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THESIS
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CROSS-LAYER DESIGN THROUGH JOINT ROUTING AND LINK ALLOCATION IN WIRELESS SENSOR NETWORKS

by

XUAN GONG

A THESIS

Presented to the Faculty of the Graduate School of the
MISSOURI UNIVERSITY OF SCIENCE AND TECHNOLOGY
In Partial Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE IN COMPUTER SCIENCE

2008

Approved by

Maggie Cheng, Advisor
Frank Liu
Rosa Zheng

ABSTRACT

Both energy and bandwidth are scarce resources in sensor networks. In the past, the energy efficient routing problem has been extensively studied in efforts to maximize sensor network lifetimes, but the link bandwidth has been optimistically assumed to be abundant. Because energy constraint affects how data should be routed, link bandwidth affects not only the routing topology, but also the allowed data rate on each link, which in turn affects the lifetime. Previous research that focus on energy efficient operations in sensor networks with the sole objective of maximizing network lifetime only consider the energy constraint ignoring the bandwidth constraint. This thesis shows how infeasible these solutions can be when bandwidth does present a constraint. It provides a new mathematical model that address both energy and bandwidth constraints and proposes two efficient heuristics for routing and rate allocation. Simulation results show that these heuristics provide more feasible routing solutions than previous work, and significantly improve throughput. A method of assigning the time slot based on the given link rates is presented. The cross layer design approach improves channel utility significantly and completely solves the hidden terminal and exposed terminal problems.

ACKNOWLEDGMENTS

The author would like to express his gratitude to his advisor, Dr. Maggie Cheng, for her guidance, valuable advice, and encouragement. Without her kind help and understanding, the author could not have reached this goal. Also, thanks go to thesis committee members Dr. Frank Liu and Dr. Rosa Zheng for their advice and their participation in the defense. Thanks to all the students in the Network Research Lab at Missouri University Science And Technology for numerous instructive discussions and their kind support of this research. The author would also like to thank Dr. Cheng for her illuminating explanations of wireless networks in CS385 and CS485 classes.

Finally, the author would like to thank his family for their help and encouragement. With their help, the author has studied hard and lived happily in the peaceful town of Rolla, Missouri.

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1. INTRODUCTION

1.1. SENSOR NETWORKS

The sensor is a small transducer, cheap low-power device that responds to a physical stimulus (as heat, light, sound, pressure, magnetism, or a particular motion) and transmits a resulting impulse (as for measurement or operating a control), then expresses these in the human friendly data format. This is the advantage from the aspect of carry and deploy, but it also makes the sensors have limited processing speed and storage capacity.

A wireless sensor network (WSN) is a wireless network consisting of spatially distributed autonomous sensors. After the initial deployment (typically ad hoc), sensor nodes are responsible for self-organizing an appropriate network infrastructure, often with multi-hop connections between sensor nodes. The onboard sensors then start collecting acoustic, seismic, infrared or magnetic information about the environment, using either continuous or event driven working modes. The flowing of data ends at special nodes called base stations (sometimes they are also referred to as sinks). A base station links the sensor network to another network (like a gateway) to disseminate the data sensed for further processing. Base stations have enhanced capabilities over simple sensor nodes since they must do complex data processing; this justifies the fact that bases stations have workstation/laptop class processors, and of course enough memory, energy, storage and computational power to perform their tasks well.

Although there have been significant improvements in processor design and computing, advances in battery technology still lag behind, making energy resource considerations the fundamental challenge in wireless sensor networks. As a consequence, there have been active research efforts on exploring performance limits of wireless sensor networks. These performance limits include, among others, network capacity (see e.g., [39]) and network lifetime (see e.g., [37, 38]). Network capacity typically refers to the maximum amount of bit volume that can be successfully delivered to the base-station ("sink node") by all the nodes in the network, while network lifetime refers to the maximum time limit that nodes in the network remain alive until one or more nodes drain out their energy.

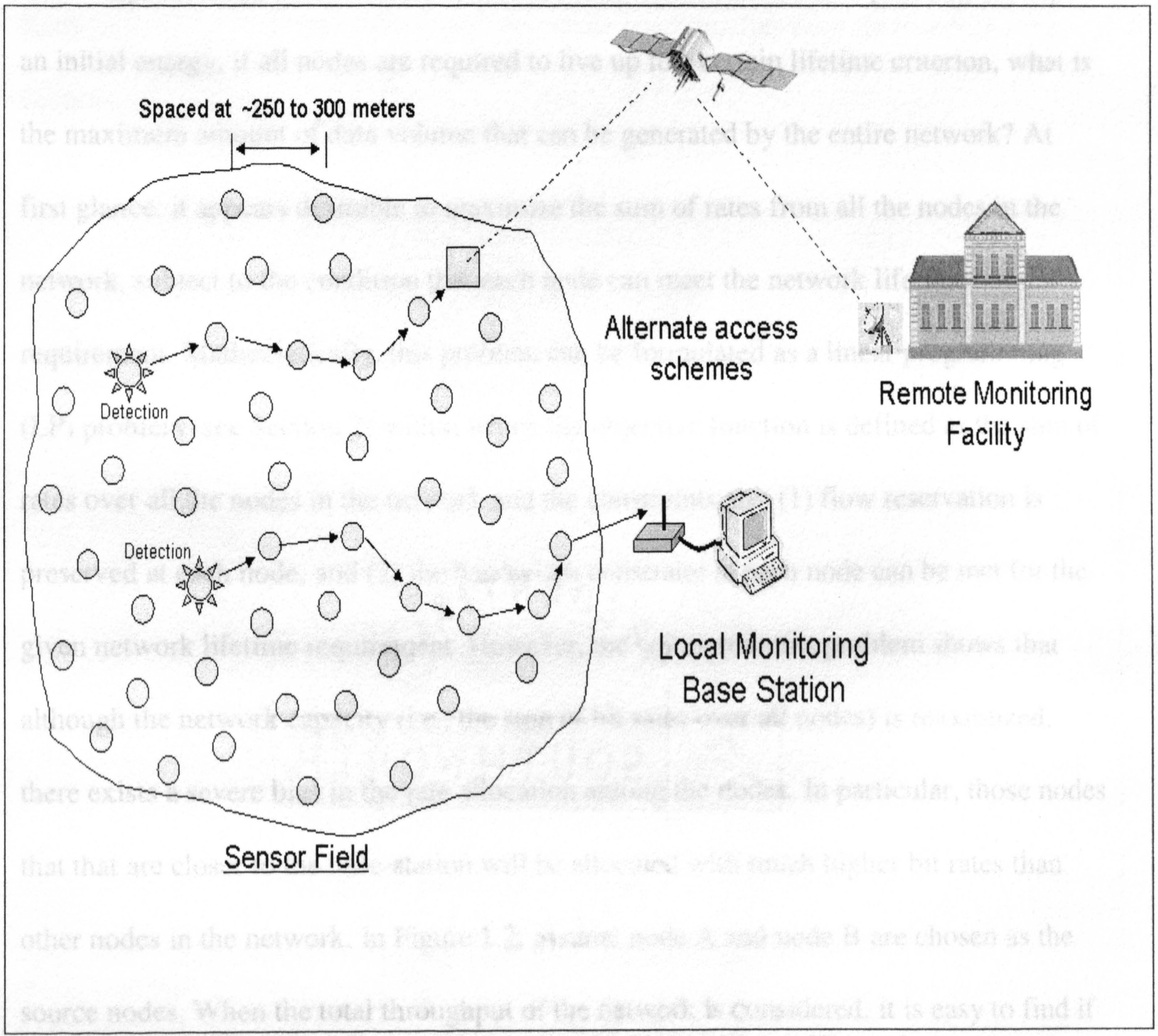


Figure 1.1 Typical Structure Of Wireless Sensor Network

1.2 THROUGHPUT

In general computer networks, throughput is the amount of digital data per time unit that is delivered over a physical or logical link, or that is passing through a certain group of network nodes. In senor network, total amount of data received per second by the sink node is referred while every node except sink node can be a source node and send the data to the sink node.

Specifically, for a wireless sensor network where each node is provisioned with an initial energy, if all nodes are required to live up to a certain lifetime criterion, what is the maximum amount of data volume that can be generated by the entire network? At first glance, it appears desirable to maximize the sum of rates from all the nodes in the network, subject to the condition that each node can meet the network lifetime requirement. Mathematically, this problem can be formulated as a linear programming (LP) problem (see Section 2) within which the objective function is defined as the sum of rates over all the nodes in the network and the constraints are: (1) flow reservation is preserved at each node, and (2) the bandwidth constraint at each node can be met for the given network lifetime requirement. However, the solution to this problem shows that although the network capacity (i.e., the sum of bit rates over all nodes) is maximized, there exists a severe bias in the rate allocation among the nodes. In particular, those nodes that that are closer to the base-station will be allocated with much higher bit rates than other nodes in the network. In Figure 1.2, assume node A and node B are chosen as the source nodes. When the total throughput of the network is considered, it is easy to find if node B send the data as much as it can and node A do not send anything, the network throughput will achieve the maximum. Because node A is far from the sink node, if it want to send data to the sink node, it need many reply node to be the receiver and these nodes will consume the bandwidth, but if node B is the only node which send the data to the sink node (node B is only one hop from sink node), it does not need relay node. Under the bandwidth constraint, node B will send as much as it can and node A will do nothing in the effort to get the maximum throughput.

The fairness issue associated with the network capacity maximization objective calls for a careful consideration in the link allocation among the nodes. In this thesis, this fairness issue has been considered and the center condition has been set to achieve the fairness.

