the bandwidth required by each device. As the network reaches saturation, the aggregate bandwidth increases towards the channel bandwidth and it becomes more difficult to satisfy the bandwidth guarantees of all the devices, especially in networks with a large population.

Another important aspect is the complexity of implementing QoS at the MAC layer. Most existing protocols use complex algorithms for achieving QoS. As noted earlier, this increases the footprint of the MAC protocol both in terms of memory requirements and CPU-time. Both of these resources are at a premium in mobile devices and their use needs to be minimized.

4.3 Optimization Opportunities

To achieve our goal of improving bandwidth utilization at the MAC layer, we note that there are two overheads that can be minimized. An obvious overhead is the MAC control overhead while the other, which is typically neglected, yet significant, is the PHY overhead. In the following we present some ideas to minimize these overheads in our application scenario.

4.3.1 Minimizing MAC overhead

In the WiMedia frame structure, control packets are exchanged during the beacon period of each frame to perform actions like bandwidth reservation, conflict resolution etc. The beacon period consumes a minimum duration of 512μsec (when only 2 devices are operating in the network) in each frame of length 65.536msec, resulting in a constant MAC overhead of about 1% [Ellisys - Wimedia Alliance 2009]. As more devices join the network the beacon period increases and hence the MAC overhead increases up to 6%.

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An important characteristic of video traffic is the average duration of the video - the average length of feature films is about 90 minutes and the average length of YouTube videos is between 3 and 4 minutes [Cheng *et al.* 2008]. Hence the average time for which active transmissions occur is several orders of magnitude greater than the duration of a single MAC frame.

Streaming video from a source to a TV/Monitor requires transmitting n data packets every second where n is the frame rate of the video. This means that the bandwidth required by the source node does not change over the entire duration of the stream. On the other hand, if the source is transmitting an encoded video stream, algorithms based on the statistical characteristics of MPEG-4 or H.323 video streams [Dai & Loguinov 2005] have been developed to predict bandwidth requirements [Fan 2007]. Using these algorithms, nodes can accurately predict and reserve bandwidth over periods of up to a few seconds.

This allows us to minimize the frequency of exchanging control packets and as a result, each frame can accommodate larger periods of high rate data transmissions for each beacon period.

4.3.2 Guaranteed Delay vs PHY overhead tradeoffs

Video streaming applications are tolerant to small variations in delay and only require a guaranteed delay bound (less than a maximum tolerable delay). For video applications the tolerable delay is less than 50msec [Cranley *et al.* 2003, Pantel & Wolf 2002]. Thus the MAC layer only needs to keep the delay within this limit and it not necessary to provide the minimum possible delay to each packet.

The slotted structure of the WiMedia frame allows for low delays of less than 4msec by allowing multiple transmission opportunities within each frame. However, this increases the physical layer overhead as it requires the transmission of a standard preamble for every transmission opportunity. A study in [Ellisys - Wimedia Alliance 2009] shows that the percentage of PHY overhead increases to

In our application scenario, all communication is assumed to be single hop. Hence the transport layers do not introduce any delays (assuming all processing delays are negligible) and there is no need for a routing protocol.

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12.3% at 480Mbps from about 2% at the base rate of 53.3Mbps. However, using burst transmissions reduces the PHY overhead to about 5% at 480Mbps. Burst transmissions significantly reduce the number of PHY preambles that need to be transmitted per byte of PHY payload and as a result improve the bandwidth utilization.

Figure 4.1 shows the variation of delay and the PHY overhead with the number of transmission opportunities per frame. The result indicates that even if only one transmission opportunity is available every frame the delay is within the tolerable limit of 50msec for streaming video. However the PHY overhead is significantly reduced which translates into an improved bandwidth utilization of 98% as opposed to about 88% when using 16 transmission opportunities per frame.

Thus it is advantageous to trade delay for minimizing PHY overhead by aggregating data and transmitting it as a burst.

In summary, we find that the traffic generated by home networking applications have a relatively constant bandwidth requirement. This allows us to effectively reserve bandwidth over multiple data transmission periods and increase the interval between beacon periods. Further, aggregating the data improves bandwidth utilization while still providing guaranteed delay bounds within the tolerable limits of the applications considered.

4.4 Distributed TDMA based Medium Access Control (DT-MAC) Scheme

We use the discussions and observations presented in the previous sections to design a distributed, light weight, energy efficient, TDMA based MAC protocol called DT-MAC. The key motivation is the inadequacy of existing protocols in handling future network conditions. We aim to use this design as a basis for future enhancements and optimizations.

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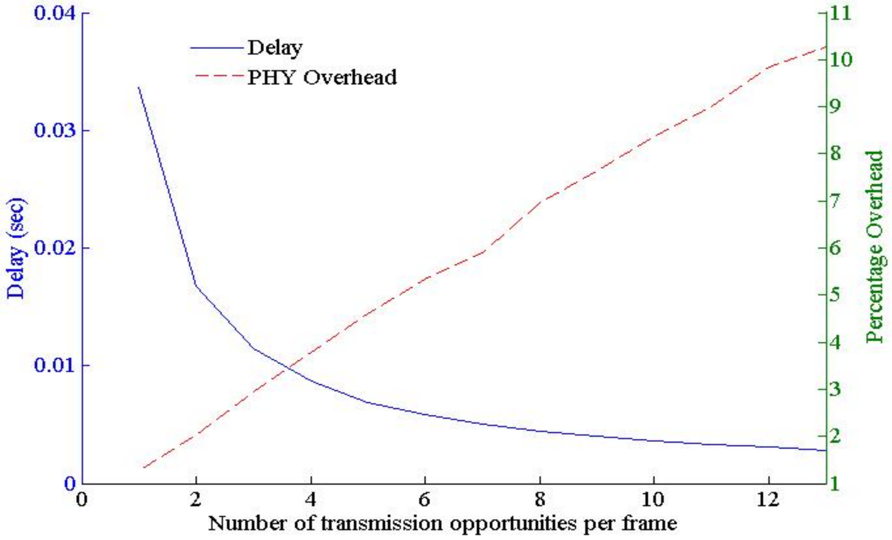

Figure 4.1: Effect of slotted transmission on delay and overhead

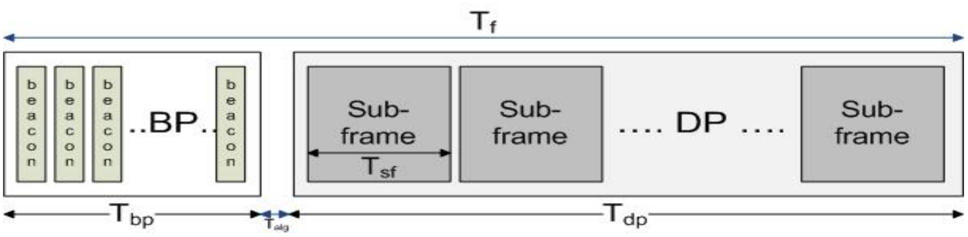

Figure 4.2: The DT-MAC Frame Structure

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4.4.1 The Beacon Period

As explained in Section 4.3, the frame structure is designed to minimize overhead by decreasing the ratio of the beacon period to the data period. Further, to control the overhead we propose to transmit all control messages *only* during the beacon period. This restriction increases the delay incurred in exchanging control messages when each node transmits only one beacon in each beacon period (as in the WiMedia frame). For example, if a node requests a bandwidth reservation in frame n, it will receive an ACK from the destination in frame $n + 1$. This will cause an initial access delay of T_{dp} which might be unacceptable for some applications.

Hence we need bidirectional communication between any pair of nodes within each beacon period. To achieve this, we propose to split the beacon period into two equal halves called the Advertise Period (AP) and Finalize Period (FP) as shown in Figure 4.2. These periods are further divided into slots of equal duration T_b. Each node transmits an Advertise Beacon (AB) in the AP and a Finalize Beacon (FB) in the FP. The AB and FB slots are paired (i.e) if a node transmits its AB in the n^{th} AP slot it must transmit its FB in the n^{th} FP slot.

Control information is exchanged by transmitting pre-defined messages called Information Elements (IE) in the beacon (Refer the ECMA-368 specification [ECMA 2008] for the specifics of the IEs). For example, if a source node needs to reserve bandwidth, it sends out a Distributed Reservation Protocol (DRP) IE in its AB with information on the amount of bandwidth required. The destination node ACKs this request by transmitting the DRP IE in its FB . This strategy allows nodes to send request messages during the AP and receive ACK/NACK during the FP. *Thus any control action can be resolved within one beacon period allowing the corresponding changes to the DP to be executed in the same frame.* Although, transmitting two beacons per beacon period appears to increase the overhead, its performance improves significantly when the duration of the data period increases.

Depending on the number of active nodes in the network, a node can propose to expand or shrink the beacon period to either accommodate more nodes or reduce the duty cycle. To do so a node transmits a suitable IE in its AB and

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the other nodes ACK the proposed change in their respective FBs. If an ACK is received from all the nodes in the network then the beacon period is changed to the proposed value starting with the subsequent frame. Since all the nodes have to wake up during the BP, this enables the nodes to control their duty cycle and conserve energy when there are only a few nodes in the network.

4.4.2 Beacon Setup Procedure

Since the MAC is distributed we need an algorithm that can be executed independently by each node to find a suitable slot to transmit its beacons. Algorithm 2 describes the procedure followed by each node to join the network.

When a node is switched ON, it scans the channel to see if there are any beacons already being transmitted. If yes, the node listens to the channel for a duration of $2 \cdot T_f$ so that it can be sure it has received all the beacons that are currently being transmitted. Based on the information it has received each node determines the number of empty slot pairs in the beacon period and chooses a suitable slot pair to transmit its beacons. When choosing a slot pair, a node always tries to install its beacons adjacent to existing beacons so that all the beacons occupy contiguous slots. If there are no beacons being transmitted, the node decides that it is the 'first node' in the network and installs its beacon at a randomly chosen instant.

Since this process is independently executed by each node, it is possible that two or more nodes that are concurrently executing the procedure might choose the same slot to install their beacons. To resolve such a conflict we use the Beacon Collision Information Element (BCIE) in the beacon to indicate collisions. Whenever a node detects a beacon collision, it transmits a BCIE with the slot number in which the collision was detected. If a node is trying to install its beacon in the slot indicated by the BCIE, it restarts its beacon installation procedure.

4.4.2.1 Synchronization - In a completely distributed way!

This procedure implicitly enables each node achieve time synchronization with the 'first node' that entered the network. By scanning the channel each node is able to find the beginning of each frame which is the beginning of the beacon

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Algorithm 2 : Beacon Setup Phase

if Beacon(s) are sensed **then**
    Continue sensing beacon(s) for a time period $2 \times T_f$ to ensure that no beacon is missed
    Synchronize the reference time with the first beacon
    Determine the empty slots
    Install the beacon in the empty slot
    Listen to other beacons to see if there is a collision in the chosen slot
    if No collision is reported in chosen slot **then**
        Finalize beacon installation and go to MAC_ACTIVE state
    else
        Restart procedure
    end if
else
    Assumes itself to be the first node in the network
    Install the beacon at a randomly chosen time and go to MAC_ACTIVE state. This becomes the start of frame for nodes subsequently joining the network.
end if
End

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of the 'first node' in the network. Each node synchronizes its local clock to this starting point and hence implicitly achieves time synchronization by correcting for the transmission delay of the beacon (this is easy as the size of the beacon is fixed and known). Any error in synchronization can be attributed to the propagation delay of the beacon which is usually of the order of a few nanoseconds and can be offset by using suitably designed guard times between transmissions. The protocol enables all the nodes in the network to be time synchronized without any additional overhead and hence makes Time Division Multiple Access (TDMA) of the DP possible. Even with low accuracy clocks the network can be synchronized as there is an opportunity for resynchronization at the beginning of every frame.

4.4.3 Resolving Bandwidth Reservation Conflicts

In the DT-MAC frame structure control information is exchanged only in the beacons during the BP and is not transmitted at any other time during the frame. This means that we must ensure that conflict free bandwidth reservation can be achieved by all the nodes in the network within the beacon period. The division of the beacon period into the AP and FP is a key feature of the frame structure that enables us to effectively resolve any conflicts. In the following we discuss the scenarios in which conflicts in bandwidth reservation can occur and present solutions specific to the DT-MAC frame structure.

Consider a collision domain as shown in Figure 4.3(a), in which the nodes in the network are within 2 hops of each other and their transmissions can collide. In this scenario, Nodes C and D cannot hear each other and are unaware of the reservations made by each other during their ABs. However, nodes A and B have heard the reservations requested by both C and D. It is possible that both nodes request transmission periods that overlap. In this scenario, the destination nodes can help in resolving such conflicts. Let us assume that A's beacon slot is before Bs. In this case, A uses its FB to suggest a transmission period to C that will also allow D to transmit to B without a conflict or NACK C's request if it cannot find such a transmission period. B acts based on the information in A's FB and either suggests a conflict free transmission period to D or NACKs D's request in its FB.

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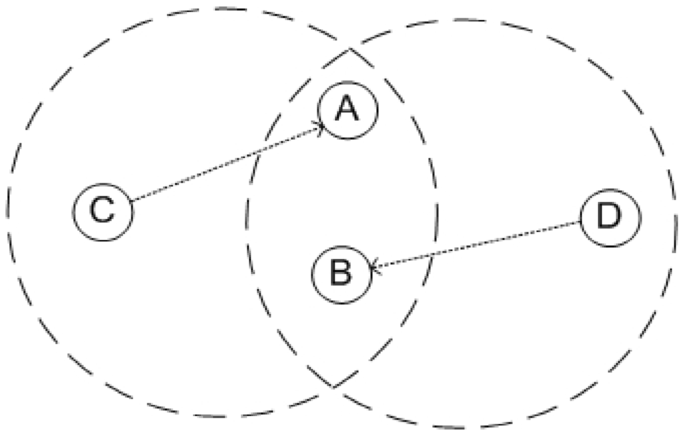
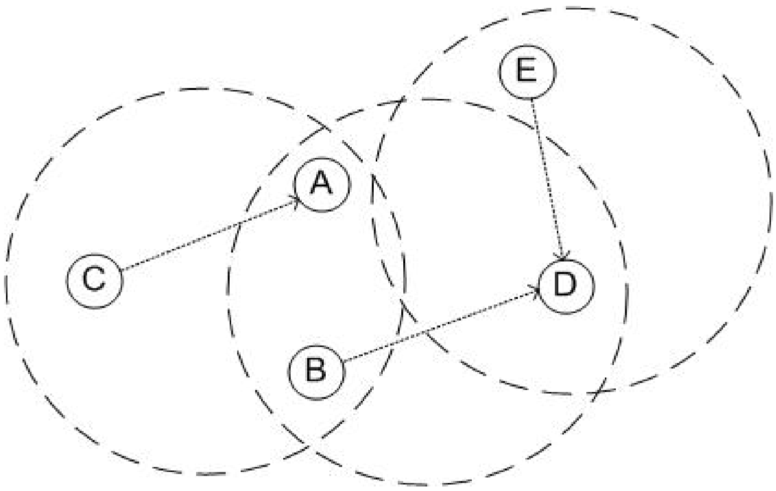


(a) Conflict Scenario 1



(b) Conflict Scenario 2

Figure 4.3: Conflict Resolution

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In another conflict scenario, two nodes that are not within transmission range of each other can request overlapping transmission periods to the same node in their ABs as shown in Figure 4.3(b). A similar procedure can be used by the destination node to resolve such a conflict.

In general, we assume that all nodes are cooperative and always try to ensure conflict free bandwidth reservation. Similar procedures can be used to resolve conflicts in other control messages like Frame Modification (explained in Section 4.4.5).

4.4.4 Handling Beacon Loss

Although beacons are transmitted at the base rate of 53.3Mbps the cluttered radio environment of Home Networks and the many interference sources can cause errors and loss of beacons. In the DT-MAC frame structure beacon loss is more critical that in the WiMedia MAC as all bandwidth reservation during the data period is done *only* during the beacon period. The loss of a beacon can cause a node to determine a wrong schedule which will cause collisions during the data period.

We note that it is easy to detect bit errors in beacons by using the standard Cyclic Redundancy Check (CRC) to check the integrity of the beacon data. However, we also need a method by which a node is able to detect beacon loss (i.e) when the physical layer fails to detect the beacon correctly. Further, each node must be able to *independently* detect beacon losses as the protocol is completely distributed.

To resolve this problem we present a method of checking beacon loss by calculating a CRC over multiple beacons. When filling out the CRC field of its beacon a node calculates the CRC over the data in all previous beacons and its own beacon. When a node receives a beacon, it checks for beacon loss by calculating the CRC over all the previously received beacons and the current one. If the CRC does not match it implies that a beacon has been lost.

When a node realizes a beacon has been lost it does not perform any further transmission during the current frame as they might result in collisions. It is possible to develop some rules by which a node can still transmit without colliding

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based on the remaining information it receives in the AP and FP. However, we leave the study of the possibilities for our future work.

4.4.5 The Data Period

The Data Period (DP), which is the remainder of the frame excluding the BP consists of k sub-frames, each of duration T_{sf}. The duration of subframes can be dynamically changed by the nodes using the following procedure. When a node wants to expand or shrink the data period it transmits a new IE called the Frame Modification IE (FMIE) in its Advertise beacon and proposes a value for T_{sf}. The remaining nodes ACK or NACK this request by transmitting an FMIE in their Finalize beacons. If all the nodes have ACKed the request the nodes that proposed the change transmits a confirmation using the FMIE in the subsequent beacon period and the number of subframes is changed from the next data period. Depending on the application requirements of all the nodes in the network, a suitable value for T_{sf} can be chosen by this method. For our application scenario, we choose the value of T_{sf} to be 64msec.

The data period can also be expanded or shrunk in integral number of subframes. We must note that a large number of subframes will increase the delay incurred when a node needs to allocate new bandwidth or modify an existing reservation as it will have to wait until the next beacon period. Thus we restrict the range of values of k from a minimum of 1 to a maximum of 16 which maintains a maximum access delay of less than $16T_{sf} + T_{bp}$ which is approximately equal to 1 second in our application scenario.

The subframes are not divided into slots as in the WiMedia MAC, but, are treated as one whole unit of time in which each node can dynamically reserve bandwidth. This allows us to minimize the PHY overhead as explained in Section 4.3.2. Bandwidth reservation in each sub-frame may be done using standard reservation algorithms optimized for video traffic as described in [Reddy *et al.* 2007, van der Schaar *et al.* 2006, Kozlov *et al.* 2005, Daneshi *et al.* 2010].

Alternately we design a customized transmissions schedule calculator algorithm that is designed to work in a distributed manner to such that when the algorithm is executed by a node, it obtains the transmission schedule of all the

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nodes in the network including itself. Hence, it knows when it has to wake up to transmit or receive data during the DP which enables the node to effectively minimize energy consumption.

4.4.6 Transmission Schedule Calculator Algorithm

As mentioned earlier the design of the protocol follows a distributed control ideology in which all nodes are peers. Thus it does not make sense to have a particular node *provide* the transmission schedule for all other nodes. The TSC algorithm is designed to be executed on each node at the end of the BP and before the start of the DP so that all nodes can independently calculate the transmission schedule. Since the same algorithm is executed by all the nodes in the network, the transmission schedule generated by each node will be the same, provided the input to the TSC is the same for all the nodes.

The TSC takes the number of bytes in the queue and the traffic type of all the nodes in the network as input. Since this information is broadcast by every node in its beacon all nodes can provide the TSC with the same information and thus obtain the same output, which is the transmission schedule.

In this paper we propose a TSC algorithm that can meet the requirements of most traffic types that might be generated in a network. It must be noted that by changing the TSC the capability and performance of the network can be changed/optimized for specific scenarios. The only constraint is that all the nodes in the network must execute the same algorithm and provide the same input to it.

Preliminaries :
Before going into the design of the TSC algorithm it is necessary to understand the properties of the different types of traffic that flow through a network and classify them on the basis of their throughput, delay and jitter requirements. The aim of this classification is to enable the TSC algorithm to handle various traffic types optimally.

To keep the design simple, these classes must be defined so that the MAC protocol can independently classify each packet into the different classes with low complexity. There should be no need for deep packet probing as it will result

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in a significant amount of processing delay as well as energy consumption. The class definitions must enable the TSC to handle/schedule the traffic in an efficient manner. The reader must not confuse the classes described here with the priority classes as defined by 802.1p, these classes exist only within the MAC protocol and are for the sole use of the TSC.

In current networks, there are a host of different applications that generate data having different requirements. However, at the transport layer there is a sense of unification of the traffic generated by the application layer. *All the traffic in any network uses one of either the TCP or the UDP transport protocols.*

We propose to use just two classes based on the transport protocols that the data packet uses.

1. All TCP traffic requires an ACK to be sent by the destination for data sent by the source. The source data rate is dependent on the ACK's sent by the destination. *We call this class of traffic Request-Response (RR) based traffic.*

2. On the other hand, for UDP traffic, the rate of data generated by the source does not depend on whether ACK's are received from the destination. *We call this class of traffic One-Way (OW) traffic.*

It is evident that HTTP, File Transfer (FTP) and all related types of traffic fall into RR class while Video/Audio Streaming, VoIP fall into the OW class. The reader must observe that all traffic types can be classified into these two broad categories.

The classification of packets into RR or OW classes is done when they arrive at the MAC queue and this information is later used by the TSC algorithm.

The Algorithm :
The TSC algorithm takes the number of bytes in the queue, b_i, and the traffic class, c_i, of each node as inputs. We can calculate the total number of bytes, $\bar{B} = \sum_i b_i$, that need to be transmitted by all the nodes in the frame. If the aggregate bandwidth requirement is less than the capacity of the shared medium, the problem of allocating bandwidth is trivial. Each node is allocated a duration of t_i within the DP in which it can transmit all the data in its queues.

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Sometimes, it is possible that the aggregate bandwidth requirement is greater than the available bandwidth when traffic spikes occur. In this scenario we propose to divide the available bandwidth among all the nodes in the ratio of the bytes in queue of each node to the total bytes, $\frac{b_i}{B}$. This ensures that fairness is guaranteed to all the nodes in the network at all traffic loads.

We must observe that for RR traffic, ACK's are generated by the application layer of the destination only after data is reserved from the source. During the BP, the source advertises the number of bytes in its queue for a particular destination. Since the destination's application layer will generate ACK's only after the data packets are received (which will happen only during the DP) it is possible that the destination does not have any data in its queue and hence does not obtain a transmission opportunity. This will adversely affect the performance of request response traffic as it will introduce significant delays. So we propose that for every node that advertises RR traffic in its beacon the destination node is by default allocated bandwidth proportional to the bandwidth requested by the source. This proportion is calculated as

$$\lceil \frac{b_i}{MPDUsize} \rceil \cdot ACKsize \tag{4.2}$$

where b_i is the number of bytes in the queue of the server, *MPDU size* is the maximum MAC protocol data unit size and *ACK size* is the size of the ACK packet generated by TCP which is typically 40 bytes. In this way we can considerably reduce the delay encountered by RR traffic and prevent TCP from throttling the source rate due to a high delay.

The TSC also takes into account the priority of the traffic at each node, which is indicated by the ToS field in the IP header, by reordering the transmissions to minimize the delay for the node with the highest priority data.

This algorithm executes in $O(nlogn)$ time and an optimized implementation can be easily executed in every frame by the nodes. We would like to note that the TSC proposed is only an initial version and we are currently exploring optimizations to improve the performance.

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Algorithm 3 : Transmission Schedule Calculator

```
From the beacons received initialize ∀i,
    b_i ← bytes in queue of node i,
    c_i ← traffic class of node i,
    qos_i ← QoS priority class of node i
    n ← number of nodes in the network,
    B̄ ← Σ_{i=1}^{n} b_i
for i ← 1 to n do
    if c_i == RR traffic then
        Increase bytes in queue of destination by
        b_i / MPDUsize · ACKsize
    end if
end for
if B̄ can be transmitted within T_dp then
    ∀i ∈ {1, ··· , n}, t_i ← Duration to transmit b_i bytes
else
    ∀i ∈ {1, ··· , n}, t_i ← (b_i / B̄) × T_dp
end if
Sort the transmissions based on qos_i
Schedule the transmissions sequentially from the start of the DP in the sorted
    order
End
```


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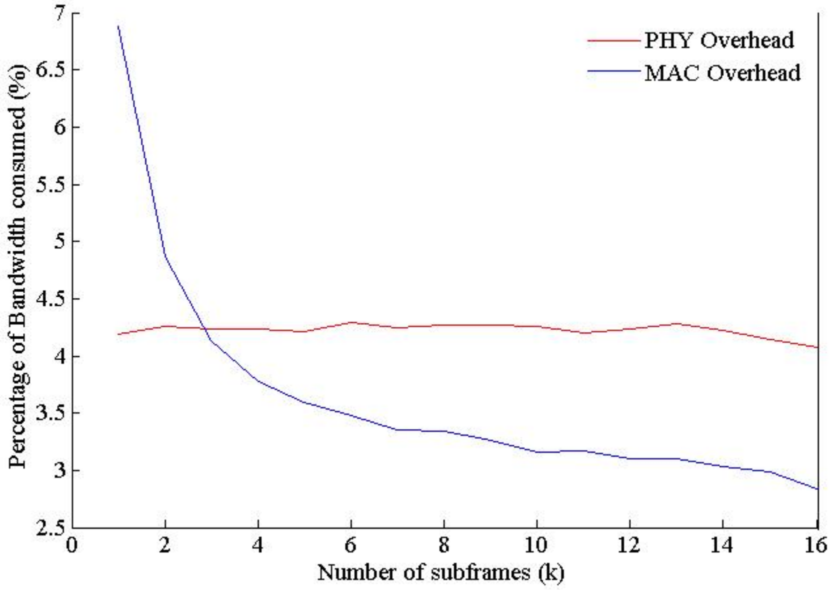

Figure 4.4: MAC and PHY overhead of the DT-MAC frame structure vs the WiMedia frame structure

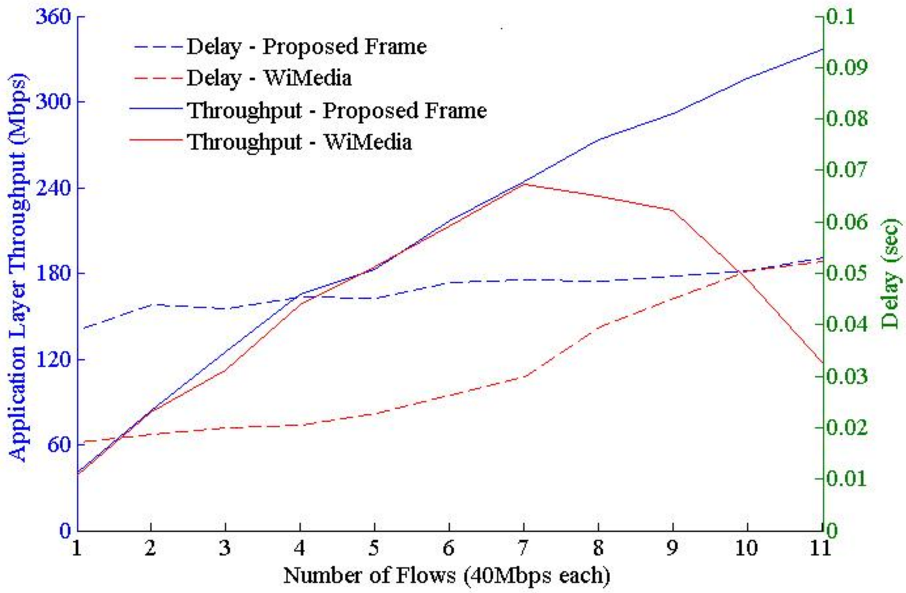

Figure 4.5: Throughput and Delay comparison of the DT-MAC frame structure vs the Wimedia frame structure

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4.5 Comparison of DT-MAC with WiMedia

In this section, we present a few simulation results on the gains achieved in terms bandwidth efficiency and overhead reduction. We use NS-2 as the simulating platform and have added the WiMedia MAC using the defined frame structure as well as the DT-MAC frame structure. We simulate the MB-OFDM physical layer using the model defined in [IEEE P802.15 Working Group, Anuj Batra et.al. 2003] by calculating the Bit Error Rates for indoor channel conditions and simulating the corresponding packet loss rates in NS-2. The results presented are an average of 10 independent simulation runs.

Figure 4.4 shows the percentage overhead (MAC + PHY) when the bandwidth is saturated for the number of subframes ranging from 1 to 16. When the number of subframes is equal to 1 the performance is the same as WiMedia. However, as the number of subframes increases, we can see that we can obtain up to a 10% increase in bandwidth utilization due to overhead reduction. This translates into an increased throughput of about 40Mbps at the applications layer at a channel rate of 480Mbps. Note that the PHY overhead remains constant as the number of transmission opportunities is the same in each subframe. The PHY overhead will change only when the number of transmission opportunities changes as shown in Figure 4.1.

Next, we study the bandwidth utilization of the DT-MAC frame structure by introducing video streams of 40Mbps each until the channel becomes saturated. The physical layer data rate is 480Mbps, burst preamble is enabled, $T_{sf} = 64msec$, $T_{bp} = 512\mu sec$, $k = 16$. We use the isozone-fit algorithm described in [Elmagarmid *et al.* 1995] for reserving bandwidth in the WiMedia frame structure and an unslotted variation of it in the DT-MAC frame structure. Figure 4.5 shows the performance of the DT-MAC frame structure as compared to the WiMedia frame structure. We can see that although the delay is higher initially, it still remains within the delay bound of 50msec. However, at higher loads the proposed frame structure performs significantly better due to the improved bandwidth utilization.

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4.6 Comparison of DT-MAC with 802.11

In this section we compare the performance of the DT-MAC to the popular 802.11 protocol. The key parameters to evaluate a MAC protocol are aggregate throughput, delay and energy consumption. We must also observe that most protocols perform well under low traffic loads and a study under these conditions is trivial. Hence we consider only high traffic loads for the comparison of the protocols.

We study the scenario in which a pair of nodes communicate between themselves in ad-hoc manner. In this setup there are multiple streams, where the source and destination nodes of each stream are different. This scenario is relevant to future home networks in which there will be many nodes that have to exchange data using a direct link.

The simulation is setup for the first scenario as follows. There are 20 nodes in the network and each node communicates with one other node thus creating 10 independent streams of data. The channel bandwidth is 2Mbps, Propagation Model is Two-ray Ground propagation, RF Transmit Power is 280mW, energy consumed for transmission and reception by a node are 600mW and 350 mW respectively. The parameters of the DT-MAC were chosen as follows - $T_f = 1sec$, $T_{bp} = 38msec$, $T_{dp} = 960msec$, $f = 1$, $T_b = 1msec$.

Fig. 4.6 shows the aggregate throughput (sum of the throughputs of each individual stream) at the Application Layer. Each stream was generating 324 byte packets which is typical of audio (CBR) and video (VBR) streaming applications at a rate of 190Kbps. Fig. 4.7 shows the average data rate for each stream. DT-MAC is able to offer a significantly higher bandwidth to each stream as well as provide a much higher percentage of the channel bandwidth to the Application Layer.

Fig. 4.6 also compares the performance of the two protocols for FTP traffic which is at the other end of the spectrum. We can see that DT-MAC takes a longer time to reach maximum throughput as compared to 802.11. Since the transmissions in DT-MAC are grouped, the round trip time is perceived to be high by TCP. This leads to TCP increasing its source rate slower.