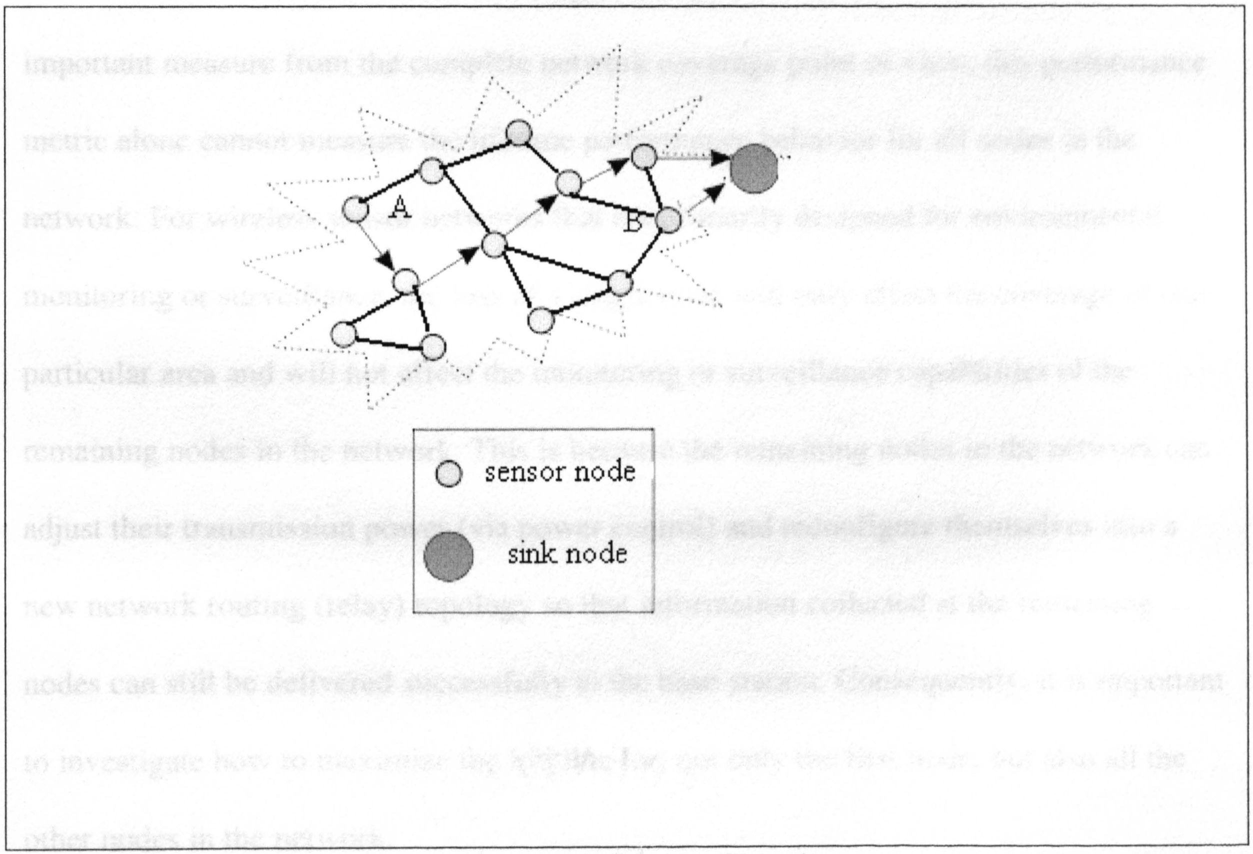


Figure 1.2 Unfairness Situation

1.3 LIFETIME

In recent years, wireless networks were extensively studied due to their potential applications in the civil and military domains, in particular for the implementation of sensor networks. Since the amount of energy that can be stored on their nodes is limited, energy efficiency is a crucial aspect in the establishment of such networks. Thus, it is essential to develop protocols that optimize the overall energy utilization of the network, in order to maximize its capability to function for the longest possible time. However, the network lifetime objective in most of these efforts has been centered around maximizing the time until the first node fails. Although the time until the first node fails is an important measure from the complete network coverage point of view, this performance metric alone cannot measure the lifetime performance behavior for all nodes in the network. For wireless sensor networks that are primarily designed for environmental monitoring or surveillance, the loss of a single node will only affect the coverage of one particular area and will not affect the monitoring or surveillance capabilities of the remaining nodes in the network. This is because the remaining nodes in the network can adjust their transmission power (via power control) and reconfigure themselves into a new network routing (relay) topology so that information collected at the remaining nodes can still be delivered successfully to the base-station. Consequently, it is important to investigate how to maximize the lifetime for, not only the first node, but also all the other nodes in the network.

1.4 OVERVIEW OF MAIN CONTRIBUTION

This thesis concerns the optimal solution to the joint and routing link allocation problem, with an objective of achieving maximum life time, maximum throughput, given the energy and bandwidth constraints. The second stage addresses with given link rates how to assign time slots. A method for assigning the time slot on a given link rate has been developed in an effort to achieve the conflict-free globally.

I analyze the necessary condition and sufficient condition for joint routing and link allocation problem. The mathematical model has been given and two Heuristics for the solution of the maximum life time have been designed. And results from these two Heuristics with the previous algorithms (MaxLife and SPR) have been compared to find which algorithm is more efficient.

The maximum throughput was also considered. The new mathematical model has been given, and two Heuristics, named Heuristic III and Heuristic IV have been designed.

Based on the link rates achieved using Heuristics I and II, the method of assigning the time slot is developed in an effort to achieve a conflict-free schedule. And these are some test cases to verify the algorithm.

2. JOINT ROUTING AND LINK ALLOCATION IN WIRELESS SENSOR NETWORK

2.1 INTRODUCTION

Wireless sensor networks are resource scarce, which is manifested energy, link bandwidth, and computing power. While it has been widely accepted that energy constraint limits the total amount of data being transmitted and plays an important role in sensor network lifetime, the impact of bandwidth constraint has long being ignored. In previous work related to energy efficient routing and data aggregation, wireless link bandwidth has often been optimistically assumed to be large enough. In a sensor network in which every node transmits towards the sink, the aggregated bandwidth requirement can actually be surprisingly high. Even in a simple chain topology, if the link raw bandwidth is B, the allowed source rate is only 1/3 B, as shown in Figure 2.1. The allowed source rate could be worse in a complicated network topology with higher node degree. If the required bandwidth is higher than the link capacity, the end-to-end throughput, or end-to-end delay, which is devastating to delay sensitive sensor network applications will not be guaranteed

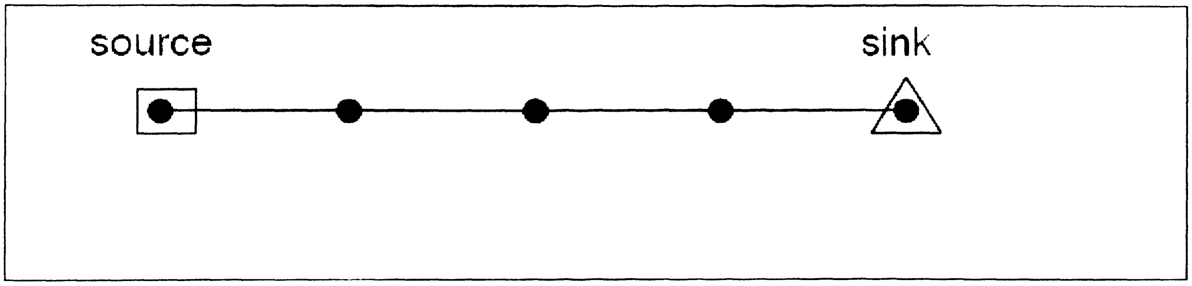


Figure 2.1 Simple Chain Topology

In most previous work on energy efficient routing, routing decisions are made to optimize the energy aspect and tend to ignore the bandwidth limitation. In the following example given in Figure 2.2(a), a maximum lifetime routing algorithm would choose any of the routing topologies shown in Figure 2.2(b), (c) and (d) because they all lead to the same lifetime. However, (b) and (c) demand much higher bandwidth than (d). Suppose that there exists an optimal MAC layer solution that requires the minimum bandwidth to support a given routing. If the source is generating 3 units of data per second, (b) requires a bandwidth of 7 units per second by the optimal solution (and 9 units per second by our solution); (c) requires 9 units per second by the optimal solution (and 9 units per second by our solution); and (d) only requires 4.5 units per second by the optimal solution (and 4.5 units per second by our solution).

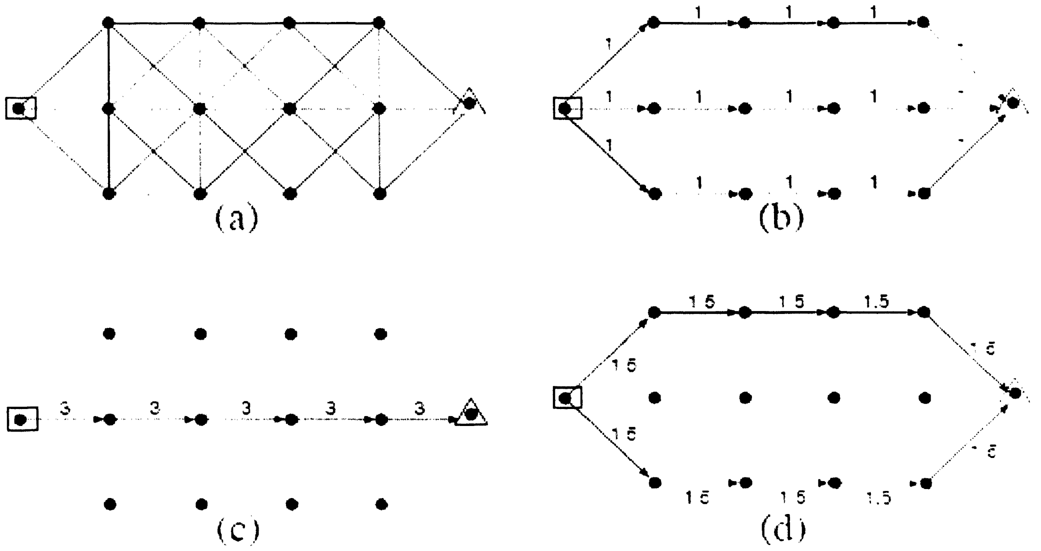


Figure 2.2 Topology Example I

In the alternate scenario shown in Figure 2.3, the solution that provides the longest lifetime is actually the worst in terms of the bandwidth requirement. A shortest path routing algorithm would choose (b) for the purpose of maximizing lifetime. The max flow through the node in the network is 1, but the required bandwidth may be much higher than in other routing topologies because almost every node in this network becomes the receiver and relay node. The node m is the receiver and it requires 9 units of bandwidth. Although the routing topologies in (c) and (d) have less max life time, the max bandwidth they require is also less than the routing topology in (b).

Using the above two examples, a randomly deployed network was sought. The one that likely to be used as a relay node was usually at the core of the network (because every one chooses what is best for itself selfishly). This unfortunately is also the area of highest interference due to the broadcast nature of wireless transmissions. Sending a lot of data to the core is likely to cause network congestion, so traffic is detoured before it becomes congested. However, it is difficult to enforce a generic policy of how traffic should be routed, and sending every packet along the outlier is also not the solution. This thesis provides a solution that decides not only the routing topology but also the actual data rate on each link, rather than a generic policy. Link rates are computed by solving an optimization problem that includes both energy and bandwidth constraints.

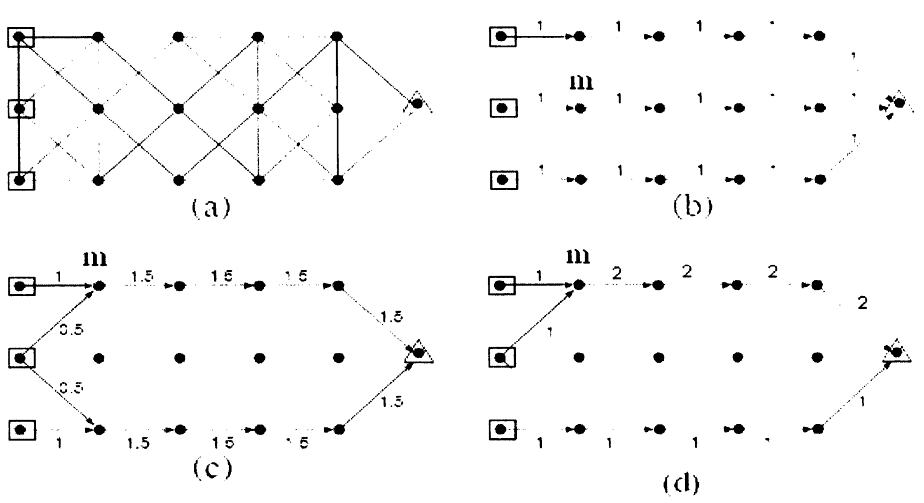


Figure 2.3 Topology Example II

2.2 CONDITIONS FOR CONFLICT-FREE TRANSMISSION SCHEDULE

In logic, the word necessity and sufficiency refer to the implicational relationships between statements. Formally, a condition A is said to be necessary for a condition B, if (and only if) the falsity (/nonexistence /non-occurrence) of A guarantees (or brings about) the falsity (/nonexistence /non-occurrence) of B. In other words, the absence of A guarantees the absence of B. A necessary condition is sometimes also called "an essential condition". In other side, a condition A is said to be sufficient for a condition B, if (and only if) the truth (/existence /occurrence) of A guarantees (or brings about) the truth (/existence /occurrence) of B. In other words, it is impossible to have A without B. If A is present, then B must also be present.

A: The Necessary Condition For Conflict-free Transmission Schedule.

In Figure 2.4, using node v as an example, the necessary conditions are:	
1) Rdv + Rve <= B	2) Rdv + Rab <= B and Rdv + Rbc <= B

Notes: Condition 1) says if node v is receiving, it can not be sending. Condition 2) says if node v is receiving, none of its neighborhood will be interference with the node v. If node v can have the conflict-free schedule, these two are necessary conditions. However, just based on the view of node v, there is no way to know whether the other links can be scheduled the same time. In fact, (a, b) and (b,c) can not be scheduled at the same time because of the conflict in node b; but (b,c) and (v,e) can be scheduled at the same time, since there is no link between node b and node e or between node c and node v. Apparently, with each node locally satisfying these two conditions, which can be summarized as Rdv +max{Rve+Rab+Rbc} <= B, the conflict-free schedule globally can still not be guaranteed.