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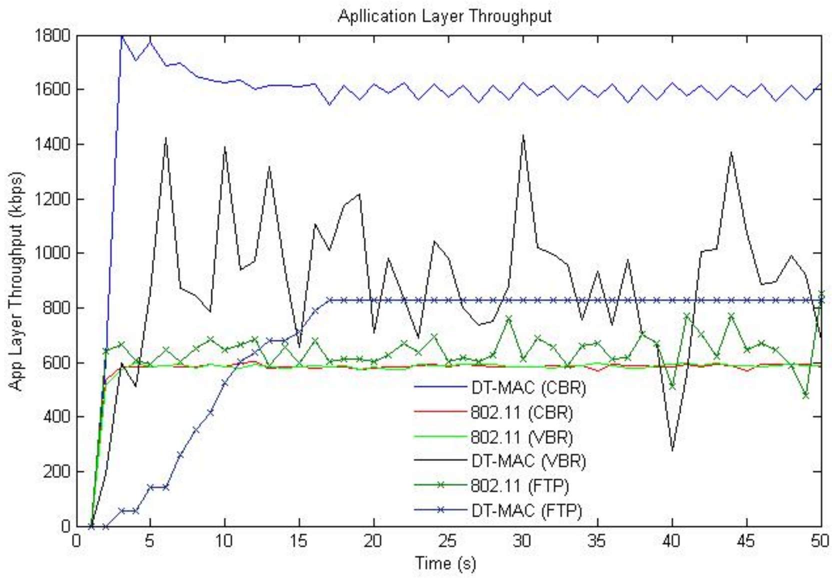

Figure 4.6: Aggregate Application Layer throughput for CBR, VBR and FTP traffic

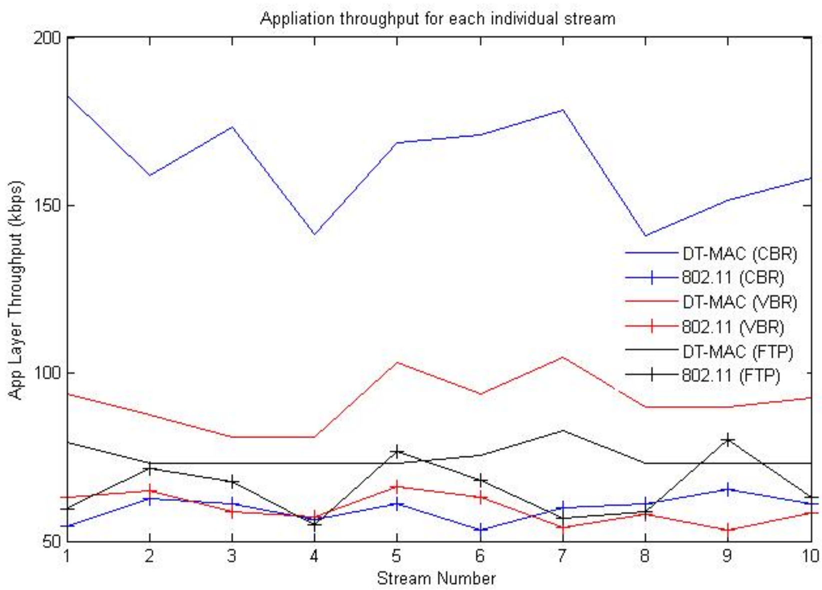

Figure 4.7: Average Application Layer throughput for each individual stream (CBR, VBR and FTP traffic)

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Figs. 4.8 4.9 compare the delay and jitter suffered by the CBR and VBR data streams for DT-MAC and 802.11. The significantly higher percentage of bandwidth that is available to the Application Layer translates into a reduced delay and jitter for the packets. The improved performance in terms of delay and jitter will be able to provide better performance for video and audio applications.

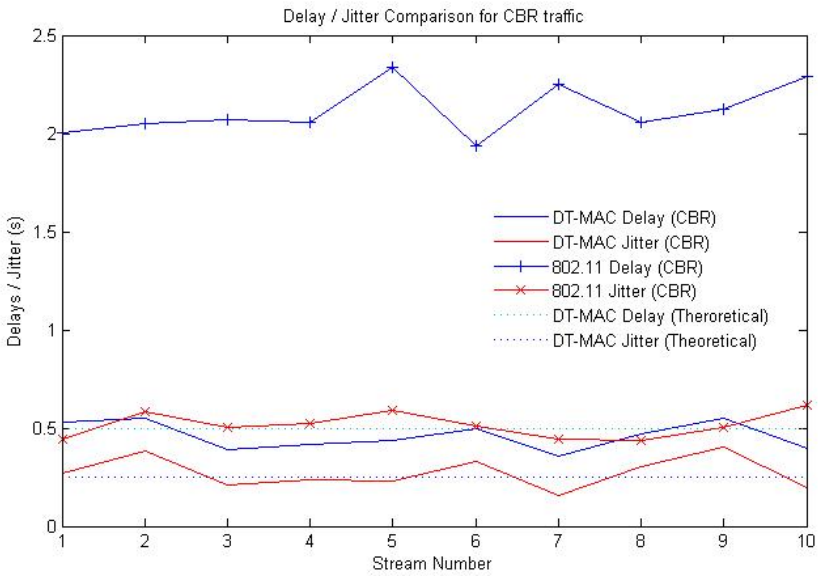

Figure 4.8: Delay and Jitter Performance for CBR traffic

In terms of energy consumption, the design of DT-MAC allows the nodes to sleep during each frame if it knows that there is no transmission destined for it. When the traffic load is high, most of the bandwidth is occupied and the nodes wake up only when they have to receive data. This allows for a significantly lesser energy consumption as compared to the basic 802.11 protocol. Fig. 4.10 compares the energy consumed per unit time for the two protocols for different traffic types. For 802.11 the energy consumed is not traffic dependent, but for DT-MAC the energy consumed is traffic dependent since each traffic type creates a different sleep/wakeup pattern for the nodes.

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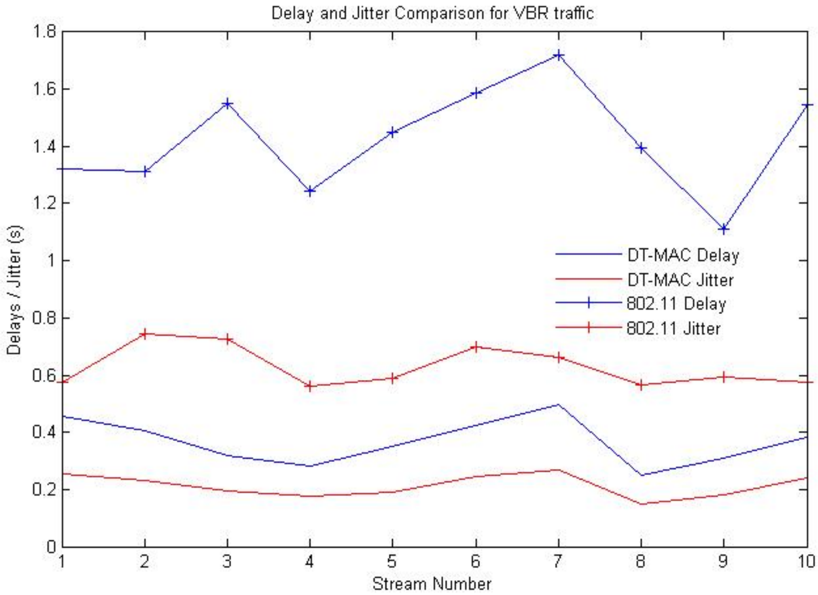

Figure 4.9: Delay and Jitter Performance for VBR traffic

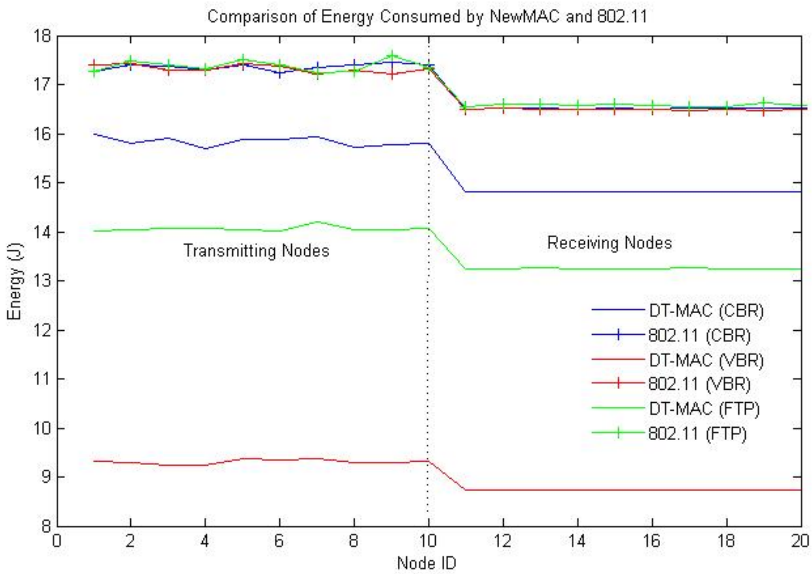

Figure 4.10: Energy consumption for different traffic types)

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4.7 Summary

This work was motivated by the needs of the next generation wireless networks. We have studied the requirements and shown that current MAC protocols are inadequate to efficiently meet the future needs. We have also studied the inefficiencies of current MAC protocols to establish a baseline for the design of a new MAC protocol. The lessons learnt from this study has been used to design a new TDMA-based MAC protocol. In order to understand its performance better, we have developed theoretical results for parameters like delay, jitter and overheads. The results show that the performance of the protocol is significantly better than 802.11 in a general LAN setup.

The protocol that we have designed does have some limitations. However, the motivation of this work was to establish a new design philosophy for future MAC protocols and we feel that this work achieves its goals. The design of the MAC protocol allows for future research to improve the performance of the protocol and for starters, we have discussed a few enhancements on the basic design.

Our plan for the extension of this protocol includes optimizing its performance for multi-hop networks, focusing on synchronization strategies that do not limit the number of nodes. We also aim to investigate the optimization of the TSC and dynamically changing the beacon period to improve the performance of the protocol.

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Chapter 5

Distributed Data Collection Protocols

Tier 1 and *Tier* 2 networks together provide a strong platform for the future of ubiquitous computing. They provide the necessary infrastructure to sense and collect many different types of information for a wide variety of applications. Without an effective mechanism that enable the collection of data from these networks we cannot tap their potential completely. In this chapter we explore efficient, distributed methods to collect and disseminate information in *Tier* 2 networks.

In order to contextualize the problem and ease of presentation we consider collection of data from nodes monitoring a parking lot. We design a distributed data collection and dissemination protocol called Hear-Hear that can be used for any adhoc deployment of nodes. It uses a novel strategy of simultaneous collection and dissemination to minimize the cumulative delays of first collecting and then disseminating the information. A key feature of Hear-Hear is that its operation is independent of the topology and it can operate with the similar efficiency irrespective of the size of the network. We evaluate the performance of Hear-Hear analytically, through simulations and using a practical wireless sensor network deployment.

The problem is to develop a method to collect data from the nodes monitoring the parking lots within a relatively short duration. However, we do not want our

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design to be constrained by the specifics of our deployment, since other applications might involve large scale deployments across large geographic expanses. In an urban scenario there might arise a need to setup and tear down parking lots temporarily, say, for special events or if fine grained monitoring is required for a short period. So we require that the algorithm should operate without any topological constraints. In order to achieve this we develop a broadcast based design in which every node only broadcasts its messages and does not require to perform any unicasts. Also, we assume no knowledge of the topology and cannot use any routing mechanism that is topology based. Further, we must also ensure that the data collected is consistent and reliable so we do not incorrectly redirect commuters to occupied parking spaces.

Another important consideration is the fact that in open parking lots or underground parking lots, none of the nodes might be within the range of the basestation. In such cases it might be viable for one of the nodes to be equipped with an 802.11 radio and serve requests from passing cars directly. In order to minimize the infrastructure needed and ease of deployment we should not fix the node at which this service is available. In other words any node in the network should be able to serve as the basestation, if provided the right equipment. We envision a system in which any node in the network can act as the basestation or an external mobile basestation might query any node in the network to obtain the data. In order to achieve this, our design has to be distributed because and the global information must be propagated to every node in the network. Given these requirements, a poll-based data collection is more suitable as the continuously changing data at the sensors will cause a high overhead in a push-based system. Also, polling is useful for dynamically changing the sampling rates of the data as the activity at different nodes might change during the course of time.

5.1 The Hear-Hear Protocol

The design challenges of Hear-Hear are to

1. Collect and disseminate occupancy data from each node in an arbitrarily connected multihop network.

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2. Operate reliably under diverse channel conditions.

3. Not require any dedicated infrastructure, centralized control or topology information.

4. Minimize implementation complexity to allow inexpensive deployments.

A *pull-based* method satisfies these requirements better than a *push based* method, as it obviates the need for any dedicated infrastructure and provides the flexibility of collecting data as and when needed by the commuters. This also has a lower overhead in applications where node data is continually changing.

Following this rationale Hear-Hear works on an *on-demand* principle. When data is needed, a *Data Acquisition* (DA) packet is injected into the network. Individual nodes add their local data and broadcast the packet to propagate it through network. The size of the data at each node is only a few bytes, thus allowing the data of all the nodes in the network to be contained in a DA packet of meaningful size. When a node receives a DA packet with information about other nodes it stores the new information locally.

5.1.1 Data Acquisition (DA) Packet

The DA packet is a special packet intended for collecting and disseminating data in the network. The DA packet contains fields for the sequence number and pre-allocated data fields for the local data of each nodes in the network. The *Information Content*, I, of a DA packet is defined as the number of information elements from unique nodes that the packet contains at a given time. A DA packet is said to have complete information when all its fields have been populated with data from the nodes in the network.

5.1.2 Method of Propagation

Hear-Hear uses broadcast to propagate the DA packet though the network. Although this eliminates the need for topology information and the overhead of a routing protocol, it still has to overcome packet losses due to the unreliable wireless medium. Broadcasting the DA packet means that we cannot use an

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ACK-based feedback mechanism to indicate successful packet delivery due to the ACK flooding problem. Hence, we need a retransmission mechanism that can be executed independently by each node and still avoids network flooding. We design a novel Information Content based timer, called the Re-Broadcast (RB) timer, to dynamically change the retransmission schedule of each node. The timer has no overhead and is calculated independently at each node based *only* on local information. Before discussing the specifics of the RB timer design, we present the operation of Hear-Hear in detail to help the reader better understand the finer points.

We control the retransmission of sensors by explicitly stating the maximum number of transmissions possible by a sensor. We implement a timer based mechanism to prevent the arbitrary retransmissions by nodes. Thus each node has a rebroadcast timer that dynamically schedules when a node can transmit its data. that does not rely on ACKs for feedback

5.1.3 Operation

The Data Request Generator (DRG) is an external entity (e.g. a commuter's laptop or PDA) which initiates Hear-Hear by injecting an empty DA packet - a DA packet with all the data fields initialized to null - into the network. On receiving a DA packet, a node always updates its locally stored copy of the DA packet (which initially has only its local information) with any new information from the received packet and transmits this updated local copy (Updated DA packet) either immediately or after a delay based on the following. On receiving a DA packet for the first time, a node immediately broadcasts the updated DA packet and starts its RB timer where as on receiving a DA packet subsequently, it updates its locally stored copy with any new information (if any) from the packet and restarts its RB Timer based on the *new* Information Content(if any).

These rules for transmission ensure that the DA packet is propagated over the multihop network and causes the Information Content of the locally stored

One solution is to fix the maximum number of broadcasts that each node can attempt. While this can prevent the network flooding problem, we need to note that the time between the retransmissions can significantly affect performance as scheduling retransmissions arbitrarily could lead to flooding or data starvation in the network.

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DA packet at each node to monotonically increase. A formal description of the Hear-Hear protocol is presented in Algorithm 4. Note that the timeout value for the RB timer plays a critical role in the number of messages transmitted and the Data Collection Delay (time taken to collect information from all the nodes). The following section describes the design criteria for the timeout value of the RB timer and its effects on the performance of Hear-Hear.

5.1.4 Re-Broadcast (RB) Timer

To ensure reliable packet delivery while avoiding network flooding, we develop a controlled broadcast technique using the RB timer to schedule retransmissions at each node, thus adding robustness towards packet drops/losses. Each node follows two simple rules to operate the RB timer:

1. Whenever the local information is updated (due to an incoming DA packet), it stops any existing RB timer and starts a new RB timer

2. On expiry of a RB timer, a node immediately broadcasts its local information and restarts the RB timer

Since the retransmissions are based on the RB timer's timeout value, small timeouts would lead to frequent retransmissions causing flooding and energy depletion while conservative values would incur significant delays in the data collection. Further, our goal is to improve the probability of the DA packet propagating through the network while maximizing the information content at each node, in the shortest time possible. Hence it is advantageous to retransmit a packet that has more information content *as soon as possible* to maximize the information content of other nodes.

Based on these insights we propose the following heuristic for the timeout value, t_{rb}, of the RB timer. *The t_{rb} value should be inversely proportional to the information content of its updated DA packet.*

Formally, $t_{i_{rb}} \propto s^{-k\frac{I_{i_{local}}}{I_{max}}}$, where $I_{i_{local}}$ is the information content of the local copy of the DA packet at the i^{th} node. I_{max} is the maximum information content of the DA packet, s is the timer decay parameter and k is a constant. If we

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Algorithm 4 : Operation of Hear-Hear

```
Initialize
Set state = IDLE
Set maxRetry = I_max
Set localSeqNo = 0
if DA Packet received then
  if state == IDLE and
  localSeqNo ≤ sequence number in DA packet then
    Update packet with local information and store a copy
    Broadcast updated packet immediately
    Calculate Information Content (I_{i_local}) and start the RB Timer with time-
    out value t_{i_rb} based on (I_{i_local})
    set state = MONITOR
    set localSeqNo = sequence number in DA packet
  else
    if Received DA packet has new Information compared with local DA
    packet and
    localSeqNo ==sequence number in DA packet then
      Update the local DA packet with new information received
      if Local DA packet has complete information then
        Broadcast the Local DA packet and set state = IDLE
      else
        Calculate the new Information Content (I_{i_local}) and restart the RB
        Timer with a new timeout value based on the updated (I_{i_local})
      end if
    end if
    if RB Timer Expired and maxRetry > 0 then
      Broadcast the Local DA packet
      maxRetry − −
    end if
    if maxRetry == 0 then
      set state = IDLE
      maxRetry = I_max
      localSeqNo + +
    end if
  end if
end if
```


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were to choose a direct proportionality it would lead to nodes with lesser information making frequent and hence wasteful retransmissions. Choosing an inverse exponential proportionality ensures that such nodes wait longer to rebroadcast, allowing the DA packet to propagate to other nodes. Empirically, we found that using a timer the exponent value ranging between $[-3, 3]$ produced the best results for networks with less than 50 nodes. This results in the following timer function -

$$t_{i_{rb}}(i) = s^{-(\frac{6i}{I_{\max}}-3)} \tag{5.1}$$

To substantiate our heuristic we compare the delay between the time the DRG injects a DA packet into the network to the time it receives a complete DA packet and the total number of messages exchanged during this period for different decay parameters. Figure 5.1 presents the results from a simulation in which the nodes were placed in a topology similar to our deployment. The radio was modeled based on the specifications of the XSM motes and a Two-Ray Ground propagation model was used to capture the performance of an outdoor deployment. The maximum number of retransmissions attempted by a node is set to 10.

The results indicate a definite tradeoff between the delay and the total number of messages exchanged using different decay parameters. As predicted, the delay for a linear decay parameter is very high while that of the exponential decay parameters is much lower. An interesting point to note is that, between the exponential decay parameters, the total number of messages do not increase exponentially and there is an optimum value ($s = 2$ has the minimum delay) beyond which the delay increases. This is because a higher decay parameter will cause nodes with more data to transmit very frequently, resulting in collisions and loss of packets thus increasing the delay. The deployment and the remaining results presented in the paper use $s = 2$ as the timer decay parameter.

5.2 Upper Bound on Data Collection Delay

In the following we analyze the data collection delay which quantifies the efficiency of Hear-Hear in collecting information from all the nodes in the network and

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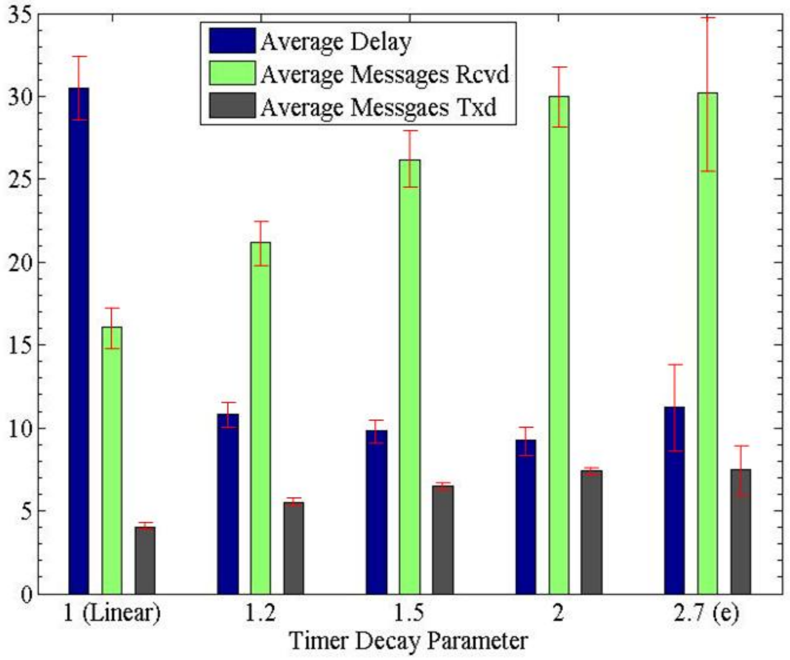

Figure 5.1: Comparison of Delay and Message Overhead for different timer decay parameters

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provide an upper bound. Formally, *Given a packet error probability p_e and an arbitrary network connectivity graph, there is a deterministic upper bound $\bar{T}$, on the delay between the injection of an empty DA packet and the reception of a DA packet with complete information by the Data Request Generator (DRG).*

To calculate the value of the average delay T, we observe that there is a minimum delay, t_a, for each node to access the channel. Node i restarts its rebroadcast timer each time $I_{i_{local}}$ is updated and hence the time before a node attempts the next retransmission is $t_{i_{rb}}(I_{i_{local}})$. Also, each node attempts a maximum of r retransmissions of the DA packet when $I_{i_{local}} < I_{max}$ and a maximum of r' transmissions when $I = I_{max}$. So we can write the expression for T as

$$\sum_{i=1}^{n} \left[t_a + \sum_{j=1}^{r} \left\{ j(1-p_e)p_e^j t_{i_{rb}}(i) \right\} \right] + \left[t_a + \sum_{j=1}^{r'} \left\{ j(1-p_e)p_e^j t_{i_{rb}}(I_{max}) \right\} \right] \quad (5.2)$$

The expression consists of two distinct components - the first is the time taken for the DA packet to reach the node that is farthest away (h_{max} hops) from the DRG and the second is the time taken for the DA packet, which now has complete information, to return to the DRG. Using Eq. (5.2) we can calculate the average delay.

In the worst case each node will attempt r and r' retransmissions when $I_{i_{local}} < I_{max}$ and $I_{i_{local}} = I_{max}$ respectively. Hence we can derive the upper bound $\bar{T}$ by setting $j = r$ and $j = r'$ in the first and second components.

$$\bar{T} = \sum_{i=1}^{n} [t_a + r t_{i_{rb}}(i)] + [t_a + r' t_{i_{rb}}(I_{max})] \quad (5.3)$$

The deterministic upper bound indicates that if the DRG receives a complete DA packet, it will do so within $\bar{T}$.

The values of r and r' must be chosen depending on the packet loss rates in the network. Choosing a small value for r may result in the DA packet not reaching all the nodes while choosing a large value for r' may result in wasteful retransmission of the complete DA packet.

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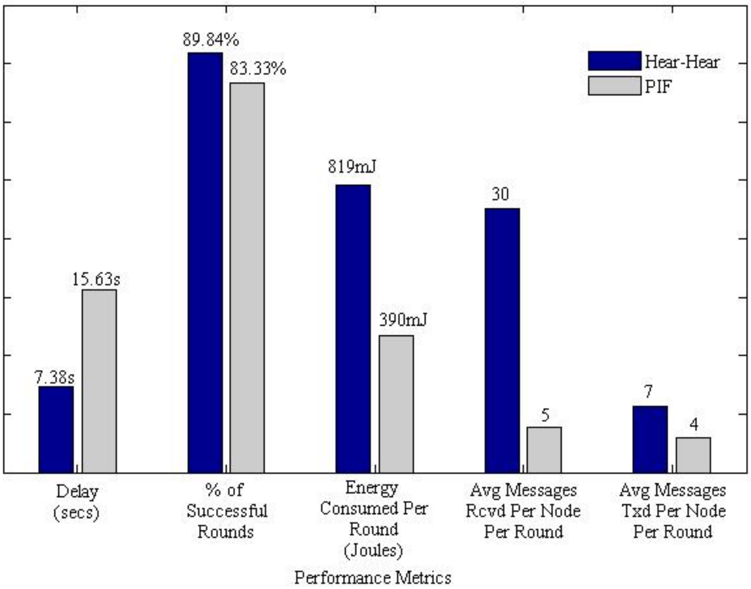

Figure 5.2: Performance comparison Hear-Hear and PIF in a Static Network

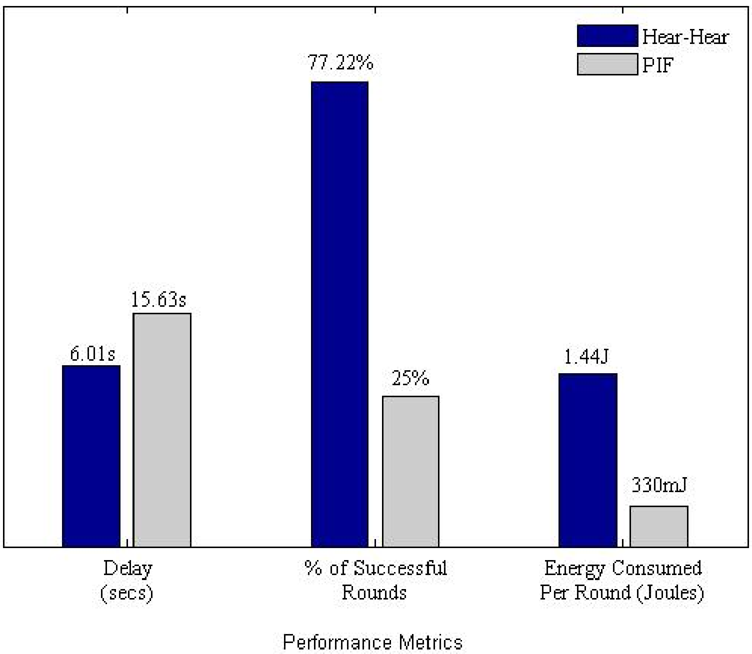

Figure 5.3: Performance comparison Hear-Hear and PIF in a Mobile Network

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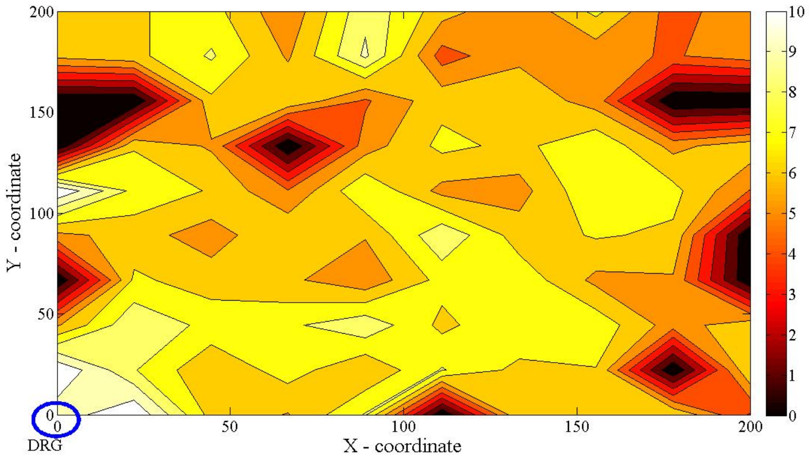

Figure 5.4: Delay Profile of Hear-Hear

Further, each node starts executing the algorithm when it receives the first DA packet and stops executing when $I_{i_{local}} = I_{max}$ or if it has reached its maximum number of retransmission attempts. Thus the initiation and termination of the algorithm is locally determined at each node.

5.3 Evaluation of Hear-Hear

In the following we compare the performance of the Hear-Hear protocol with Propagation with Information Feedback (PIF) based schemes using standard metrics like time to disseminate data to all nodes and message overhead. We also study its performance under situations in which the nodes are mobile and and highlight some of the features of Hear-Hear that make it suitable for other applications also. The performance of Hear-Hear in the parking lot monitoring application indicates it's viability for other applications with similar requirements. Hence in the following section we evaluate Hear-Hear and highlight some of its features.

In the results presented below, all simulations were run with 30 nodes, which were randomly placed in a 200m×200m area. The average degree of connectivity of each node was 4 and the maximum number of hops from the basestation was 5. The radio was modeled on the specifications of the XSM motes and a Two-Ray

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Ground propagation model was used to capture the characteristics of an outdoor deployment. The maximum number of retransmissions attempted by each node was set to 10.

5.3.1 Performance

Figure 5.2 presents the performance metrics of Hear-Hear as compared to the PIF protocol which also has comparable features to Hear-Hear. An important metric we evaluate is the delay in receiving information of *all* the nodes. As can be seen from the Figure 5.2 Hear-Hear's delay is significantly lesser than that of PIF making it more suitable for applications that require real-time data collection. It must also be noted that, in PIF only the basestation gets the global data, where as in Hear-Hear *each* node in the network has the global data. The combined collection and dissemination of data by Hear-Hear also improves its resiliency as indicated by the higher percentage of successful rounds. In terms of energy consumption, PIF performs better than Hear-Hear due to the lesser number of messages transmitted and received.

5.3.2 Suitability for mobile networks

A highlight of Hear-Hear is, that it is resilient to dynamic topology and its performance in a mobile network does not significantly degrade from that in a static environment. As Figures 5.2 and 5.3 indicate, Hear-Hear successfully completes 89% of the rounds in a static network and 77% in a mobile network. Figure 5.3 also shows the comparison of PIF and Hear-Hear in a mobile network. The results show that Hear-Hear outperforms PIF in terms of both delay and percentage of successful rounds.

5.3.3 Better performance with mobile rather than a static basestation

The location of the basestation with respect to the network does not matter in any way to the performance of Hear-Hear. In fact, it might be advantageous for the basestation to inject the query into the network at some location and receive

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the global information at another location. Figure 5.4 shows the geographic delay profile which is the time taken to obtain the global information from the time of injection of the DA packet with respect to the (x,y) coordinates of the nodes. The DA packet is injected into the network at the point (0,0) indicated by the blue circle. The results show that the nodes further away from this point have significantly lesser delay than the nodes closer to it. This is from the fact that the DA packet collects more information as it propagates through the network and nodes further away from the point of injection are likely to be the first to get the complete information. The information then propagates back to the point of injection, which justifies the phenomena. This can be useful in applications where basestation is mobile and data has to be collected over a large geographical area.

Traditional methods, on the other hand, incur routing overheads from the user across the multihop network to the basestation and back, as only the basestation has global information. Simultaneous request by multiple users can cause more resources to be consumed for routing the queries to the basestation rather than the actual data collection process itself. In such a scenario, Hear-Hear offers a distinct advantage as at the end of *one* round, all nodes have the global data and can quickly disseminate this information to the user.

5.3.4 Flexibility

The advantages of using the DA packet is not limited to simultaneous collection and dissemination. Simple modification to the DA packet can be used to obtain data from different subset of nodes, by allocating fields for only the nodes of interest. Further improvements can be made to obtain different types of data at different times based on the users need.