B: The Sufficient Condition For Conflict-free Transmission Schedule. The sufficient condition that provides guaranteed data rate from all sources to the sink and a conflict-free transmission schedule at the MAC layer. The necessary condition provided in 2.2 (A) just ensures at node v the required bandwidth of sending and receiving can be satisfied, but it can not always make sure that there is a conflict-free schedule in MAC layer. In Figure 2.4 even if the node v has satisfied the necessary condition including its neighborhoods alone, it is still not way to make sure that there can be conflict-free. It requires that Rdv + max {Rve + Rbc} + Rab <= B to make the transmission conflict-free. But unfortunately, it is not enough. From the view of time sharing channel, the period of time assigned to each transmission is proportional to the link rate. In order to map the link rate to the time slot in MAC layer, assume that SL denotes the time slots assigned to the given link. Suppose Rbc < Rve, so the corresponding SLbc should be the subset of SLve in order to let them to transmit at the same time. But if there is a more complicate routing topology, then such condition is not enough. Suppose there is another link named (v',e'), and it requires that SLbc should also be the subset of SLv'e'. Obviously, there is no way to guarantee both of relations can be satisfied at the same time. Look at the Figure 2.4 (c). Suppose the link (v',e') is 2 distance from the link (b,c), and there is no way to see it by only check the one-hop neighborhood of the node v. Just thinking about a much more complicit topology, there could be far more subset requirement just like what the link (v', e') needs.

Recheck the necessary condition, such conditions can only guarantee the local conflict-free but not the globally. So, the sufficient condition should be introduced. the sufficient condition can be get by replacing the max value to the sum of all values:

Rve + Rdv + Rab + Rbc <= B.

As shown in Figure 2.4 (b), there are not transmissions on links (v, e), (b, c), (a, b) and (d, v) scheduled at the same time. Look at the topology in Figure 2.4 (a), it is easy to find that the node a, node b, node d and node v are connected together. So, whatever these links are scheduled at the same time, it will be interference with each other. It can also be generalized to: sending and all neighbors' transmissions should not be overlapping. This may be too restricted, but if this condition is satisfied at each node, it guarantees that the conflict free time slot assignment globally can be achieved. The sufficient condition may need more bandwidth than it actually demands, but it guarantee the congest-free in the whole network.

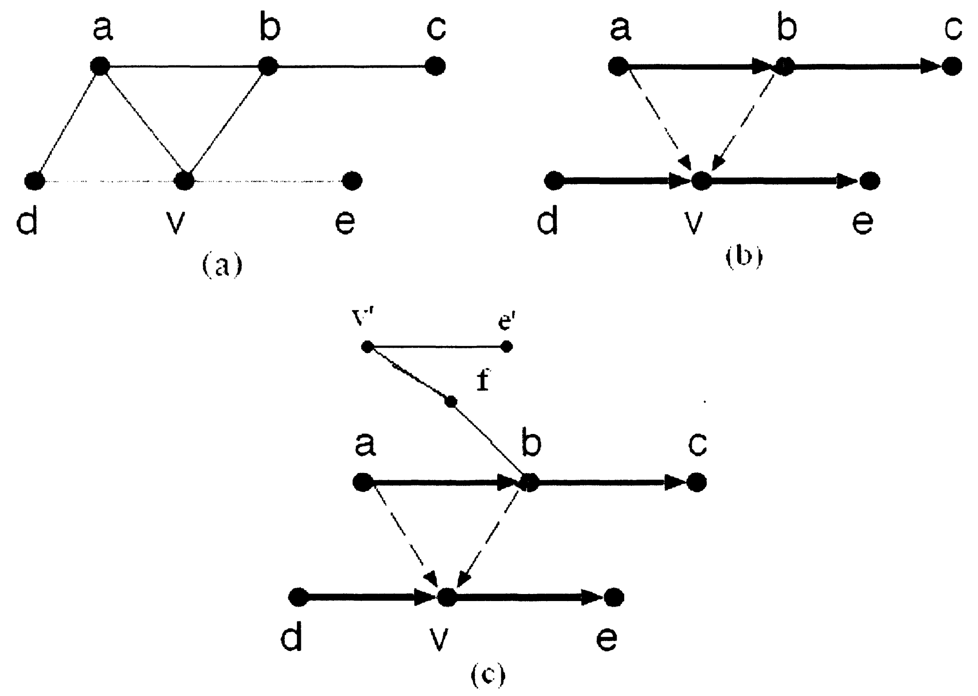


Figure 2.4 Topology Example III

2.3 PROBLEM I: SOLUTION TOWARD THE MAXIMUM LIFETIME

Assume there are n nodes in the sensor network, each node i has initial battery energy Ei (J), and the capacity of each wireless link is B (bits per second). Each node i generates sensory data at a rate of Ri bits per second (Ri > 0 if node i is a source, Ri = 0 if it is a pure relay node, and Ri < 0 if it is a sink). Assume nodes consume energy on transmitting, receiving and sensing (i.e., generating sensory data), and their energy consumption rates are Pt, Pr, and Ps J per bit respectively and also assume Pr and Ps are constants. In this model, further assume that every node transmits at the same power level; therefore Pt is also a constant. The network life time in this thesis means how long the network can work until the first node in the network die. The energy-bandwidth constrained maximum lifetime routing problem can be formally stated as follows: Suppose sources are pre-selected and each node i's rate Ri is known, but the transmission rate from node i to node j is unknown. Let T be the total network lifetime. The rate allocation problem is to compute the data rate Rij on each link (i, j), given each node i's Ei, Ri and link capacity B, such that the total network lifetime T is maximized and the rate allocation can be accommodated by wireless link capacity and energy reserve.

Assume every node used the same transmission power Pt that is pre-determined. Therefore links are all symmetric. Ni is defined as the neighborhood nodes of node i excluding node i itself. To maximize lifetime T is equivalent to minimize 1/T. For convenience, the variables fi need to be introduced:

fi = 1, if $\sum_{j \in Ni} R_{ji} > 0$;

fi = 0, otherwise,

So, if node i is a receiver, fi = 1, otherwise fi = 0. And the sink node is always a receiver.

Thus the rate allocation problem has been formulated as the following.

Table 2.1 Mathematical Model for Maximum LifeTime Problem

Minimize

$$1/\mathrm{T} \qquad (1)$$

Subject to

$$\sum_{j\in Ni} (R_{ij} - R_{ji}) = R_i ; \qquad \forall i \quad (2a)$$

$$P_s R_i + \sum_{j\in Ni} (P_r R_{ji} + P_t R_{ij}) <= E_i / T ; \qquad \forall i \quad (2b)$$

$$\sum_{j\in N_i} R_{ij} + f_i \cdot \sum_{j\in N_i} \sum_{k\in N_j} R_{jk} <= B ; \qquad \forall i \quad (2c)$$

$$0 <= R_{ij} <= B ; \qquad \forall i, \forall j \; (2d)$$

$$f_i = \{0,1\} ; \qquad \forall i \quad (2e)$$

In this formulation, R_is are given in such a way that the sensing nodes are positive R_is, sink nodes have negative R_is, the absolute value of such is equal to the total of all source R_is and relay nodes have zero R_is. Equality (2a) indicate that data rates satisfy the flow conservation. Inequality (2b) is the energy constraint, and the inequality (2c) is the bandwidth constraint. In flow network, each link (a,b) has a fixed link capacity c(a,b) and the flow f(a,b) <= c(a,b). But in the view of wireless communication, it is different. Because of the nature of the wireless transmission, not only the capacity on each link needs to be considered, but also consider it on a collision domain. In other words, the amount of data that one link can transit depends not only the given link raw capacity itself, but also the quantity of data transited over other links in the same collision domain as the given link. Inequality (2c) ensures all links in the same collision domain have a total capacity that can not exceed B. Specifically, if node i is a sender but not a receiver, it only needs to satisfy that all the outgoing flow from i is bounded by B; if node i is a receiver, it needs to satisfy that node i's receiving, node i's transmission and other interference node's transmission have a total rate at most B(Obviously, it is the sufficient condition); if the node i is neither a sender nor a receiver, 2c is automatically satisfied. Inequalities 2d and 2c are constrains for the variables.

The mathematical model defined by objective (1) and inequalities (2a - 2e) considers the bandwidth constraint while optimizing sensor network lifetime, therefore the solution to this model contains the optimal solution to the energy-bandwidth constrained maximum lifetime routing problem. However it is not linear because fi is also a variable. In the following, two heuristics have been designed that both work around the nonlinear problem by using information from the shortest paths (in terms of hops) from sources to the sink. The shortest paths represent the minimum-energy routing topology if data is not aggregated[12]. Heuristic I bear the characteristics of shortest path routing, and Heuristic II bears the characteristics of the mathematical-programming based optimal solution, but they both include bandwidth constraints for consideration.

Heuristic I: Scalable Rate Allocation on Shortest Paths. The first heuristic starts from the shortest paths from sources to the sink, but the rate on each link is determined by the available bandwidth.

Table 2.2 Heuristic I: Scalable Rate Allocation on Shortest Paths

1) Compute the shortest path from each source node to the sink;

2) Assume source rate is one unit, check against condition (2c) for each node, and find the most bandwidth-contentious node i. Let LHS=required bandwidth of node i's collision domain. Then compute the scale factor a (see Figure 5): a = B/LHS. Set $\Delta f = \min\{a/2, R_i\}$;

3) Push out Δf amount of flow from each source to the sink then update the remaining input flow $R'_i = R_i - \Delta f$ for each source i;

4) Repeat 5) - 7) until push through R'_i for each source i or the network is fully saturated:

5) Find the shortest paths for nodes with $R'_i > 0$ based on the current available nodes and links. Nodes that are saturated on (2c) and their neighbors are not eligible for relaying. In case of a tie, give higher priority to nodes with more remaining energy; if there is still a tie, give higher priority to nodes with smaller degree;

6) Decide the scale factor a in a similar manner as in step 2). If pushing $\min\{a, R'_i\}$units does not decrease lifetime, then set $\Delta f = \min\{a, R'_i\}$; otherwise, set $\Delta f = \min\{a/2, R'_i\}$;

7) Push out Δf amount of flow from each source with $R'_i > 0$ then update the remaining input flow $R'_i = R'_i - \Delta f$

In steps 2) and 6), this algorithm uses a/2 when computing Δf for the purpose of load balancing, which makes the network last longer. A simplified version is to use a instead of a/2 when compute Δf . It runs faster, but provides shorter lifetime.

As shown in Figure 2.5. The most bandwidth-contentious node requires 7a unit, if the bandwidth is B unit, then a = B/7

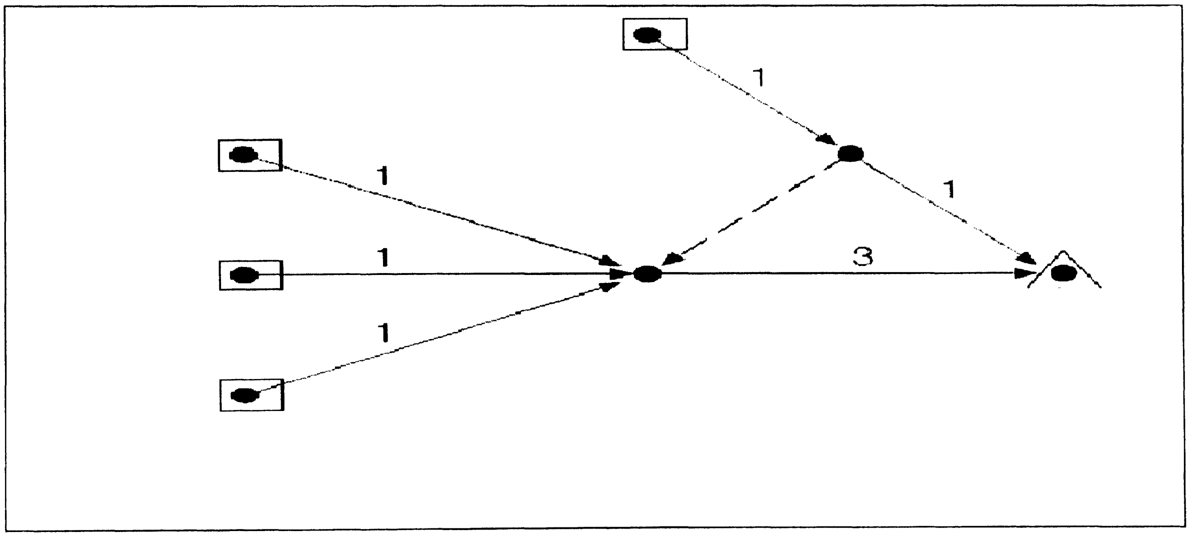


Figure 2.5 Topology Example IV

In Figure 2.6, this is a typical tie situation, there are two roads from node 1 to node 4, and both of them are shortest-path according to node1. So, when the road is chosen from the node 1 to the node 4 (the tie situation), there are the rules:

1)If it is the first time, the numbers of neighborhood nodes of such two candidate is considered, the node that is less neighborhood should be picked up, because locally if the node has less neighborhood nodes, it has less chance to be interference.