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Chapter 6

*i*Gate: A Wireless Sensor Network System for Monitoring Occupancy in Multiple Parking Lots

6.1 Introduction and Motivation

A steady growth in the usage of automobiles along with the cost and space constraints of building new parking lots has exaggerated the problem of finding parking for commuters. A survey of the parking facilities at our university shows that there are 36 fully functional parking lots distributed over two campuses with a total capacity of 16,142 cars. Whereas, during the 2008-2009 academic year, 29,323 permits were issued to faculty, staff and students. Even though not all the permit holders drive to campus every day, there is considerable difficulty in finding parking spaces, especially during peak hours. Monitoring the parking lots and disseminating their occupancy information to the commuters can help them save a significant amount of time and fuel spent in finding parking spaces.

Several parking lot monitoring systems have been proposed and built. Most of them equip each parking lot with toll collectors or mechanical gates at all entry and exit points and the movement of cars through these entry/exit points is controlled to keep track of the occupancy of the parking lot. In [Pala & Inanc

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2007], the authors describe a system that uses RFID-based tags to monitor the movement of cars through the entry/exit points.

Some modern parking lots use devices like pressure sensors at each parking spot to detect the presence of a car. Further advances in technology also enable the use of sensors that detect changes in the magnetic field [Caruso & Withanawasam 1999] caused by the presence or movement of a car to detect occupancy of a parking space. By collecting this information from each of these sensors at a central control unit, the availability of empty parking spaces can be determined at all times. Such systems offer the ability to provide drivers with information on the exact location of empty parking spaces. [Liu 2005, Moon *et al.* 2002, Chiu *et al.* 2004, Lee *et al.* 2003] describe advanced image processing techniques that are capable of detecting empty parking spaces using strategically placed cameras.

All the above mentioned solutions require setting up infrastructure which may be costly to build and operate. These solutions may not be viable for existing parking lots as the installation of infrastructure can disrupt their operation.

In this work, we present the design, deployment and operation of a low cost and easy to deploy parking lot monitoring and occupancy information system called *i*Gate (*invisible* Gate). *i*Gate provides a non-intrusive,"Plant-and-Play" approach to deployment. The main hardware component of *i*Gate is a wireless sensor network (WSN) consisting of a number of motes - a pair at each entry/exit point of a parking lot. The proposed *i*Gate system enjoys many of the advantages of WSNs that have been effectively demonstrated in other monitoring and surveillance applications as detailed in [Szewczyk *et al.* 2004, Mainwaring *et al.* 2002, Burrell *et al.* 2004, Arora *et al.* 2004; 2005].

The main software component of *i*Gate addresses two important and orthogonal aspects of the design. The first is the sensing and accurate classification of entry or exit events. For example, the sensors must be able to accurately identify and differentiate cars from other objects like people, bicycles etc., that may also move through an extry/exit point.

The second is the communication of information about these entry or exit events across the WSN so as to compute the occupancy of each and every parking lot. Further, the users should be able to query the occupancy information from

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any location within the service coverage area of *i*Gate, without involving a central entity. This requires a distributed approach to information processing.

6.1.1 Our Contributions

This work addresses the aforementioned challenges, and makes the following contributions -

1. Detection and Classification: We designed and implemented a decentralized algorithm to compute the direction of vehicle movement independently at each entry/exit point in the network. Our algorithm is easily configurable, to match the requirements of various deployment scenarios, by adjusting a set of key parameters. We present an extensive analysis of these key parameters and discuss the effects of these parameters on the accuracy and the performance of *i*Gate.

2. A self-synchronizing MAC protocol for energy efficient monitoring: We present a novel MAC protocol that enables the motes at an entry/exit point to independently synchronize between themselves with negligible overhead. Our protocol maintains a very low duty-cycle by keeping the radio of the motes in sleep mode 100% of the time in the absence of detections. When triggered by a detection it synchronizes the motes quickly and enables consistent classification of entry/exit events.

3. Distributed Data Dissemination: A distributed data dissemination protocol suitable for supporting on-demand querying of the parking occupancy information by commuters. Our protocol uses novel controlled flooding techniques and operates independently of the network topology. It is scalable and performs efficiently under diverse link characteristics and message losses. Further it has a small code footprint and can be executed on minimalist embedded devices.

4. Results from a real world deployment: We deployed *i*Gate to monitor 5 parking lots with a total capacity of more than 1000 cars. We study the viability of our solution as a feasible practical application by presenting

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data and trends collected by this deployment. We show that our solution is viable and performs well in terms of accuracy, ease of deployment and maintenance. We also discuss some of the practical issues encountered with this deployment.

6.2 Detection and Classification

In this section, we describe Detection and Classification which involves the following tasks

1. Sense movement of vehicles
2. Differentiate cars from other objects that may move through the entry/exit points
3. Determine the direction of movement consistently

Passive-Infra-Red (PIR) sensors provide an effective mechanism to detect the movement of vehicles as well as distinguish between different objects. However, a single PIR sensor only measures the changes in the Infra Red (IR) field and the duration for which this change occurs. These detections provide an accurate method to detect movement but cannot be used to detect the *direction* of movement. In order to determine the direction of movement, we require two PIR sensors that are spatially separated. Figure 6.1 shows the placement of motes (each of which consists of a PIR sensor and wireless communication circuitry) at an entry/exit point to achieve this spatial separation. By measuring the temporal offset of the independent detections of the two motes at the entry/exit point, we can determine the direction.

In order to do this, we require the two motes to be time synchronized and exchange their detections in real time. For this purpose we use a self-synchronizing MAC protocol that enables the motes to independently synchronize themselves and exchange information with the other mote with *zero* overhead.

A mote is a combination of the motion sensor and wireless communication circuitry. The pair of motes at an entry/exit point (as shown in Figure 6.1) is called a node. The rest of the paper uses this nomenclature.

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In the following subsections 6.2.1, 6.2.2 and 6.2.3 we will describe motion detection, the self-synchronizing MAC Protocol and the decentralized algorithm, respectively, which together provide the platform for effective detection and classification of vehicle movement.

6.2.1 Detecting Vehicle Movement

PIR sensors are very popular in many motion sensing applications due to their low power consumption and low cost. PIR sensors are tolerant to varying environmental situations and can operate efficiently under different lighting and weather conditions. Further, they provide good sensitivity, have a large field of sensing (up to $25ft$ [Dutta *et al.* 2005]), and are less prone to false detections. In [Dutta 2004], it is suggested that a combination of PIRs, magnetometers, and acoustic sensors can be used to effectively detect and classify the movement of various objects. However, under practical deployment scenarios, we found that the field of detection and the rate of false alarms of the magnetometers and the acoustic sensors are very high. Thus, we chose to use only PIR sensors for motion detection in our work.

Hardware and Setup - We used Extreme Scale Motes (XSM) from CrossBow Technologies [Dutta *et al.* 2005], which are one of the few motes that have built in PIR sensors. They are based on the $Mica2$ platform and are specifically designed for rugged use. The XSMs are equipped with a telescopic antenna that provides a larger radio range (in comparison to other motes) of about 50 meters. These features of the XSM make it a suitable choice in our work.

As shown in Figure 6.2, the XSMs have four *Kube Electronics* $C172$ PIR sensors [Dutta *et al.* 2005], mounted at 90 degree intervals to detect movement on all four sides. However, in our application we need to detect movement of vehicles only on one side (see Figure 6.1). Accordingly, we place the XSM such that only one of the PIR sensors is facing the roadway while the remaining PIR sensors on the XSM are switched off at all times.

Motion Detection - To distinguish between various objects passing through an entry/exit point we performed motion detection experiments using XSM PIR

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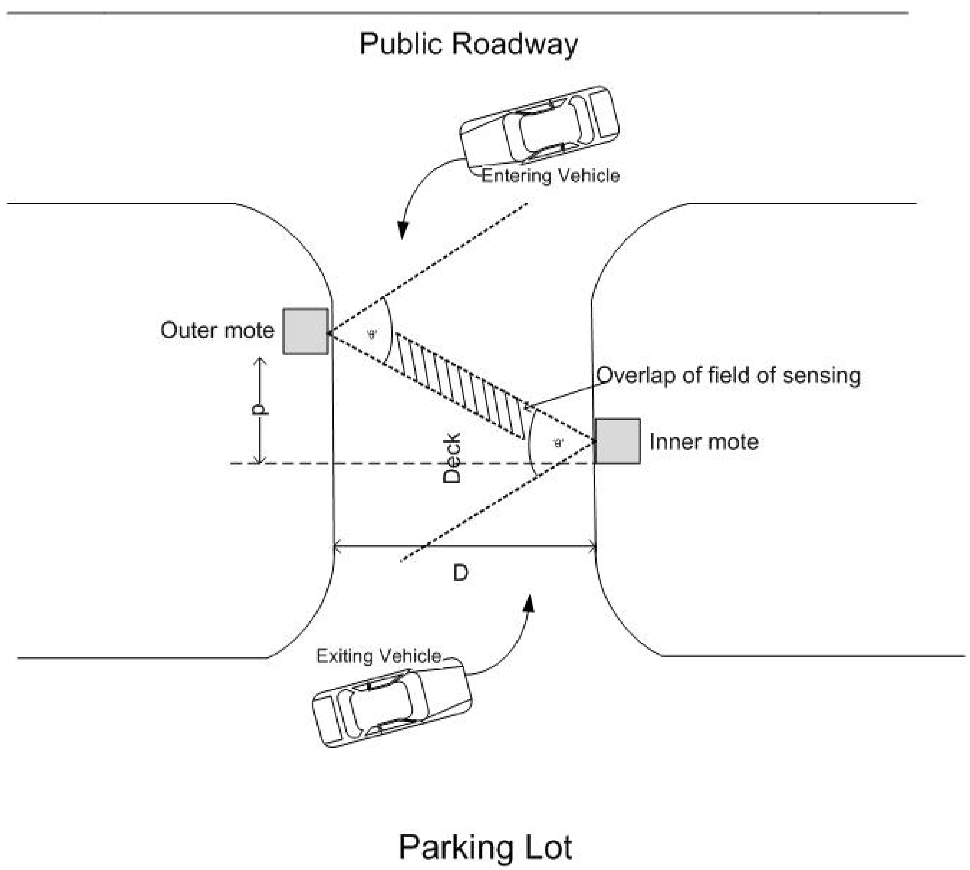

Figure 6.1: Placement of motes for monitoring

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Figure 6.2: XSM circuit board with integrated PIR sensors and the XSM ruggedized enclosure. The red circles show the PIR sensors on the board as well as on the enclosure (Figure courtesy EECS, UC Berkeley and CrossBow Technology)

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sensors on trucks, cars and people. Figure 6.3 shows the graphical representation of the readings generated by the PIR sensors for movement of these objects. The waveform shows the absolute value of the PIR readings after the analog to digital conversion process for different events. The PIR sensor readings maintain a steady value of approximately $0 \times 1FF$ when no movement is detected and generate an approximately sinusoidal waveform when movement is detected. Consequently, one can detect movement by continuously monitoring the gradient of the waveform. In addition, the duration of the gradient variation enables us to *differentiate and classify* cars from other objects.

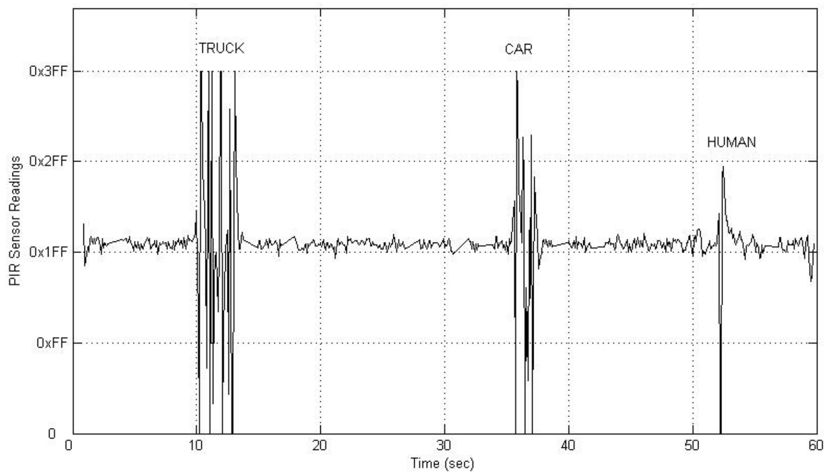

Figure 6.3: PIR Waveform for the detection of movement of various objects

A major challenge however is that due to the energy constraint, continuous monitoring is not possible. In *i*Gate, we activate the PIR sensor once every T milliseconds and sample the readings generated by the sensor. More specifically, if the gradient is greater than a particular threshold i.e., some movement has been detected we increase the sampling frequency of the PIR sensors to once every t milliseconds ($t \leq T$) in order to obtain a finer resolution on a time scale.

During our experiments we found that this steady state value changes by about ±20 based on the ambient light conditions. Hence we calculate a moving average of the steady state value to accurately determine the gradient changes (Step 1 of Algorithm 5) irrespective of the ambient lighting.

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We continue to read the PIR sensors at a frequency of once every t milliseconds until the gradient falls below the threshold, indicating that no movement is being detected. Then, we revert to sampling every T milliseconds to conserve energy. The start and end times of the detections are recorded to be supplied as the inputs to the decentralized entry-exit detection algorithm, which we discuss in section 6.2.3.

Algorithm 5 presents these steps. The algorithm is simple and yet the results from our field tests show that it is effectively able to detect different types of vehicles, ranging from small cars to buses, at a significantly wide range of speeds.

Algorithm 5 Algorithm for PIR detection that is run upon firing of the T millisecond timer

```
Gradient = abs(current reading - average steady state value)
if Gradient ≥ Threshold then
    Record the Start Time
    Disable the T millisecond timer
    Start new timer of t milliseconds,
    while Gradient ≥ Threshold do
        Collect and store samples using t millisecond timer
    end while
    Record the End Time
    Disable the t millisecond timer
    Enable the T millisecond timer
end if
```

It is important to note that the values of T and t are crucial design parameters for the system as the successful detection of movement at varying speeds is directly affected by their values. In Section 6.2.4 we develop the mathematical analysis for the selection of these parameters.

6.2.2 Self-Synchronizing MAC Protocol

In this section we describe a simple yet effective MAC protocol that allows each mote to synchronize with the other mote at the entry/exit point, independently and with minimal overhead. The MAC protocol has a simple frame structure as

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shown in Figure 6.4. The total frame duration is one second which is divided into $75msec$ for the *Beacon Period (BP)* and $925msec$ for the *Data Period (DP)*. The BP is slotted and each mote transmits its beacon in one of the slots. The DP is used for transmitting data.

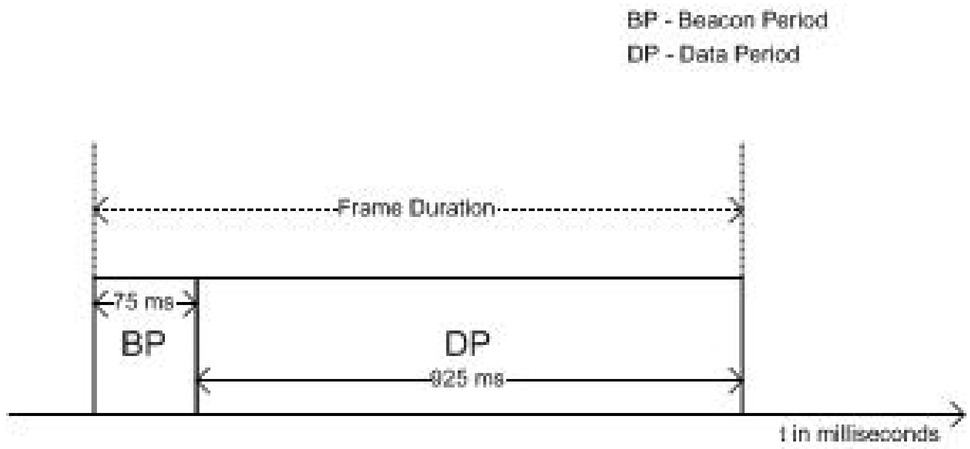

Figure 6.4: MAC frame structure

When the MAC module at a mote is switched ON (by a trigger from the PIR sensor), it wakes up the radio and scans the channel for *two* frame durations, to check for beacons. If it does not find any beacon being transmitted, then the mote installs its beacon at a randomly chosen time and the start of its beacon will be considered as the start of the frame. If the mote finds a beacon, it installs its beacon at an empty slot within the beacon period . As mentioned above it will assume the start of the frame as the start of the first beacon in the BP. There is no information exchange during the beacon installation phase and each mote independently decides where to install its beacon. Further, this mechanism enables the motes to achieve time synchronization implicitly as the start of the frame is always considered to be the start of the first beacon within the BP.

Although there is a possibility of beacon collisions when the two motes are switched ON at the same time, we keep the probability of this happening low by introducing a startup delay at each mote that is randomized based on the mote ID. Further, our protocol also includes mechanisms to detect beacon collisions based on making a mote randomly listen to the slot it is supposed to transmit

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its beacon. Upon detection of the problem, the mote restarts its MAC in order to be assigned a new empty slot.

For ease of presentation, the protocol has been described in the context of only two motes. However, the *same protocol without any modifications* can be used to achieve communication and time synchronization between multiple motes within a single-hop.

Algorithm 6 Algorithm for Beacon Installation

```
1: Begin
2: if Beacons already present then
3:     Find the first beacon in the BP and synchronize start of frame to start of
       beacon
4:     Synchronize local time of mote with the local time of beacon
5:     Install self-beacon at an available slot
6: else
7:     Install self-beacon at a random slot
8: end if
```

Whenever data is generated by the PIR sensor it is passed on to the MAC module, which buffers the data until the next BP. While transmitting the beacon during the BP, the mote includes information on when it will transmit the data during the DP. The mote's radio is awake during the entire beacon period so that it can listen to the beacons transmitted by the other mote. By listening to the beacons of the other mote each mote can independently determine when it should wake up during the data period to receive information from the other mote. Consequently, there is a significant power saving as the radio is awake precisely when it is required to receive data while sleeping at all other times.

6.2.2.1 Implementation details

In order to enable the motes to have the same absolute value of the local system time, each mote also transmits its local system time in its beacon. This allows other mote to synchronize the absolute values of their system times to the mote that transmits the first beacon. This scheme provides an easy method for the motes to have approximately the same system time in a distributed manner

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without external supervision. It should be noted that the system times of the motes will not be exactly the same due to propagation delays and local clock drifts, however, we have experimentally determined in our deployment that it is possible to achieve a synchronization with an error of less than $5msec$ between the two motes using the CC1000 radio module. (Finer synchronization can be easily achieved by using higher data rates and better radio modules.) Thus, in our application, the timestamp in the message of a mote can be directly used by the other mote without any correction. This is very useful as it reduces processing overhead for each packet, in terms of offset correction, and hence aids in reducing the overall complexity.

6.2.3 Decentralized Entry-Exit Detection Algorithm

In this section we present our simple decentralized algorithm that is executed by each mote for entry-exit detection. The algorithm takes the start and end times of the PIR detections by the mote as the local input and the start and end times received from the other mote as the received input. Using this information the algorithm accurately determines the direction of movement of the vehicle and consequently, decides whether a vehicle entered or exited the parking lot.

As shown in Figure 6.1, the mote that is closer to the parking lot is designated the *Inner* mote while the other one is designated the *Outer* mote.

The basic idea behind the algorithm can be explained easily by a visualization of the start and end times of the detections of both the motes on a time scale as in Figure 6.5. If start and end times of the *Outer* mote detection are before the those of the *Inner* mote, the algorithm decides that the direction of movement is in the direction from the *Outer* to the *Inner* mote, and hence that the vehicle entered the parking lot. Similarly, if the *Inner* mote started and ended detections before the *Outer* mote then the algorithm decides that the vehicle exited the parking lot. To minimize false detections the motes need to be placed in an optimal manner as described in 6.2.4.

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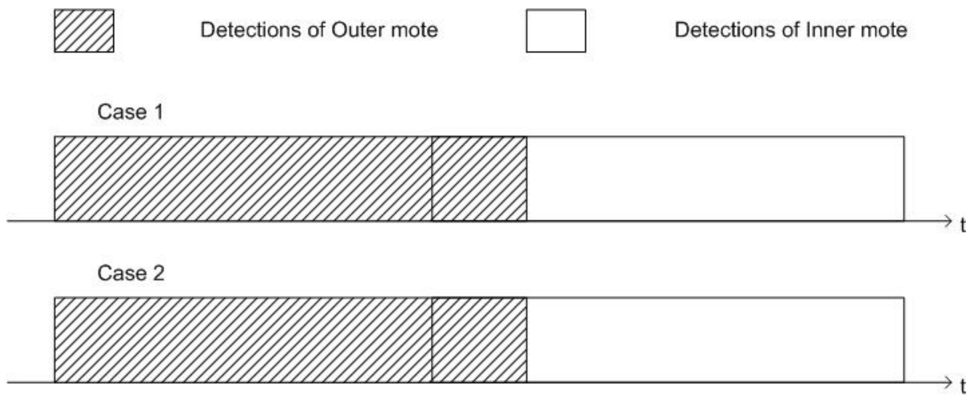

Figure 6.5: Timing of the readings for various cases

6.2.4 Analysis of Design Parameters

In this section we discuss the various parameters that govern the performance of the system and develop mathematical formulae for their design. We also discuss the effects of these parameters on the accuracy of the decentralized algorithm and provide the reader an insight on how to determine the best possible configuration for a given application scenario by way of presenting suitable design parameters for some of these scenarios.

6.2.4.1 Placement Of Motes

In order to achieve a generic design, we allow all the entry/exit points of the parking lot to be bidirectional ("i.e.ällow traffic in both directions). We also allow the cars to travel at a significantly wide range of speeds through the entry/exit points. The motes are placed on the opposite sides of the entry/exit point as shown in Figure 6.1.

An analysis of the decentralized algorithm presented in Section 6.2.3 shows that the accuracy is considerably improved if the start and end times of the detections of the two motes are separated as shown in Figure 6.5. More specifically, the vehicle should enter the field of the mote that is nearer to its lane of travel and then enter the field of the mote that is farther from its lane of travel. It is also necessary that it leaves the field of sensing of the mote that is nearer to its lane of travel before it leaves the field of sensing of the mote that is farther.

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In order to ensure that the detection of the motes are optimally separated, we require that the motes and hence their fields of detections are separated by an optimal perpendicular distance. We define this parameter as the *Distance of Separation* ('d') as in Figure 6.1. The distance of separation governs the *region of overlap* of the fields of detections of the two motes. We require that the fields of detections are neither completely disjoint as shown in Figure 6.6(a) nor should they be completely overlapping as shown in Figure 6.6(b). The optimal sequence of detections occur when the motes are separated by an optimal 'd' as shown in Figure 6.6(c).

Since the distance of separation is critical to the accurate operation of the decentralized algorithm, we give a procedure to calculate the distance of separation as follows.

We have experimentally determined that the accuracy of the system was highest, when the overlapping edge of the field of sensing of each mote passes through the intersection of the perpendicular drawn from the other mote and the line of travel of the vehicles on the farther lane. Without loss of generality, we approximate the line of travel of the vehicles to be along the middle of each lane. By exploiting the geometry, we then write the expression for the optimal distance of separation as follows

$$d = tan(\frac{\theta}{2}) * 0.75 * D \text{ meters} \tag{6.1}$$

Table 6.1 shows the optimal values of d for different Deck Widths (D) and Angles of Sensing (θ).

6.2.4.2 Timer Durations for the PIR Sensors

It is important to note that the values of T and t are important design parameters for the system as the successful detection of movement at varying speeds is directly affected by their values. We need to consider that the speeds of the vehicles passing through the entry/exit points of different parking lots may vary. Since the PIR sensor readings are sampled every T seconds (according to the coarse resolution timer), the speed of the vehicles directly affects the chance of movement detection. A low rate of sampling will lead to false negatives as it would not wake up in time to detect movement - a car might pass through the entry/exit point

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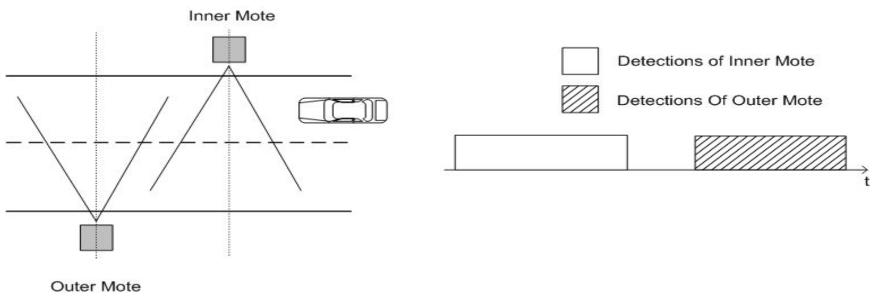
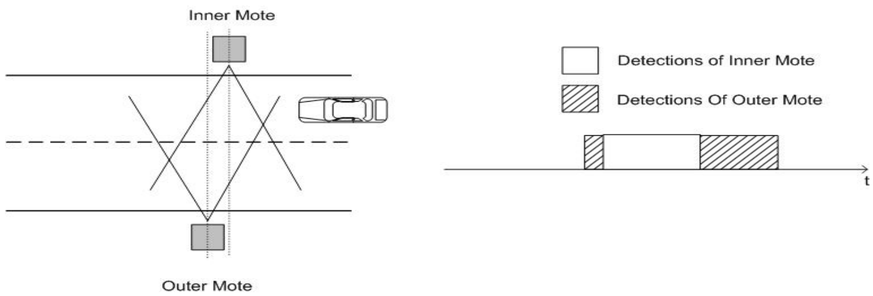
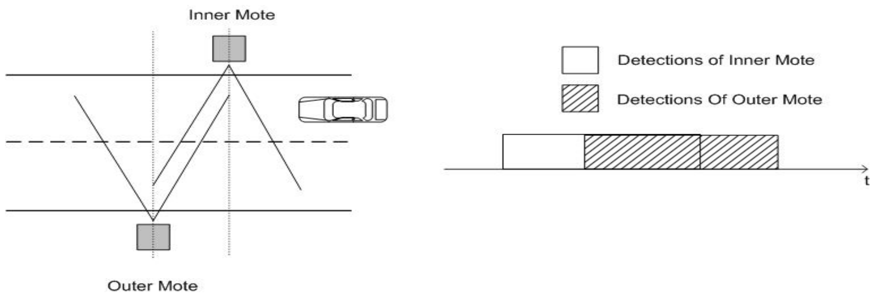


(a) Distance of Separation too large



(b) Distance of Separation too small



(c) Optimal Distance of Separation

Figure 6.6: Effect of the distance of separation of the motes on the detections

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between two successive sampling instants. A high rate of sampling will lead to unnecessary depletion of energy.

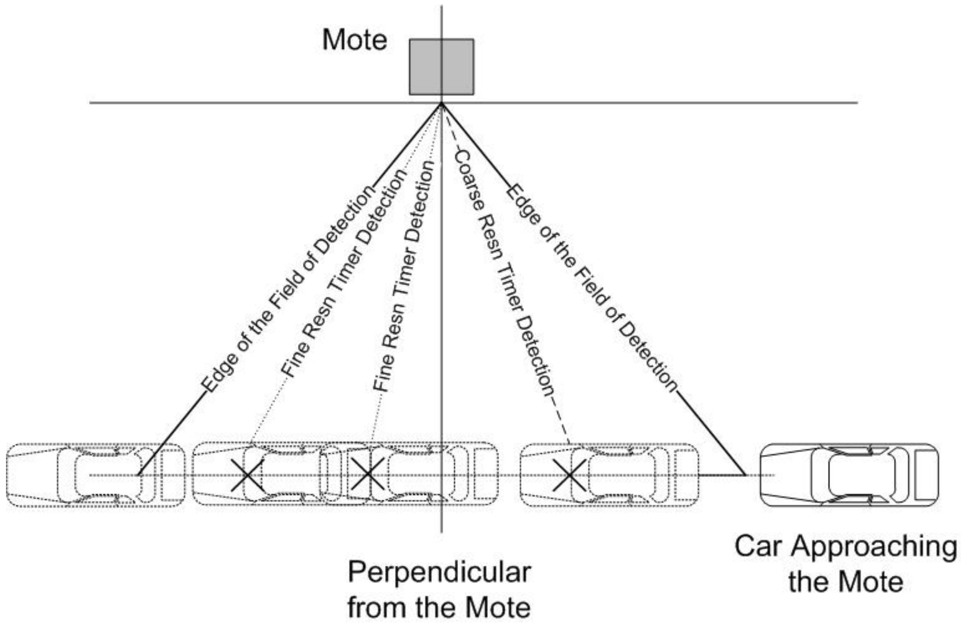

Figure 6.7: Ideal scenario for detecting movement of a car through the field of the mote

From Figure 6.1 it is obvious that the mote that is closer to the lane of travel of the vehicle should always start sensing first, while the mote that is farther away should start sensing later. Figure 6.7 shows a car traveling from right to left. In the worst case scenario it is possible that the PIR sensor was sampled just before the vehicle entered the field of sensing. For accurate detection of movement using the algorithm described in Section 6.2.1, we require that at least one detection of the vehicle passing through the field of sensing is made before the vehicle crosses the perpendicular drawn from the mote. We select this distance to exploit the geometry. This distance allows for the fine resolution timer to be started and obtain at least a few readings. We have experimentally corroborated that this method improves the accuracy greatly.

Ideally T should be such that the maximum distance the vehicle can cover within the duration T is less than half the length of the field of sensing along the line of travel of the car. It should also be noted that the length of the field of

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Table 6.1: Distance Of Separation For Various Angles and Deck-Widths

Deck Width (m)	Angle of Sensing (degrees)	Distance of Separation (m)
4	110	4.284
	90	3
	70	2.1
8	110	8.568
	90	6.0
	70	4.2
10	110	10.71
	90	7.5
	70	5.25

sensing along the line of travel of the vehicle is lesser for the mote that is nearer to the lane of travel of the vehicle as compared to the mote that is farther away.

If the speed of the car were to be v meters per second and the time taken for the car to travel from the edge of the field of sensing to the perpendicular drawn from the mote is equivalent to the resolution of the timer, the value of T is given by

$$T = (tan(\frac{\theta}{2}) * 0.25 * D) * \frac{1}{v} \text{ sec} \tag{6.2}$$

Recall that our system also provides a fine resolution timer whose significance is to enhance the reliability readings and improve the accuracy of the system. As per the rationale of the initial timer mentioned above and the need for at least n ($n \geq 2$) detections, before the car exits from the field of sensing of a mote, the resolution of the fine timer is calculated as

$$t = tan(\frac{\theta}{n}) * 0.25 * D * \frac{2}{v} \text{ sec} \tag{6.3}$$

The concept of the detection using two timers is also depicted in Figure 6.7. Furthermore, Table 6.2 gives the resolution of the timers suitable for various speed ranges.

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Table 6.2: Parameters for the Parking Lot Monitoring Application

Speed Range (mph)	Avg. Speed (mph)	T_{max} (sec)	T_{avg} (sec)	t_{max} (sec)	t_{avg} (sec)
5-25	15	0.127	0.213	0.0426	0.0709
26-40	33	0.0795	0.0967	0.0267	0.03226
41-60	50.5	0.0532	0.06325	0.01774	0.021085

6.2.4.3 Energy Consumption

In this section we present an analysis for the total energy consumption of the motes. The energy consumption of the motes depend on two operational modes: 1. when there are detections and the motes are in the ACTIVE mode, and 2. when there are no detections and the motes are in the IDLE mode. The total energy consumption for each state can be further categorized into the energy consumption of Radio, PIR Sensors and Processor modules. In the following, we consider the ACTIVE and IDLE modes of these modules and their corresponding energy consumption in those states to derive an approximate energy consumption model.