2)If it is not the first time, the remaining energy should be considered. The node are chosen which has more remaining energy. In that case, more flows can go through this node. And if the node has more remaining energy, it means that the flow through the link containing the given node is less. So if this kind of node has been chosen, the life time of the network would not be decreased. If it still has tie situation, then the numbers of neighborhood nodes should be reconsidered.

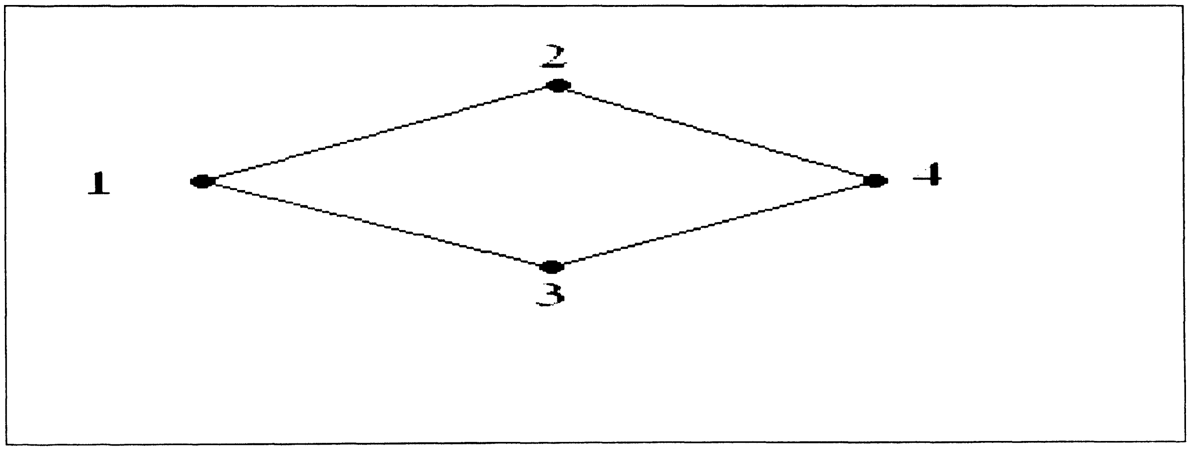


Figure 2.6 Typical Tie Situation

And about the step 6 of heuristic I, the reason why the condition Δf = min{a/2, R'_i } has been set when it decreases the life time is that the tie situation is considered. the flow can not be pushed totally from the given link, because it is possible that there exits a link in which there is less flow through it and it can be chosen at the next shortest-path algorithm running. In that case, the flow can be averaged, and possibly get longer life time. Also consider the Figure 2.6, assume at this time, the path 1-2-4 is chosen, and further assume Δf = 3 at this time. Also, assume the life time T = 1. If Δf is pushed, the life time will decrease, T= 1/4. Now, if Δf = 1.5 is set, then the life time T = 2/5. It is right that the life time also decreases. After the next shortest-path chosen, based on the rule, there will be a new shortest-path chosen from node 1 to node 4, that is 1-3-4, and Δf = 1.5 is pushed. Then life time is also 2/5. Comparing with the life time T= 1/4, life time can be improved by using this method.

Heuristic II: Optimizing Lifetime With Bandwidth Constraint. Since the mathematical model defined in (1) and (2a- 2e) has an objective of maximizing lifetime, if it can be converted to a linear program in a controlled manner, it is likely to produce a close-to-optimal solution in terms of lifetime. The following describes an algorithm that chooses the likely-to-be relay nodes and set their f_i = 1 to make the program linear.

Table 2.3 Heuristic II: Optimizing LifeTime With Bandwidth Constraint

```
1 Set $f_i = 1$ for the sink, and $f_i = 0$ for all other nodes; solve the linear program; update $f_i = 1$ if $\sum_{j \in N_i} R_{ji} > 0$; if 2c) is satisfied $\forall i$, return link rates $R_{ij}$ for all (i, j); otherwise, go to line 2.
2 Compute shortest paths from source nodes to the sink.
3 Set $f_i = 1$ for receiving nodes; solve the linear program; update $f_i = 1$ if $\sum_{j \in N_i} R_{ji} > 0$.
4 Repeat line 3 until there is no update for $f_i$ (converge) or the linear program becomes infeasible.
5 If it converges, output link rates $R_{ij}$ for all links (i, j).
```

Table 2.3 Heuristic II: Optimizing LifeTime With Bandwidth Constraint : Con't

```
6 If it becomes infeasible: if $f_i = 1$ but $\sum_{j \in N_i} R_{ji} = 0$, set $f_i = 0$ and $R_{ji} = 0, \forall j \in N_i$ as
  input, solve the linear program again; if it is still infeasible, report infeasible.
```

Comments: the algorithm will terminate either with a valid solution or become infeasible. There won't be endless iterations in line 4. In the worst case, eventually all $f_i = 1$. In most of the simulations, it requires solving the linear program two to four times to converge.

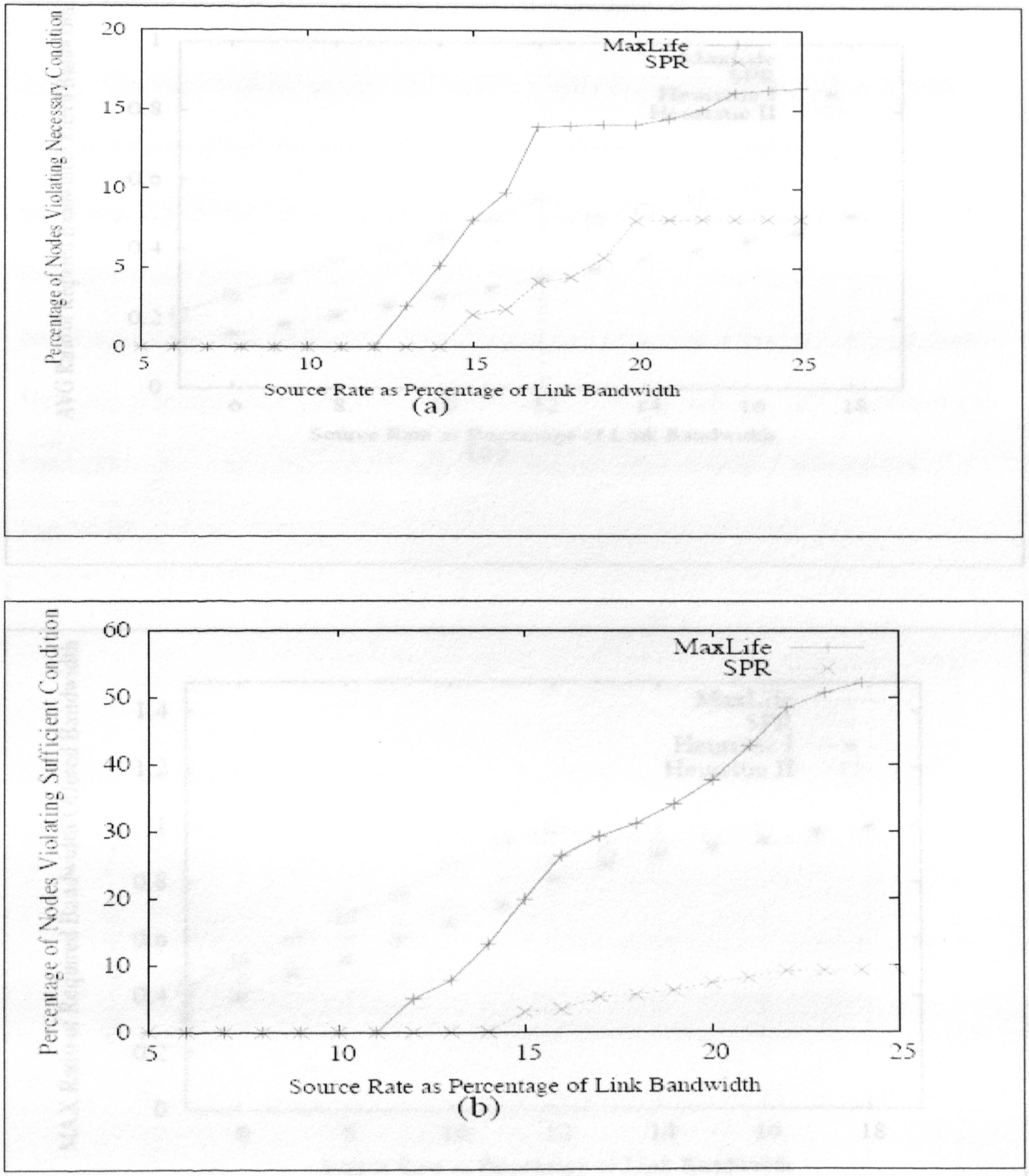
The lp_solve is used to solve the program. At first, set all $f_i = 0$ excluding the sink node (set the $f_i = 1$ for the sink node all the time). Then update the f_i, solve the linear program again to get the link rate and check whether it is satisfies the bandwidth constraint and energy constraint. Basically, when the bandwidth is large enough, it always satisfies and the solution is always optimal.

When the bandwidth is not enough, the nodes in the shortest path from the source to the sink are used as receiver, and set their $f_i = 1$, but the link is still unknow. The lp_solve is used to solve the Linear Programming, and check the flow of all the nodes. If the f_i of this node is 1, that means this node is a relay node and there should be some flow through it, otherwise the f_i of this node should be 0. Based on this rule, the bandwidth constraint is used to check every link. If at the beginning the f_i of the given node is 0, but there exists some flow through it that means this node is a relay node in this process of solving, in that case set $f_i = 1$. After all nodes are checked in the network, if there are some changes in the value of f_i. the Linear Program need to be solved based on the new f_i information again. Then repeat the step to check all nodes in the network. If it is coverage that means the value of f_i of all nodes do not change, the solution can be get. If it is still infeasible, do such operations: set $f_i = 0$ and $R_{ji} = 0$, $\forall j \in N_i$ as input if f_i = 1 but $\sum_{j \in N_i} R_{ji} = 0$, and run the linear program again. Hopefully, it can get the coverage, if not report infeasible.

The algorithm will terminate either with a valid solution or become infeasible. In the worst case, eventually all $f_i = 1$. In most of our simulations, it requires solving the linear program two to four times to converge.

In the simulation study, it is been investigated how the bandwidth constraint can change the routing decision and eventually affect the lifetime of the sensor network. First, the results from the existing algorithms are compared with that of our two heuristics and the observation are made which algorithm is more likely to cause network congestion and fail to push through the applied load. In a network of 50 nodes with node positions randomly chosen, 4 source nodes are randomly chosen and the increasing source rate are applied on them. The initial energy is set as 1 J, the Pt is set as 0.1 J/bit. The optimal solution for maximizing lifetime from [2](labeled as MaxLife), shortest path routing(labeled as SPR), and Heuristic I and Heuristic II proposed in this paper are compared. It can be found that when each source node's data rate Ri is increased to 12%

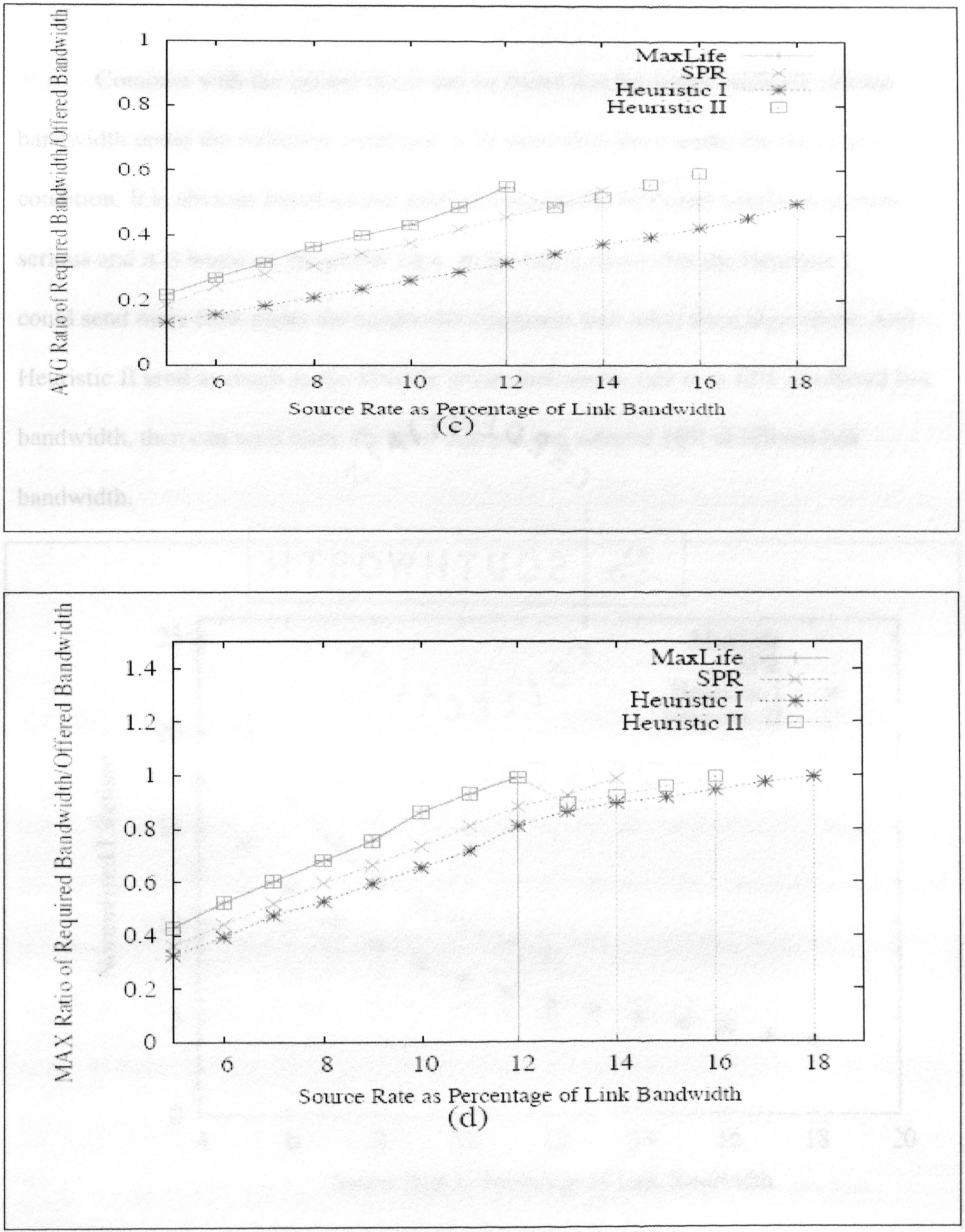
~13 % of the given link bandwidth, MaxLife starts to congest, i.e., some collision domain requires more bandwidth than what is available, and SPR starts to congest when it is increased to 15%. Heuristic I can push through without congestion when the load is increased to 18% and Heuristic II can support as much as 16%. The vertical lines in Figure 2.7 (c) and (d) indicate after this point, increased data rate can not be put through. In terms of the degree of congestion, manifested as the ratio of required bandwidth over offered bandwidth after the vertical line, our data shows(not plotted in Figure 2.7 (d) the maximum demand could be as high as 150% of the given bandwidth for MaxLife while our heuristics can still operate within less than 100% of the bandwidth. Even under the low traffic load, the average bandwidth requirement of SPR is still higher than Heuristic I. Figure 2.7 (a) and (b) are based on the necessary condition and sufficient condition respectively. If a routing scheme violates the necessary condition, that means there is absolutely no way to push through the applied traffic load; when it violates the sufficient condition, it only means there is no guarantee a valid transmission schedule at the MAC layer to support the routing can be found. In the second simulation, four algorithms on their contribution toward lifetime have been compared. As shown in Figure 2.8, when there is enough banwidth, MaxLife does not have bandwidth violations and achieves the optimal solution; Heuristic II achieves the same optimal solution; but when bandwidth does pose a constraint, Heuristic II can still push through 40% more data than MaxLife, and Heuristic I can push though 60% more data than MaxLife. Heuristic II achieves the best performance on lifetime and second best on throughput; Heuristic I achieves the best performance on throughput, which is consistent with our observation from the first simulation in Figure 2.7.



(a)

(b)

Figure 2.7 Simulation Results I



(c)

(d)

Figure 2.7 Simulation Result I : Con't

Compare with the (a) and (b), it can be found that the nodes violating offered bandwidth under the sufficient condition is far more than those under the necessary condition. It is obvious based on our analysis because the sufficient condition is more serious and it is based on the global view. In the (d), it shows that the Heuristic I could send more flow under the bandwidth constraint than other three algorithms. And Heuristic II send as much as the Maxlife before that source rate is as 12% of offered link bandwidth, then can send more 4% after that and can achieve 16% of offered link bandwidth.

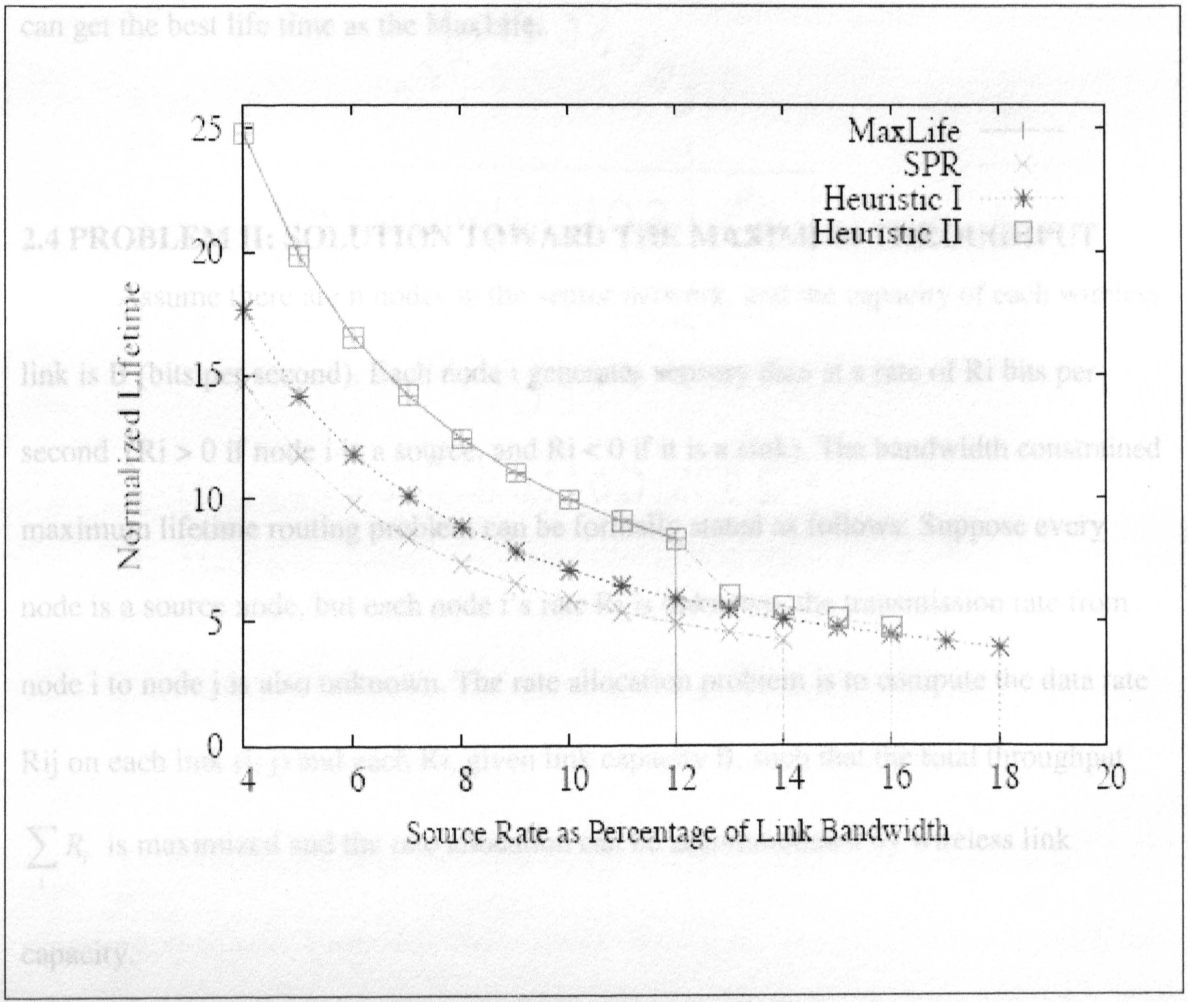


Figure 2.8 Simulation Result II.

It is assumed that sending one unit of data consumes 10 percentage of total energy, and Pr and Ps are small enough to be ignored. From the Figure 2.8, it shows when the bandwidth is enough, the life-time of MaxLife and our Heuristic II are best, because at this time the bandwidth constraint need not be considered, just need to check the energy. So, the linear Program can give us an optimal solution. But when the bandwidth is not enough, the situation is changed. As shown in the Figure 2.8. When the source rate grows to the 12% of the offered link bandwidth, the MaxLife can not send any more flow. In this situation, the Heuristic I can send the more flow than other three algorithms. And the Heuristic II is the second best, but when the bandwidth is enough, it can get the best life time as the MaxLife.

2.4 PROBLEM II: SOLUTION TOWARD THE MAXIMUM THROUGHPUT

Assume there are n nodes in the sensor network, and the capacity of each wireless link is B (bits per second). Each node i generates sensory data at a rate of Ri bits per second (Ri > 0 if node i is a source, and Ri < 0 if it is a sink). The bandwidth constrained maximum lifetime routing problem can be formally stated as follows: Suppose every node is a source node, but each node i's rate Ri is unknown, the transmission rate from node i to node j is also unknown. The rate allocation problem is to compute the data rate Rij on each link (i, j) and each Ri, given link capacity B, such that the total throughput $\sum_i R_i$ is maximized and the rate allocation can be accommodated by wireless link capacity.

Focused on the maximum throughput, the energy constraint will not be concerned. Assume that every nodes excluding sink node can send out data. In that case, some nodes in the network should do two jobs at the same time: as relay node and source node. Total throughput is considered. That means every node send out the maximum unit of data under the bandwidth constraint.

As it was mentioned before, the energy constrain will not be considered in this part. So the mathematical model can be formulated as follows:

Table 2.4 Mathematical Model For Maximum Throughput Problem

Maximize:

$$\sum_{i} R_i \qquad (1)$$

Subject to

$$\sum_{j \in Ni} (R_{ij} - R_{ji}) = R_i; \qquad \forall i \quad (2a)$$

$$\sum_{j \in N_i} R_{ij} + f_i . \sum_{j \in N_i} \sum_{k \in N_j} R_{jk} <= B; \qquad \forall i \quad (2c)$$

$$R_L \le R_{ij} \le R_H \qquad (3)$$

R_L: Minimum required source data rate (should >0).

R_H: Maximum possible source data rate (should <B).