Idle Mode - The energy consumed by the Radio module can be categorized as energy consumed when transmitting, receiving, and when the radio is OFF. From the brief analysis in Section 6.2.2 we infer that, in a time frame of one second, the radio module transmits the beacon for $7.5mSec$, receives a beacon for $7.5mSec$ and is OFF for the remaining $985mSec$. The power consumption in these states are $48mW$, $24mW$ and $3\mu W$, respectively, resulting in a total energy consumption of $542.949\mu J$.

Similarly the Processor module is in the ON state for $20mSec$ and in the SLEEP state for the remaining $980mSec$ and the power consumption in these states are $30\mu W$ and $24mW$ respectively. The total energy consumption by the Processor module is $509.4\mu J$. The PIR component of the nodes is in the ON state for the entire duration, and at a rate of $0.88mW$ consumes $0.88mJ$ of energy. Thus the total energy consumed in this mode is $1.932mJ$.

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Active Mode - The detection of movement results in the exchange of messages between the motes and this increases the duration for which the Radio and Processor modules are active. A closer analysis shows that the radio module transmits for $22.5mSec$, receives for $22.5mSec$ and is OFF for the remaining $955mSec$. Similarly, the Processor module is ON for $80mSec$ and is OFF for $920mSec$. The PIR module continues to remain on for the entire duration. Proceeding with the energy calculations as above we can show that the total energy consumed in this mode is $4.45mJ$.

On an average, the number of detections during a period of 24 hours was estimated to be 1500 on weekdays and 200 on weekends, which gives the average number of detections per day to be 1128. From the above analysis we calculate the total energy consumption per day as approximately $170J$. Since the average energy provided by 2 AA batteries is about $30KJ$, this translates into an average lifetime of approximately 6 months for each mote. Hence, the running and maintenance costs of our system are relatively low.

6.2.5 Performance in a Single Parking Lot

In order to verify the performance and accuracy of the decentralized entry-exit monitoring algorithm of the system and also obtain useful statistics on the occupancy of a single parking lot we deployed our system over a span of couple of weeks in September and October 2008. We verified the accuracy of the system by occasionally taking manual counts of the occupancy of the parking lot during the deployment.

The parameters for our deployment were set based on the results presented in Tables 6.1 and 6.2. The distance of separation of the motes was calculated as $d = 3.5m$. The coarse resolution timer was calibrated to fire every 500 milliseconds and the fine resolution timer was calibrated to fire once every 100 milliseconds. To avoid frequent false detections and also compensate for slowing down of the cars while entering the parking lot, a decay parameter was set to stop the fine resolution timer.

The system was evaluated on three typical weekdays between 1pm and 7pm and manual counts were also taken during the time the system was operational.

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Figure 6.8 shows a comparison of the occupancy on three typical weekdays between 1 pm and 7 pm. We can see that the occupancy trends are very similar for all the days between 1 pm and 4 pm. After 4 pm there is a notable decrease in the occupancy on Friday as compared to Monday and Wednesday. We can also see a consistent pattern in the slight increase in the occupancy between 3 pm and 4 pm as the faculty parking lot is open to students after 3 pm on weekdays.

In order to further validate our system under different occupancy conditions we measured the occupancy trend on a weekend. Fig.6.9 shows the occupancy trends on a weekend. The graph also shows a marked decrease not only in the occupancy of the parking lots as compared to the weekdays but also the rate of decrease is significantly lesser than that of Weekdays. However, though the occupancy on Sundays between 10:30 am and 11:30 am is higher than that on Saturdays due to various events on campus till noon, the rate of decrease is also high. There is a marked increase on occupancy between 6:45 pm and 8:30 pm due to students using the campus facilities for academic purposes.

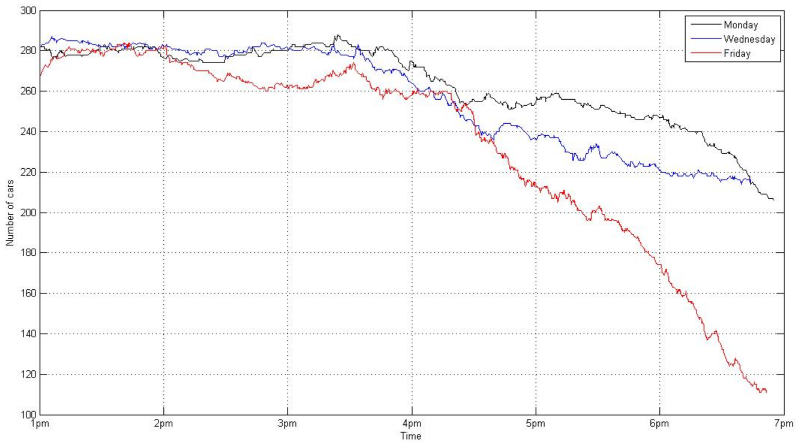

Figure 6.8: Occupancy on weekdays

Our deployment results suggest that the performance of the decentralized entry-exit algorithm in combination with the self-synchronizing MAC protocol are capable of reliably and accurately detecting and classifying the entry and exit of cars through the parking lot. Further, the tunable parameters provide the

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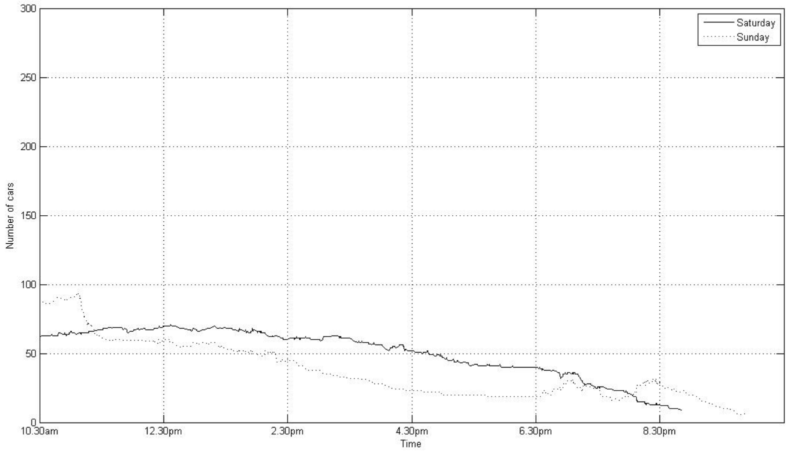

Figure 6.9: Occupancy on weekends

means to modify the system to perform extry/exit detection for other applications as well.

6.2.6 Reliability issues

In terms of network connectivity the system performed very well. An analysis of the packet error rates shows that it was less than 10^{-5}. We attribute this to the fact that the XSM radio module operates in the 900Mhz band that is largely tolerant to various ambient conditions, and that the telescopic antennas of the XSMs improve their reliability of communication.

The PIR sensors of the motes displayed sporadic erratic behaviors when the ambient temperature was extremely low (in the region of $-5\,°C$). In such cases, no movement detection was observed, however the radio transmission would still work. This condition was not consistent and occurred unpredictably. After the motes are kept in room temperatures, the PIR sensors would return to their normal operations most of the time. However, in some other cases, the nodes stopped functioning completely, and did not respond to hardware resets. Our investigations showed in those cases that the culprit was memory corruption, which may also be indirectly linked to cold weather conditions.

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With respect to the performance of the system in terms of accurately detecting the number of cars there are certain limitations that need to be addressed in future. For example, when two cars are passing through the entry/exit point at the same time (i.e., one car is exiting the parking lot while one is entering at the same time) some false detections are observed. A possible solution to this problem is to use a pair of nodes on each edge of the roadway and dedicate each pair for detections in each direction (i.e., each pair of nodes will only detect movement in the lane that is closer to them). The nodes then need to negotiate with the nodes on the other side of the road to identify and resolve these detections.

Over time the synchronization of local system time between the nodes is lost due to clock drift. Although the two nodes have the same notion of time, due to the self synchronizing MAC protocol, the absolute local system times of the nodes will drift due to the drift of the individual system time. The application does not require very tight time synchronization,though a considerable loss of synchronization, which occurs if the clock is not corrected, will classify genuine events as cases of errata, or vice versa and hence will affect the performance of the system.

This is an implementation issue and in future work, a possible solution to this problem is to run the beacon setup process every hour as this is much easier compared to a continuous clock correction policy. In this way the fault tolerance of the system will also be improved as there is no need for a 'master node' to which the other nodes have to synchronize.

6.3 Distributed Data Dissemination

Thus far we have described and presented results of an effective solution for detection and classification of vehicles. This solution is suitable to monitor occupancy of a parking lot with a single entry/exit point. However, in reality parking lots have different shapes and sizes and are likely to have multiple entry/exit points. This means we need to collect the total number of cars entering and leaving each entry/exit point to compute the *overall* occupancy of that parking lot. Further, this may require communication between the motes at different entry/exit points over multiple hops due to the limited range of the radio.

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Before we describe a multi parking lot occupancy dissemination protocol we first outline the requirements and desirable features of such a protocol as follows. First, to improve the utility to commuters, the solution should help them make a decision on which parking lot to choose, so that the search and travel time is minimized. Second, to facilitate quick adoption and use, we do not require commuters to install customized hardware on their vehicles. Instead the commuters should be able to query for and receive this information on commonly used devices like cell phones and laptops.

Our goal is to achieve the design objectives, by reliably collecting data from *each* node (the two motes at an entry/exit point is collectively called a node) in the multihop network. This is especially critical in parking lots with multiple entry/exit points as the non-availability of even a single node's data, means that we cannot determine the occupancy of that particular lot. To avoid the overhead of tracking the mobile commuter to deliver the query results, we need to disseminate this information to all the nodes so that the commuter can receive it from any node along his/her travel route. Further to accommodate various deployment scenarios, the process should be capable of operating in any adhoc multihop network without requiring the nodes to maintain routes or remember their neighbors.

6.4 Multi Parking Lot Deployment

We installed a pair of XSM motes, collectively called a node, at each entry/exit point of 5 parking lots, covering an area of approximately 100,000 square meters. Each node executes the robust and energy efficient entry/exit monitoring algorithm presented in 6.2.3. By keeping a count of the entry/exit events at each node we compute the occupancy of the parking lot.

In total we deployed 15 motes (2 motes at each of the 7 entry/exit points and 1 mote acting as a relay) creating a multihop network as shown in Figure 6.10. Commuter queries were generated periodically by a static XSM mote placed in a building, acting as DRG. Note that the global information was not routed to the static mote but was collected from the broadcasts of the nodes which were one hop away from the static mote, similar to how a commuter would collect if he/she

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were on the move. In order to allow commuters to view the occupancy data we developed a web interface (shown in Figure 6.11) through which the information collected by the static mote was made available.

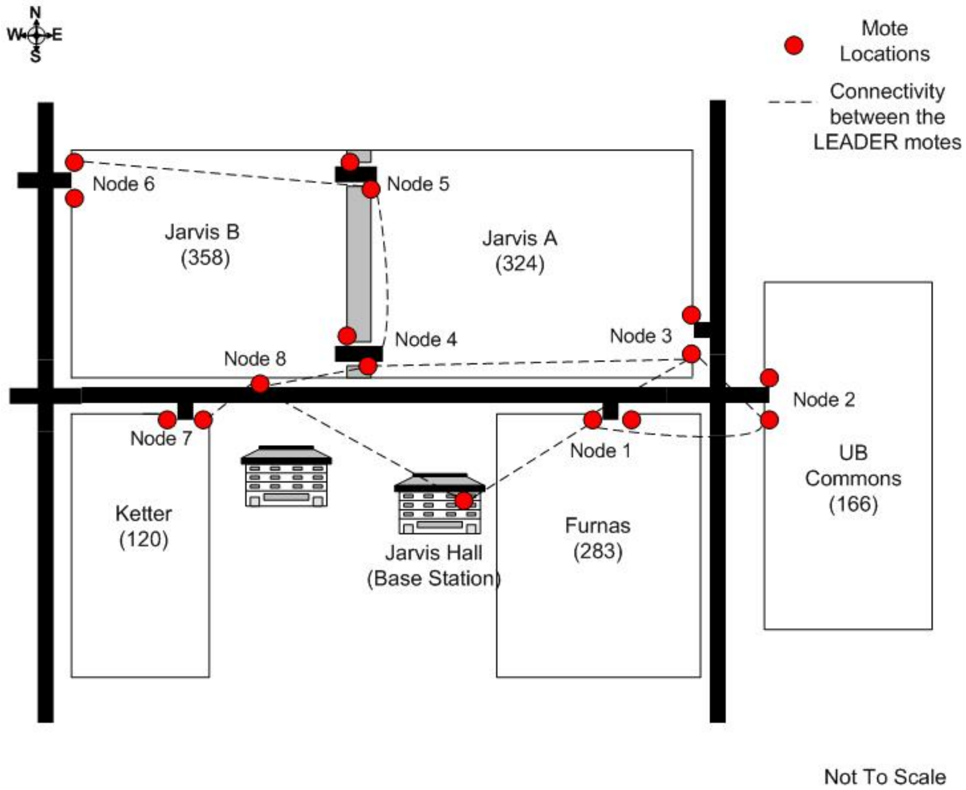

Figure 6.10: Deployment Scenario

Connectivity between the nodes was measured by first deploying the motes and placing an XSM mote programmed to measure the RSSI of packets received from the motes, at each node. The RSSI received at each mote over a period of one hour was averaged and compared to the sensitivity threshold of the XSM radio module. The connectivity shown in Figure 6.10 shows the links which had consistent connectivity i.e. where the received RSSI was consistently above the sensitivity threshold. There were some links whose connectivity was intermittent, for example between node 4 and node 7, due to the lack of a line-of-sight. However we placed a relay mote(mote 8) as shown in Figure 6.10 to over come this problem and ensure consistent connectivity.

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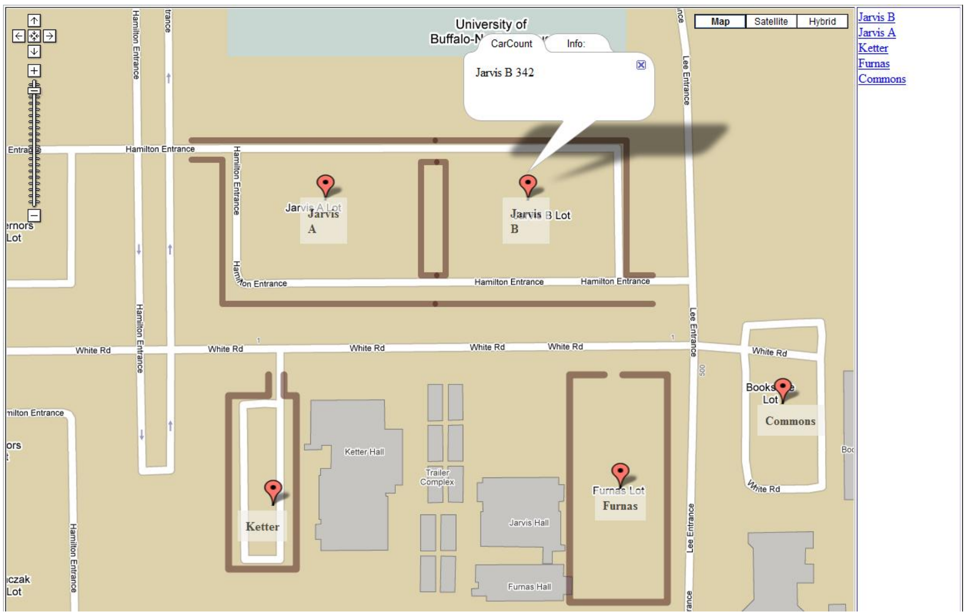

Figure 6.11: Screenshot of the website

6.4.1 Parameter Tuning in the Deployment

We apply the analysis in Section 5.2 to develop bounds on Hear-Hear's performance in our specific deployment scenario. Our deployment consists of $n = 8$ nodes placed at a maximum number of 4 hops from the DRG. We assume a conservative estimate of the packet error probability as $p_e = 0.1$ to account for the environmental factors like a row of trees, interference from cellular towers, movement of cars etc. We use the MAC protocol described in Section 6.2.2 and its channel access duration is $t_a = 1sec$ and the timer decay parameter is set to $s = 2$. Each node's maximum retransmit counts r and r' are set to 4 and 2 respectively. The value of I_{max} is set to n to collect data from all the nodes.

The lower bound on the probability that every node in the network receives a DA packet is calculated as $\underline{\mathrm{P}} = 0.9985$. This is a very high value and for most practical cases will meet the requirements of the application. We also find that for our deployment $T_{avg} = 10.496$ seconds and $\bar{T} = 61.85$ seconds. Again, in the context of our application the average delay is small enough to provide real-time updates.

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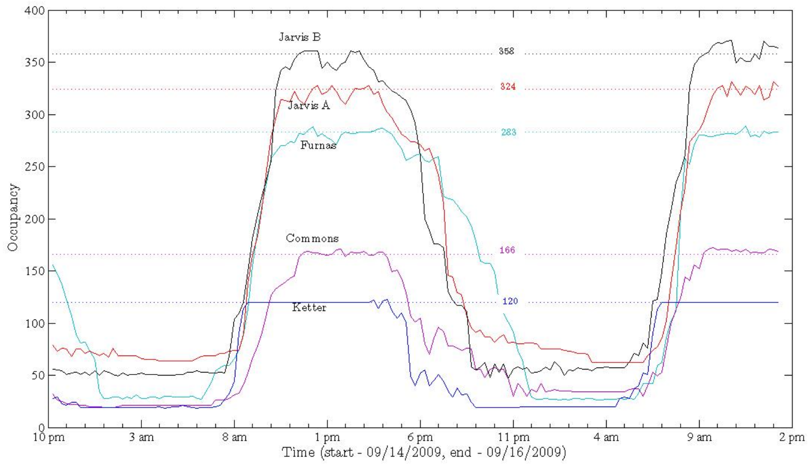

Figure 6.12: Occupancy of the monitored parking lots over a period of 40 hours

6.4.2 Measurements and Results

6.4.2.1 Occupancy/Activity Trends:

Figures 6.12 6.13 show the data collected using Hear-Hear translated into the occupancy patterns of the monitored parking lots with the capacity of each lot marked using dotted lines. In order to verify the accuracy of the data collected we manually surveyed the parking lots to collect occupancy information for a period of 4 hours. We found that the data collected by *i*Gate had a maximum error of 10 cars which does not significantly affect the results presented.

The patterns that emerge from the data are quite interesting. For example, the Ketter and Furnas parking lots get filled between 7:30 and 9:00 am and they reach their full capacity before the other lots. Although this appears to be because of their lower capacity the actual reason was found to be the proximity of these parking lots to the academic buildings. A closer inspection of the plateaus of the graph shown in Figure 6.12 indicates that we have sufficient reliability and granularity to detect even the cars that were searching for parking spaces when the parking lot was already full.

By modifying *only* the DA Packet injected by the DRG, we were also able to collect activity information from the nodes deployed at the Furnas and Commons lots. Using this information we were able to generate a time of day profile for

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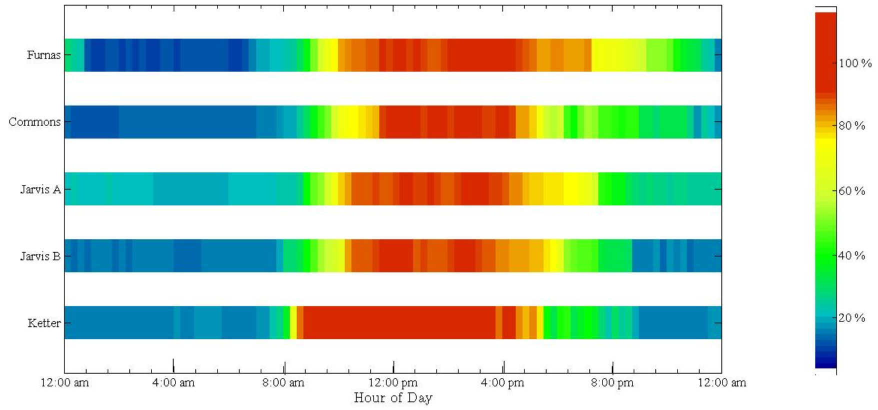

Figure 6.13: Percentage occupancy of the monitored parking lots over 24 hours

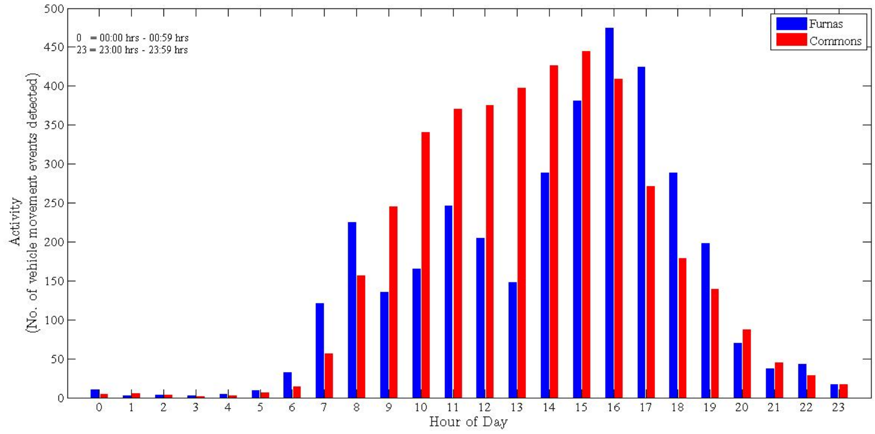

Figure 6.14: Time of day profile based on activity

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these lots as shown in Figure 6.14. Such a profile can be used by authorities to better manage the parking lot and streamline traffic flow. This also demonstrates the flexibility of Hear-Hear in terms of collecting different types of information from a subsets of nodes, without restarting the network.

6.4.2.2 Performance of Hear-Hear in the field deployment:

We studied the performance of Hear-Hear with respect to reliability and time to termination. The results presented are over a period of 40 hours during which we initiated the Hear-Hear protocol every 5 minutes. We found that complete network data was successfully collected and received by the base station with a 92.1% reliability. Figure 6.15 shows a histogram of the delays between the initiation and termination of the Hear-Hear protocol. We can see that the theoretical average and maximum delays calculated in Section 6.4.1, agree with the results from the field. Most of the times the latency is below the theoretical average delay and is *always* below the theoretical maximum delay.

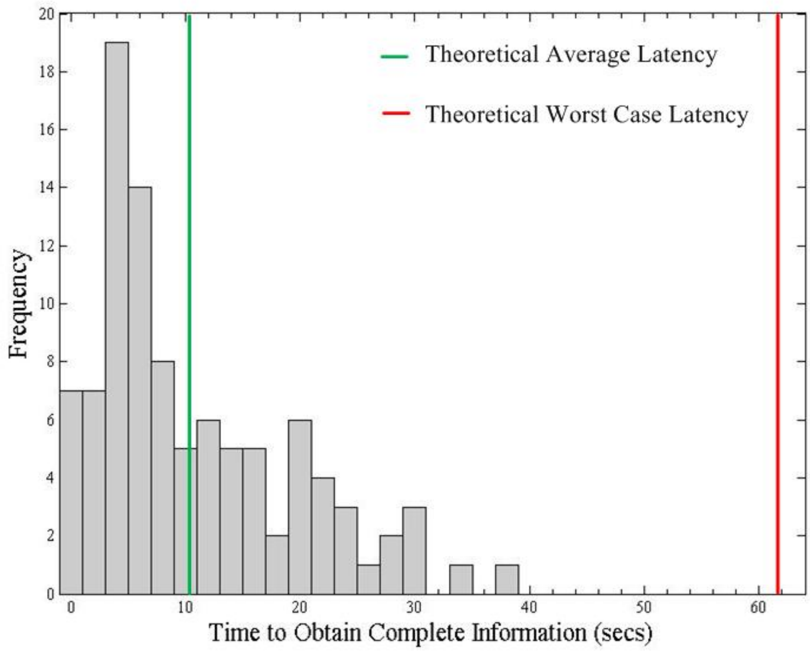

Figure 6.15: Histogram of Latency

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6.4.2.3 Energy Consumption:

We calculated the energy consumption of the motes by periodically measuring the voltage levels of the motes at the Furnas and Commons parking lots. Theoretically, the average energy consumption of the radio for running Hear-Hear is approximately $285mJ$ per hour. The PIR sensor and other electronics in the mote consume a constant $21.25J$ per hour, resulting in a total energy consumption of $21.533J$ per hour. This was verified by field measurements. The average lifetime of each mote using 2xAA batteries can be estimated at about 2 months which is satisfactory for such applications.

6.4.3 Discussion

Viability of iGate : In our set up, each mote was glued to a PVC base plate, which was fixed to a PVC pipe driven in to the ground. The setup was inexpensive, costing a total of 135 dollars for installation and maintenance over the entire period of 4 weeks during which the deployment was active. We chose this kind of a non-intrusive deployment to demonstrate its viability to monitor existing parking facilities without disrupting their operations. The low cost of the deployment and its robust performance make it suitable for monitoring open parking lots with multiple entry/exit points. It also offers an effective solution for monitoring temporary parking facilities as the cost of installation is minimal and no dedicated infrastructure is required.

Experiences from the deployment : Although the network was operational for 4 weeks, there were intermittent mote failures. Some of the motes also showed erratic behavior and sometimes would fail when it rained. Our investigations showed that, the reason for this was rain water collecting on the PVC plate and seeping through the base of the motes. Motes being dislodged by pedestrians, errant drivers, lawnmowers was also a major problem.

Another concern was disseminating code changes to all the motes in the network during the development and testing phase. While Deluge [Chlipala *et al.* 2003] made disseminating the code easy, we found that some motes did not reboot into the updated code. Consequently we were forced to tear down the network as the motes had to be manually rebooted in the laboratory. Further, the various

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connectors and wires of the XSM motes were very flimsy and manually rebooting all the motes and/or replacing their batteries consumed a lot of time.

In terms of network connectivity, we found that *i*Gate performed surprisingly well. The packet loss was negligible and this can be attributed to the good performance of the XSM radio and telescopic antennas.

6.5 Summary

In this work we presented *i*Gate, a practical WSN based parking lot monitoring and occupancy information system. *i*Gate has been designed to be robust, distributed and cost effective and we have demonstrated its use in an inexpensive and non-intrusive deployment that can be effectively used to monitor existing parking lots. *i*Gate does not require installation of custom hardware in commuter vehicles and provides occupancy information to commuters, via their personal devices like cell phones and laptops, on demand.

At the core of *i*Gate are a distributed detection and classification algorithm and a decentralized data collection/dissemination protocol called Hear-Hear. We demonstrated the accuracy of the distributed detection and classification algorithm through field deployments. It incorporates features that allow it to be configured and parameterized for a wide range of entry/exit monitoring applications. A unique feature of Hear-Hear is that it eschews the conventional overheads of topology maintenance and centralized control while still collecting data with low latency. The protocol design is resilient to dynamic topologies making it suitable for adhoc applications. It also ensures flexibility with respect to collecting different types of information from different nodes of interest with minimal changes.

*i*Gate can also be successfully used in other urban monitoring applications, such as counting the number of goods moved through loading docks, mining the behavior of customers shopping in malls and monitoring the occupancy in buildings to devise efficient evacuation strategies.

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Chapter 7

Conclusion

In this thesis we explored the problem of data collection and information exchange in wireless networks. We focused on designing completely distributed protocols for data collection, exchange and dissemination. The goal was to be able to use these system in practical applications which are highly demanding in terms of adhoc operation, topology independence and energy efficiency.

We proposed a hierarchical network structure consisting of *Tier* 1 networks that are used to sense and broadcast information and *Tier* 2 networks that collect, exchange and propagate this information. We focused on designing completely distributed protocols for medium access and data collection for such networks. In the following we list our contributions in detail.

7.1 Contributions

- We proposed a new network paradigm called Asymmetric Transceiver Networks (ATN) that consist of transmit-only and asymmetric nodes. The ATN architecture is suitable for *Tier* 1 networks and is applicable to many practical wireless sensor applications like Intra-Vehicular networks. In ATNs, the nodes are not capable of performing functions like channel sensing, time synchronization etc due to their ultra low cost and high energy efficiency requirements. We presented three distributed MAC schemes for ATNs, that are based on probabilistic transmissions but can provide differentiated QoS

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in terms of guaranteed frame delivery probabilities without using any of the conventional ARQ or scheduling schemes.

The schemes are based on retransmitting each packet an optimal number of times within a given period to ensure each node in the network achieves a delivery probability above its required threshold.

The proposed schemes are particularly suitable and cost-effective when UWB radios are used, since UWB can provide high bit rates and hence allow for multiple retransmission of a data frame within the frame generation interval. Further, UWB receiving circuits can be much more expensive than UWB transmitting circuits. Hence a significant saving in cost and energy consumption can be achieved by using transmit-only and asymmetric nodes.

- We proposed a completely distributed TDMA based MAC protocol called DT-MAC, suitable for adhoc, infrastructure-less operation, high speed data exchange and energy efficiency requirements of *Tier* 2 networks. Existing TDMA based MAC protocols operate in a centralized manner and need a controller node for exchange of control information and scheduling data transfer.

  DT-MAC solves this problem and allows nodes to communicate in a completely adhoc manner and yet use a TDMA frame structure. It allows nodes to synchronize with each other with zero overhead and the exchange of control information is designed to ensure that conflicts in bandwidth reservation can be resolved without requiring a controller node to coordinate the transmissions.

  DT-MAC brings together the bandwidth utilization and energy efficiency achieved by using a TDMA frame structure and the ease of operation in adhoc environments offered by CSMA based techniques. We studied the performance of the protocol through simulations and a real world deployment and show that it effectively meets the requirements of *Tier* 2 networks.

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- We proposed a distributed data collection/dissemination protocol called Hear-Hear. A unique feature of Hear-Hear is that it eschews the conventional overheads of topology maintenance and centralized control while still collecting data with low latency. Hear-Hear uses a controlled broadcast mechanism that allows the entire network to function as a single entity and allows users can query the network for information at any node and receive the results at any other node. This provides a significant advantage over existing systems in that it eliminates the need for a central entity to collect and disseminate the information yet allowing a querying user to be mobile.

  The protocol design is resilient to dynamic topologies making it suitable for adhoc deployments. It also ensures flexibility with respect to collecting different types of information from different nodes of interest with minimal changes.

- We presented a practical application that uses the DT-MAC and Hear-Hear protocols developed in this work to show their viability and use in real world scenarios. We developed *i*Gate, a practical WSN based parking lot monitoring and occupancy information system. *i*Gate was designed to be robust, distributed and cost effective and we have demonstrated its use in an inexpensive and non-intrusive deployment that can be effectively used to monitor existing parking lots. *i*Gate does not require installation of custom hardware in commuter vehicles and provides occupancy information to commuters, via their personal devices like cell phones and laptops, on demand.

  At the core of *i*Gate are a distributed detection and classification algorithm, a distributed MAC protocol and a decentralized data collection/dissemination protocol called Hear-Hear. We demonstrated the accuracy of the distributed detection and classification algorithm through field deployments. It incorporates features that allow it to be configured and parameterized for a wide range of entry/exit monitoring applications.

  We used the distributed synchronization and communication features of the DT-MAC protocol to establish a flexible communication platform. We

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used the Hear-Hear protocol to collect information from each node in the network. Using this information we were able to compute the occupancies of parking lots over a wide geographical area. Further, we also showed that this information can be disseminated to commuters in an on-demand fashion either via a web interface or by querying the nodes themselves. The results show that the flexibility of *i*Gate allows it to be successfully used in other urban monitoring applications, such as counting the number of goods moved through loading docks, mining the behavior of customers shopping in malls and monitoring the occupancy in buildings to devise efficient evacuation strategies.

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