New condition(3) has been used in mathematical model . This condition is necessary, so at least it seems to this problem. There is an interesting phenomenon. If this condition is not used, it would be found that the nodes which are near the sink will send as much unit as they can and total ignore other nodes. In that case, this will happen that some nodes will never send anything and some other nodes will send a lot. It is obviously. So in this new mathematical model, this condition should be concerned to achieve some kinds of fairness.

Based on the new LP, two new algorithms named Heuristic III and Heuristic IV have been designed.

Table 2.5 Heuristic IV

f_i is used as input.

1) $f_i = 1$ for sink, $f_i = 0$ for others, then solve LP

2) Set $f_i = 1$ for receiving nodes; update $f_i = 1$ if $\sum_{j \in N_i} R_{ji} > 0$. Check all receivers see if (2c) is violated.

3) Among the violated ones, find the $i = \arg\min_i \dfrac{\sum_{j \in N_i} R_{ij}}{\sum_{j \in N_i} \sum_{k \in N_j} R_{jk}}$, set the $f_i = 0$, $R_{ji} = 0$

4) Repeat line 2 and line 3 until there is no update for f_i (converge) or the linear program becomes infeasible.

5) If it converges, output

6) If it becomes infeasible: if $f_i = 1$ but $\sum_{j \in N_i} R_{ji} = 0$, set $f_i = 0$ and $R_{ji} = 0$, $\forall j \in N_i$ as input, solve the linear program again; if it is still infeasible, report infeasible.

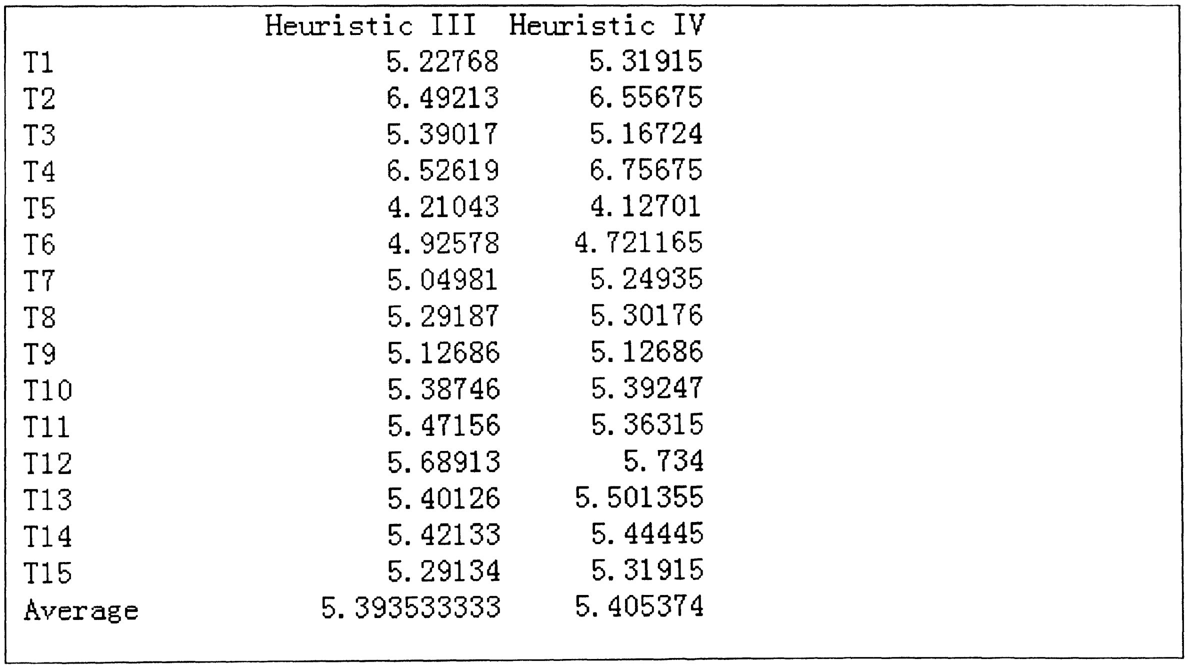
Comments: the algorithm will terminate either with a valid solution or become infeasible. There will not be endless iterations in line 5. In the worst case, eventually all $f_i = 1$. Set 3 as iteration up-bound.

Table 2.6: Heuristic III

```
$f_i$ is used as input.
1) $f_i = 1$ for sink, $f_i = 0$ for others, then solve LP
2) $f_i = 1$ for all nodes , then solve LP
3) $f_i = 1$ for sink and receiver nodes used in 1st and 2nd, then solve the LP and check if $f_i = 0$ is used as Receiver.
4) Set $f_i = 1$ for receiving nodes; solve the linear program; update $f_i = 1$ if $\sum_{j \in N_i} R_{ji} > 0$.
5) Repeat line 3 until there is no update for $f_i$ (converge) or the linear program becomes infeasible.
6) If it converges, output
7) If it becomes infeasible: if $f_i = 1$ but $\sum_{j \in N_i} R_{ji} = 0$, set $f_i = 0$ and $R_{ji} = 0, \forall j \in N_i$ as input, solve the linear program again; if it is still infeasible, report infeasible.
```

Comments: the algorithm will terminate either with a valid solution or become infeasible. There will not be endless iterations in line 4. In the worst case, eventually all $f_i = 1$. But three has been set as iteration up-bound.

In the simulation study, the total throughput has been investigated. The network of 50 nodes with node positions randomly chosen has been used. And simulation has been done for 15 times by using 15 different topologies and the average has been calculated. The results is shown in Figure.2.9. The column named iteration means how many times of iteration to get the coverage. And it shows that the results of Heuristic IV and Heuristic III are very close.



	Heuristic III	Heuristic IV
T1	5.22768	5.31915
T2	6.49213	6.55675
T3	5.39017	5.16724
T4	6.52619	6.75675
T5	4.21043	4.12701
T6	4.92578	4.721165
T7	5.04981	5.24935
T8	5.29187	5.30176
T9	5.12686	5.12686
T10	5.38746	5.39247
T11	5.47156	5.36315
T12	5.68913	5.734
T13	5.40126	5.501355
T14	5.42133	5.44445
T15	5.29134	5.31915
Average	5.393533333	5.405374

Figure 2.9 Total Throughput of Heuristic III And Heuristic IV

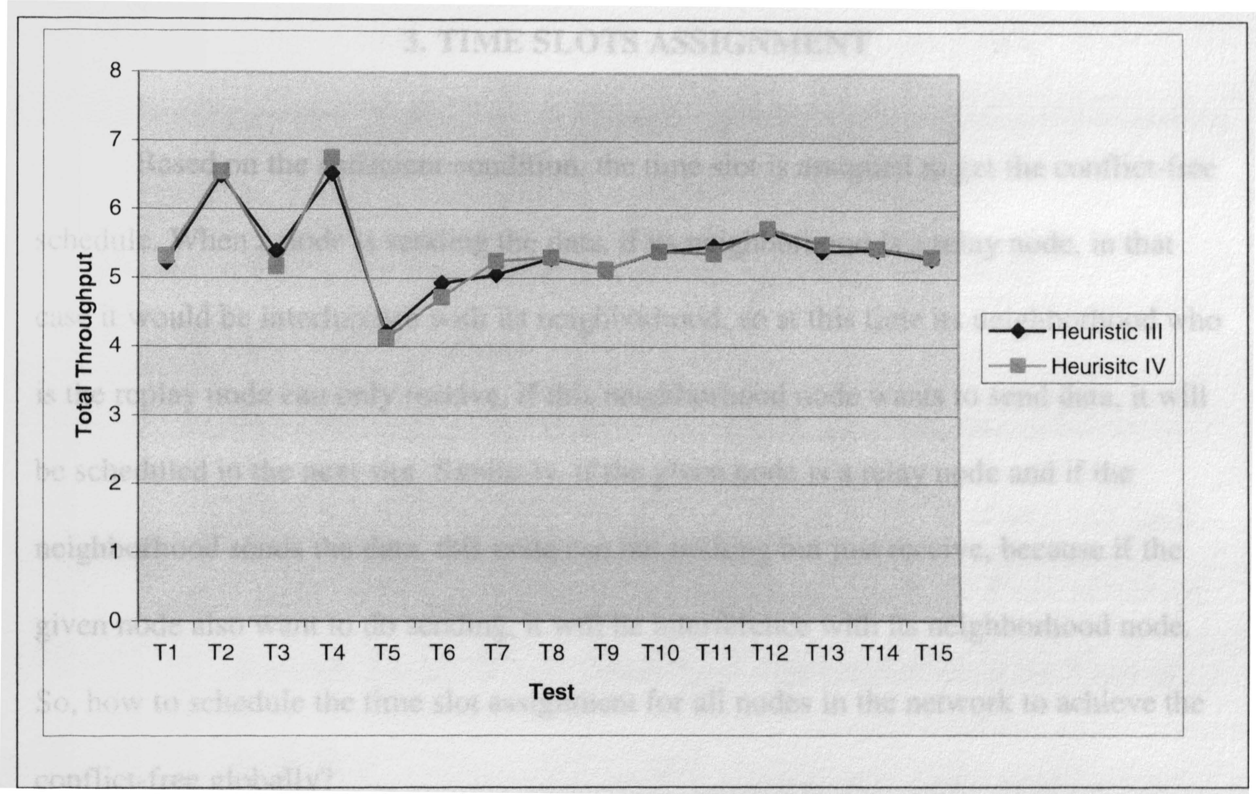


Figure 2.9 Total Throughput of Heuristic III And Heuristic IV : Con’t

3. TIME SLOTS ASSIGNMENT

Based on the sufficient condition, the time slot is assigned to get the conflict-free schedule. When a node is sending the data, if its neighborhood is a relay node, in that case it would be interference with its neighborhood, so at this time its neighborhood who is the replay node can only receive, if this neighborhood node wants to send data, it will be scheduled in the next slot. Similarly, if the given node is a relay node and if the neighborhood sends the data, this node can not nothing but just receive, because if the given node also want to do sending, it will be interference with its neighborhood node. So, how to schedule the time slot assignment for all nodes in the network to achieve the conflict-free globally?

Time Slots Assignment Algorithm:

SLOTASSIGNMENT(G(V,E),R)

Table 3.1 Time Slots Assignment Algorithm

1. Scale the link rate R_{ij} to integers
2. Find the most bandwidth-contentious node v and compute the required bandwidth B_v at that node v's collision domain:

   $$v = \arg\max_{i \in V} \left(\sum_{j \in N_i} R_{ij} + f_i \times \sum_{j \in N_i} \sum_{k \in N_j} R_{jk} \right)$$

   $$B_v = \sum_{j \in N_v} R_{vj} + f_v \times \sum_{j \in N_v} \sum_{k \in N_j} R_{jk}$$

3. Let frame size T = B_v and Let slot size $\tau = 1$

Table 3.1 Time Slots Assignment Algorithm: Con't

```
4. Generate a table of size 2 × T assoicated with each node's sending and receiveing
   schedules. (Use S row for sending and R row for receiving)
5. Let L = V(total number of nodes); repeat the following until L = $\varnothing$
    a) Randomly pick a node I from L
    b) For each node $j \in N_i$, if $R_{ij}$ > 0, assign $R_{ij}$ available slots to link (i, j);
       a slot is available if it is available in both the S row of table[i] and the R
       row of table[j]; then mark those slots unavailable in the S row of table[j];
       For each $k \in N_j$, if $k \neq i$, mark those slots unavailable in the S row of
       table[k];
    c) Mark those slots unavailable in the R row of table[i];
    d) For each node $j \in N_i$, mark those slots unavailable in the R row of
       table[j], if they are not assigned yet;
    e) Remove i from L.
```

Suppose there is a topology like Figure 3.1(a). Assume that $R_{ij} = R_{vi} = R_{ju} = 4$, R_{kw} = 6. According to the algorithm step 2, node j is the most bandwidth-contentious node; and the frame size is set as T =14 slots. Then do the following steps. Assume that node i is first chosen. At this moment both S row and R row of table[i] are empty. four slots for link(i,j) can be marked, and those slots are marked unavailable in the S row of table[j], because at those slots, node j can not receive from any other nodes excluding node i. If there exist other node excluding i send data to node j at those slots, there will be collision. So, node can not nothing except receive data from node i at those slots. When finished the time slots assignment for node i. node i can be deleted from the array L. And time slots for other nodes can be assigned.

When time slots are assigned for node k and node j, link(k,w) and link(j,u) will share the same slots. This can be fine. Although node k and node j are neighbors, whoever node k sends data to, node j can not do the receiving for avoiding the collision. When node j sends data, node k can only do the receiving. But this rule is just for the receiving, sending is different. Node j and node k can do the sending together if the destination is different. Figure 3.1(b) shows the final time slots of every node.

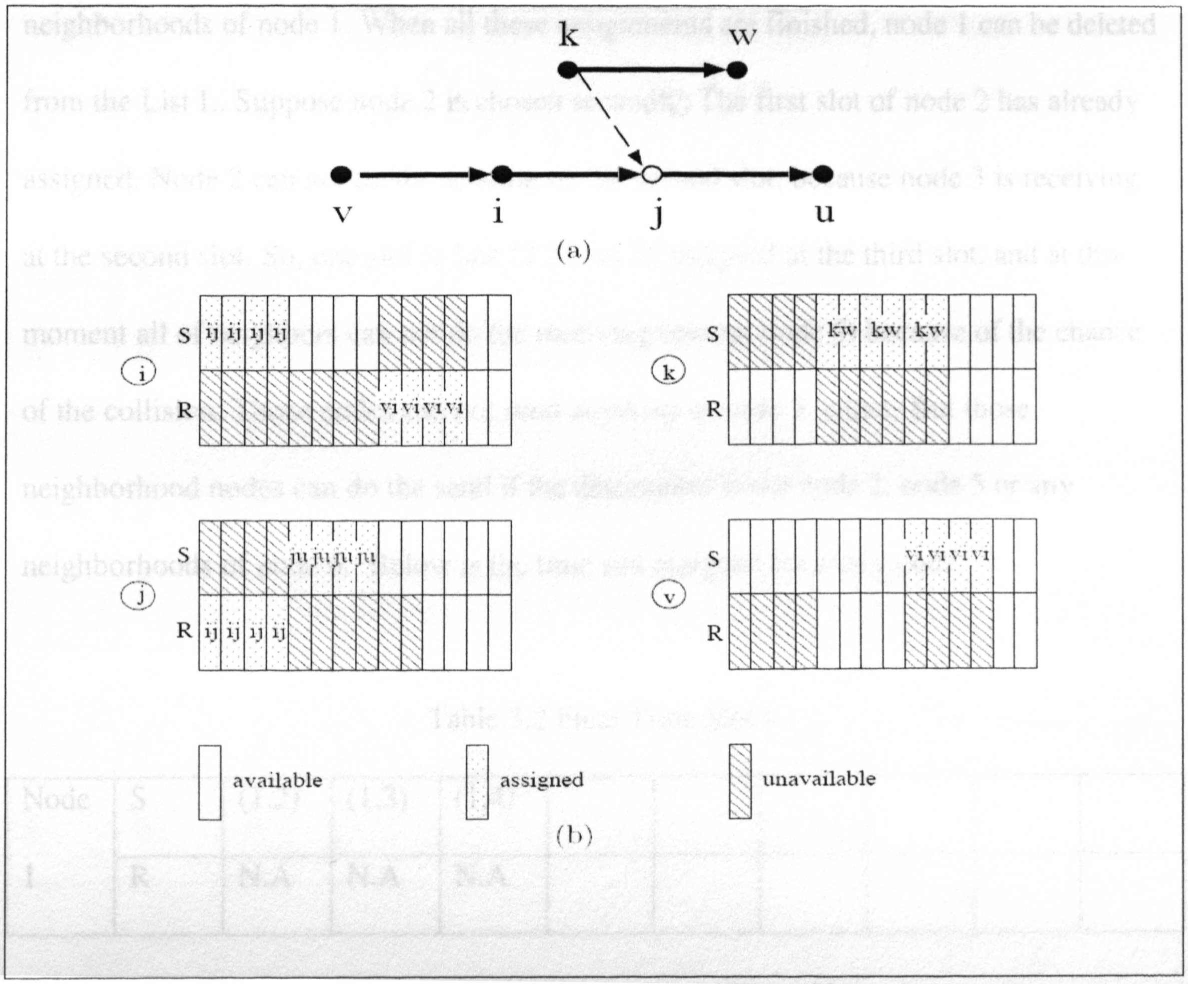


Figure 3.1 Topology And Final Time Slots

Suppose there are another topology like Figure 3.2(a), and the routing topology like Figure 3.2(b). There are totally 14 nodes, node 1 is the source node and node 14 is the sink source. Given the link rate of each link, based on the timeslot assignment algorithm, the most bandwidth-contentious node should be found first. It is easily to find that node 6 is that kind of node, and the bandwidth of node 6 is 9. In that case, let frame size T =9. Assume that node 1 is chosen first. one slot for the link (1,2) to send should be assigned, and at this moment all of neighbors of node 1 can not do the receiving (except node 2) because of the chance of the collision. Those nodes can not send anything to node 2, either. Node 2 can not do sendthing at this slot. But fortunately, those neighborhood nodes can do the send if the destination is not node 1, node 2 or any neighborhoods of node 1. When all these assignments are finished, node 1 can be deleted from the List L. Suppose node 2 is chosen secondly. The first slot of node 2 has already assigned. Node 2 can not do the sending on the second slot, because node 3 is receiving at the second slot. So, one slot to link (2,5) can be assigned at the third slot, and at this moment all of neighbors can not do the receiving (except node 5) because of the chance of the collision. Those nodes can not send anything to node 5, either. But those neighborhood nodes can do the send if the destination is not node 2, node 5 or any neighborhoods of node 6. Below is the time slot assigned for every node.

Table 3.2 Final Time Slot I

Node 1	S	(1,2)	(1,3)	(1,4)						
	R	N.A	N.A	N.A						

Table 3.2 Final Time Slots I: Con't

Node	S	N.A	N.A	(2,5)	N.A					
2	R	(1,2)	N.A	N.A	N.A	N.A	N.A			

Node	S	N.A	N.A	N.A	(3,6)					
3	R	N.A	(1,3)	N.A	N.A	N.A	N.A			

Node	S	(4,7)	N.A	N.A	N.A					
4	R	N.A	N.A	(1,4)	N.A	N.A	N.A			

Node	S	N.A	N.A	N.A	N.A	(5,8)	N.A			
5	R	N.A	N.A	(2,5)	N.A	N.A	N.A			

Node	S	N.A	N.A	N.A	N.A	N.A	(6,9)			
6	R	N.A	N.A	N.A	(3,6)	N.A	N.A			

Node	S	N.A	N.A	N.A	N.A	(7,10)	N.A			
7	R	(4,7)	N.A	N.A	N.A	N.A	N.A			

Node	S	(8,11)	N.A	N.A	N.A	N.A	N.A			
8	R	N.A	N.A	N.A	N.A	(5,8)	N.A			

Table 3.2 Final Time Slots I: Con't

Node 9	S	N.A	(9,12)	N.A	N.A	N.A	N.A			
	R	N.A	N.A	N.A	N.A	N.A	(6,9)			

Node 10	S	N.A	N.A	(10,13)	N.A	N.A	N.A			
	R	N.A	N.A	N.A	N.A	(7,10)	N.A			

Node 11	S	N.A	N.A	(11,14)	N.A	N.A	N.A			
	R	(8,11)	N.A	N.A	N.A					

Node 12	S	N.A	N.A	N.A	N.A	(12,14)	N.A			
	R	N.A	(9,12)	N.A	N.A					

Node 13	S	(13,14)	N.A	N.A		N.A	N.A			
	R	(N.A)	N.A	(10,13)	N.A					

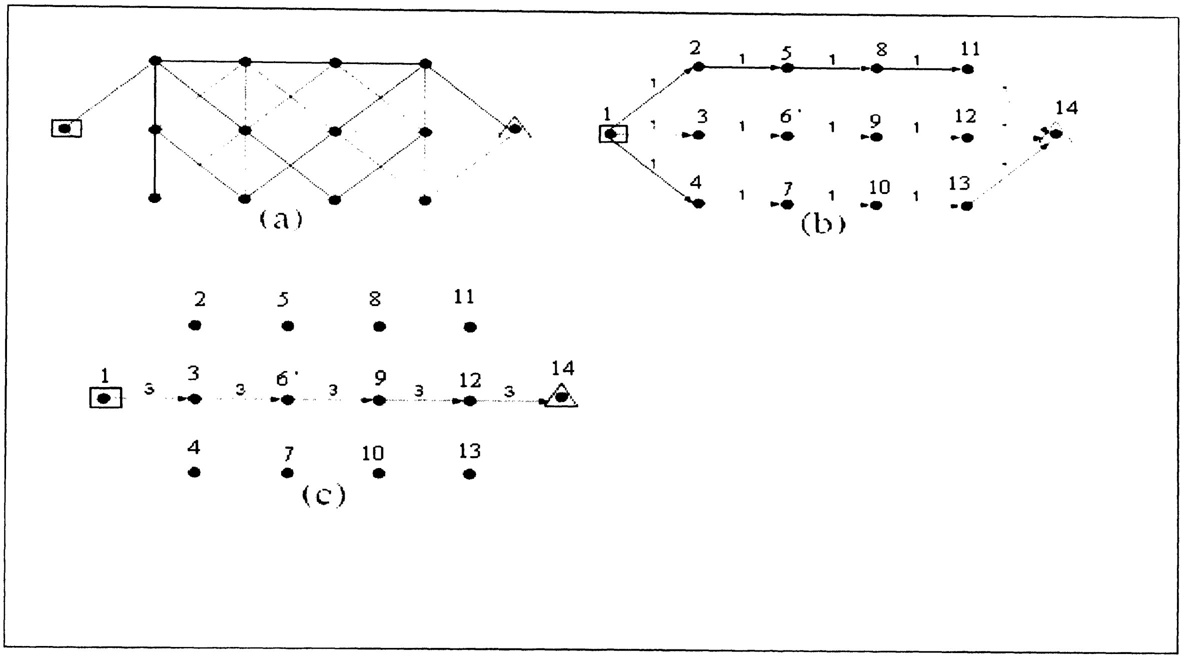


Figure 3.2 Topology Example V

From the results by using the time slot assignment algorithm, although initially nine time slots have been provided for assignment, seven of them are needed to finish the assignment for the global conflict-free schedule.

By using the same topology but different routing topology like Figure 3.2(c), different assigned time slots can been get.

Table 3.3 Final Time Slots II

Node	S	(1,3)	(1,3)	(1,3)						
1	R	N.A	N.A	N.A						

Table 3.3 Final Time Slots II: Con't

Node 3	S	N.A	N.A	N.A	(3,6)	(3,6)	(3,6)			
	R	(1,3)	(1,3)	(1,3)	N.A	N.A	N.A	N.A	N.A	N.A

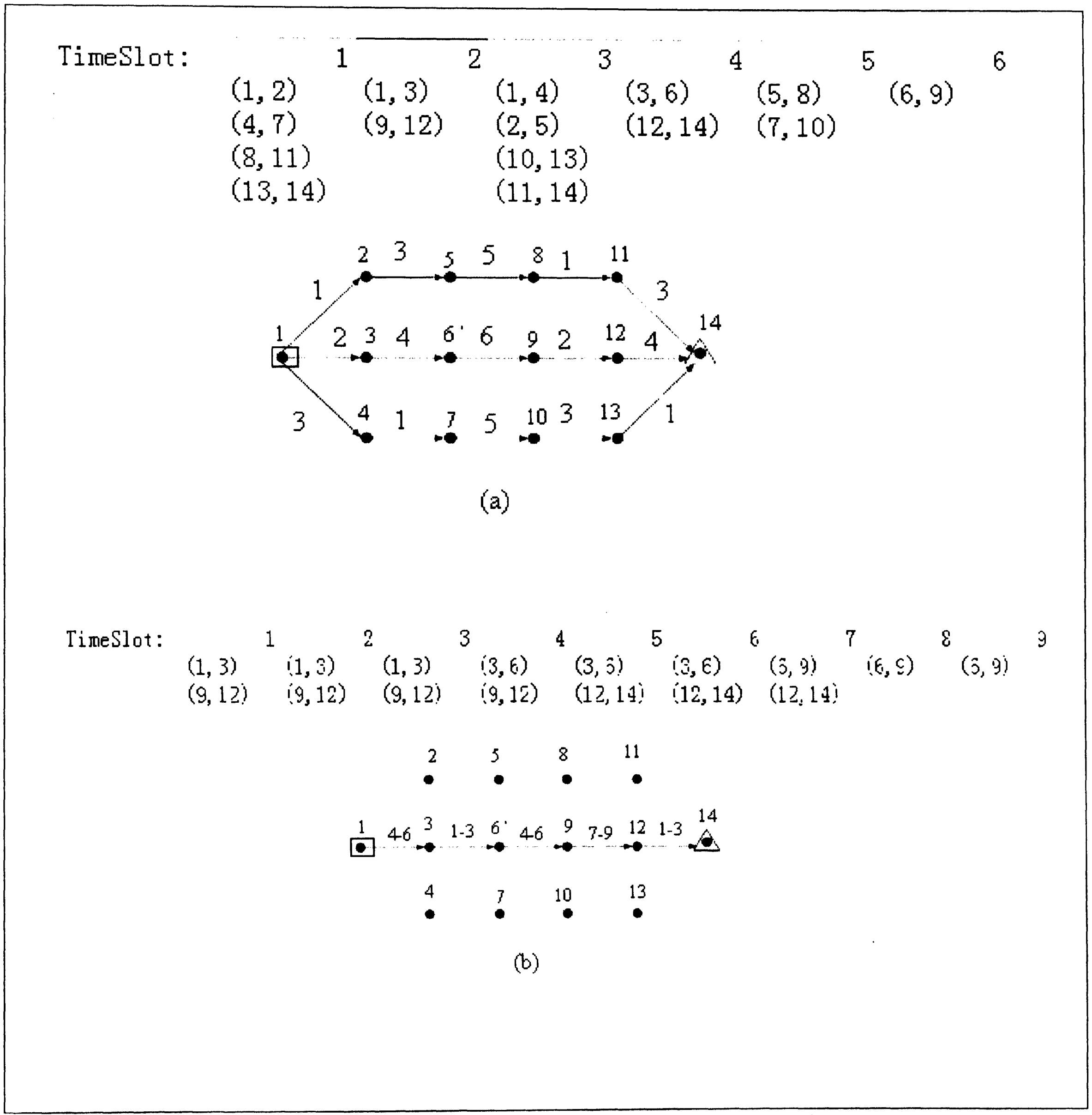
Node 6	S	N.A	N.A	N.A	N.A	N.A	N.A	(6,9)	(6,9)	(6,9)
	R	N.A	N.A	N.A	(3,6)	(3,6)	(3,6)	N.A	N.A	N.A

Node 9	S	(9,12)	(9,12)	(9,12)	N.A	N.A	N.A	N.A	N.A	N.A
	R	N.A	N.A	N.A	N.A	N.A	N.A	(6,9)	(6,9)	(6,9)

Node 12	S	N.A	N.A	N.A	(12,14)	(12,14)	(12,14)	N.A	N.A	N.A
	R	(9,12)	(9,12)	(9,12)	N.A	N.A	N.A			

Time slots for 5 nodes are assigned, because other nodes are neither receiver nor the source node. There is no flow through those nodes, these nodes can be ignored. And from the time slots assigned, nine slots are actually used, but six slots are used if the routing topology like Figure 3.2(b) is chosen.

Figure 3.3(a) is the final time slots assignment for all the links of routing topology in Figure 3.2(b), and Figure 3.3(b) is the final time slots assignment for all the links of routing topology in Figure 3.2(c).



TimeSlot:	1	2	3	4	5	6
	(1, 2) (4, 7) (8, 11) (13, 14)	(1, 3) (9, 12)	(1, 4) (2, 5) (10, 13) (11, 14)	(3, 6) (12, 14)	(5, 8) (7, 10)	(6, 9)

(a)

TimeSlot:	1	2	3	4	5	6	7	8	9
	(1, 3) (9, 12)	(1, 3) (9, 12)	(1, 3) (9, 12)	(3, 6) (9, 12)	(3, 6) (12, 14)	(3, 6) (12, 14)	(6, 9) (12, 14)	(6, 9)	(6, 9)

(b)

Figure 3.3 Routing Topology And Final Time Slots

4. RELATED WORK

The most related work includes one paper from our previous work on edge coloring for transmission scheduling [1] and one paper by Lall et al. [2]. In [1], the authors precisely depicted the conflict relation among transmissions with each color corresponding to one time slot at MAC layer. It guarantees conflict-free time slot assignment if each edge carries the same load. However, edge coloring by itself is NP-complete, and it assigns one color to each edge which implies it works best for uniform traffic load. Link rate allocation in this article is an extension from color assignment, but it works well for arbitrary traffic load because the number of time slots each edge gets is proportional to the traffic load on the edge; and furthermore, we consider nodes' energy constraint for link rate allocation. In [2], the authors proposed a distributed algorithm to compute link rates with an objective of maximizing the network lifetime. The major contribution is on the distributed implementation of the optimization algorithm. However, like most previous work on energy efficient routing in sensor networks, bandwidth is not taken into consideration.

In previous work, many algorithms transit the sensor between active, listen and sleep modes in order to make the network lifetime maximum by reducing the energy. A centralized approach for optimization of sensor activity regulates sleep/active periods by dedicating a relatively more powerful node such as LEACH [25], to control individual sensors [27]. In [28], sensor nodes are activated by a mobile access-point that is capable of strategically positioning itself to respond to desire queries. The activation of sensor nodes through centralized control may be designed to maintain traffic latency and network capacity [29], network coverage [30] or may be based upon anticipated or present traffic conditions in the network [28], sensor topology or distance from the cluster-head in the region [27]. And there are also algorithms to control the topology. The power transmission required to be assigned for a network topology is usually much smaller than the allowed maximal transmission power. Therefore, topology control can save energy and prolong the network lifetime. The topology control problems including both minimizing the total energy consumption and minimizing the maximum energy consumption are studied in [31] and [32].

Actually, I study the life time problem and give such solution on it that we not only consider the bandwidth and energy constraints, but consider the topology control. In our algorithm, we choose the shortest-path as the topology. When it meets the tie situation, we let the node do the selection by itself. Under the bandwidth and energy constraints, given the topology, we solve the LP to get the answer.

Similar work along this line includes [3]–[11] and many others. In [3], the proposed routing algorithms select the routes and the corresponding power levels such that the network lifetime is maximized. In [4], the routing problem is formulated as a linear programming problem, where the objective is to maximize the network lifetime, which is equivalent to the time until the network partition due to battery outage. Packet aggregation techniques were proposed to further reduce the energy consumption rate [5], [6], [8]. In [7], it was proposed to deploy a network clustering scheme and assign a less-energy constrained gateway node to act as a centralized network manager to further improve the energy efficiency and maximize network lifetime. Cui et al. further considered energy-efficient routing, scheduling, and link adaptation strategies together to maximize the network lifetime in [9], but the authors did not explicitly consider the bandwidth constraint in an arbitrary topology as we do. How to arrange the location of base-stations for WSN and select relay paths to maximize the network lifetime was discussed in [10], [11].

One of the major challenges in the design and operation of wireless networks is to schedule transmissions to efficiently share the common spectrum among links in the same geographic area. In previous works, a centralized scheduling policy that achieves the maximum attainable throughput region has been presented in the seminal paper by Tassiulas and Ephremides [36]. Gupta and Kumar [13] showed the asymptotic per-node capacity of a random wireless network of n nodes is $\theta(\frac{W}{\sqrt{n \log n}})$ each wireless node is capable of transmitting at W bits per second. In [14], by assuming that the transmission power of a link uv is proportional to $/uv/^k$. Wan et al. studied the minimum energy multicast routing. Li et al. in [15] studied the min-cost multicast routing when each node vi incurs a cost ci for relaying unit amount of data. Li et al. [16] studied the multicast throughput optimization problem in multi-hop wireless networks with primary interference model. The authors prove that the hardness of optimizing multicast throughput problem and give algorithms (with constant approximation ratios) for single multicast tree case and multiple multicast tree case. Notice that they assumed that two transmissions will not conflict with each other if they do not incur primary interference. However, the lack of central control in wireless networks calls for the design of distributed scheduling algorithms. Such algorithms should achieve the maximum throughput or at least a guaranteed fraction of the maximum throughput. In our algorithm, although we do not design the scheduling directly, we set the constraint of bandwidth and let the nodes decide by themselves. In addition, we assume every node in the network except the sink node is the source node and the rate is larger than the zero for the fairness. And we let the nodes decide how many data they send under the bandwidth constraint by themselves and try to get the maximum throughput.

In wireless networks, the time slots can be reallocated to achieve the maximum efficiency. [17] considered OFDM transmission in a multi-user environment and formulated the problem of minimizing the overall transmit power by adaptively assigning sub-carriers to the users along with the number of bits and power level to each sub-carrier. [18] developed a transmit power adaptation method to maximize the data rate of multi-user OFDM systems in a downlink transmission. In such system, since multiple users' data symbols are transmitted in parallel through a number of orthogonal sub-carriers simultaneously, both the multi-user diversity and the spectral diversity may be exploited using the transmit power adaptation scheme. [19] considered a time slot allocation for multi-user wireless networks. The authors desired the method to minimize required number of time slots in an effort to achieve the minimum transmission rate to satisfy the user's QoS requirement under the fixed power.

In previous works, most of algorithms are based on exponential backoff algorithm that is an algorithm that uses feedback to multiplicatively decrease the rate of some process, in order to gradually find an acceptable rate. Cali et al [33] find that dynamically adapting the contention window could let the capacity of 802.11 reach the theoretical capacity based on the estimation of the number of active stations which are in the radio transmission range. Bianchi et al [34] proposed an algorithm based on the extended Kalman filter to estimate the number of active stations. Li et al [35] showed that in order to maximize system throughput, the BC (Back-off Counter) must be equal to the number of active stations in the wireless network, and for this, they proposed a fixed collision rate back-off algorithm. We can that all these algorithms try to recover network when it meets the collision and are different from ours. Our time slot assignment algorithm is designed for avoiding the collision. .

5. CONCLUSION AND FUTURE WORK

This article provides a generic mathematical model for the optimal routing problem in an energy and bandwidth-constrained sensor network. Using the sole constraint of energy sometimes leads to unrealistic solutions that cannot be accommodated by the link capacity. This work elaborated on the sufficient condition that a given traffic load can be put through a given network and jointly optimized on both energy use and bandwidth allocation. We design two heuristics based on the mathematic model (Heuristic I and Heuristic II), then compare them with other two algorithms (MaxLife, SPT) under the sufficient condition and try to get the related optimal solution. The solution provides not only the routing topology but also the amount of data flow that should be routed to each path. The joint optimization guarantees that there exists a conflict-free time slot assignment to support the given routing solution. Based on the link rate we get, we give the algorithm on how to assign the time slots to achieve the conflict-free schedule globally. From the test case, we can get that we can actually get such schedule that there is no conflict. At last, we consider the total throughput, we assume that every node excluding the sink node can send out the data and try to compare the total throughput of two different Heuristics. To the best of our knowledge, this is the first work that explicitly considers bandwidth constraint in solving a maximum lifetime routing problem in a sensor network with arbitrary topology.

In the future, we will continue to finish the algorithm on assigning the time slot and design the bigger test case to verify it. Right now, we only have some simple test case, and this algorithm can do well in these test case. We will give some more complex tests on this algorithm. We also need to consider link rate allocation for data aggregation, in this case the flow conservation is not satisfied, a node can accept three packets and send out only one aggregated packet. Under this situation, we need to find the solution toward maximum life time and maximum throughput again. And we will also generate some test cases to verify them.

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