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**AN INCENTIVE MODEL FOR SECURE
INTERNATIONAL
TELECOMMUNICATIONS**

THESIS

Jeffrey R. Del Vecchio, Captain, USAF

AFIT/GOA/ENS/00M-2

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

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AN INCENTIVE MODEL FOR SECURE INTERNATIONAL
TELECOMMUNICATIONS

THESIS

Presented to the Faculty

Department of Systems and Engineering Management

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In Partial Fulfillment of the Requirements for the

Degree of Master of Science

Jeffrey R. Del Vecchio, B.A.

Captain, USAF

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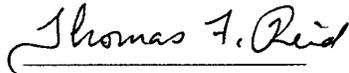
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ABSTRACT

This study developed a new defensive model for global voice communications. It uses a n -person, zero-sum, cooperative and non-cooperative game to optimize the coalitions revenue after the possibility of a network service provider being tampered by an adversary. This research optimized two measures of effectiveness (coalition revenue and network provider revenue) of international telecommunications coalitions by hardening network service providers and improving their respective revenue with incentives.

A multi-criteria optimization problem was developed to establish the strategic competition between the coalition defender and attacker. Irrespective of the amount of incentives, a applicable hardening and tampering strategy can be obtained. All methods and models are general and could be easily adapted to other specific applications. Examples of analysis was conducted on a sample network of seven nodes and presented in this study.

It was shown that the option to harden NSPs has measurable value whether or not an incentive is provided for the coalition. In addition, the adversary's tampering strategy is revealed in the *shadow prices* associated with the game constraints. Analysis proved that two objective functions have different measures of effectiveness. A network optimized for one objective is more than likely not optimized for the other objective.

Chapter 1. Introduction

Currently, the Department of Defense (DoD) relies on the Public Switched Telephone Networks (PSTN) for the bulk of its telecommunications. The PSTN is a composite of multiple interconnected networks, where each network is operated, maintained, and managed independently from the others. However, the network operators (also known as network service providers) rely a great deal on each other for routing calls to destinations outside of their network span. Based on worked out agreements among the service providers, they decide on how and where they will physically interconnect their networks. These physical points of interconnection are called Points of Presence (POPs).

In today's world of the telecommunications, there is much concern with the reliability and security of a given network. Both government and industry have viable concerns whether or not their messages are both secure from an adversary as well as to the reliability of the message reaching its destination. Likewise, reliability and vulnerability can be used as a measuring device when it is time to renew or draft a new contract with the telecommunication companies.

1.1 Significance

In telecommunication networks, traditional factors that telephone companies consider when they route external call (calls that are passed from one network onto another network) typically include costs (tariffs), revenues (retail charges), and link reliability (Bit Error Rate). Today's PSTN's may have security and reliability risk due to the path a message may be

sent. Since many government agencies use PSTN's for official voice messages, there is a keen interest on knowing what coalition that routes their information for security concerns.

It is neither the lack of technical expertise nor patriotism that causes a NSP to be a member of a coalition that has a network that may be vulnerable to adversary tampering. Instead, it is the lack of finances and possible incentive to form a stronger coalition and upgrade their network's invulnerability. Networks are primarily designed by the industry to withstand statistical failure. A planned attack by an adversary may not be taken into account when a NSP designs a network or forms a coalition.

In the highly competitive industry of voice communication, large amounts of investments are needed to keep up with ever changing industry standards. These investments are naturally invested in areas of concern that return the most revenue. Vulnerability as a whole returns little or no contributions to the NSP's revenue.

1.2 Background

A switched network strategy sends a message from a source node to a sink node as a complete message. Switched network strategy has many well-known advantages. Unfortunately, it is inefficient. The inefficiency is caused by the fact that since the message is sent as a complete message, versus packet switching, an entire link must be allocated to this message (Vararigos, 1996:693). The public telephone companies will pick a path and coalition determined upon several factors. The following are some public telecommunication companies considerations when choosing a coalition:

A. Costs: The Global PSTN consists of multiple networks interconnected by POPs.

Cost is the charge a destination network service provider (NSP) passes onto the

originating NSP for completing a call request. In the case where there is no direct interconnection (POP) between originating and destination NSP, then the originating NSP will route the call via an intermediate NSP. Cost, in this case, refers to the charge that the intermediate NSP passes onto the originating NSP for carrying the call. In sum, cost is an attribute of a network and refers to the fee an intermediate or destination NSP charges the originating NSP for carrying or completing the call.

- B. Routing Agreements: Agreements may be set up due to political reasons more so than other factors such as cost and reliability. A political example would be if network 1 makes an agreement with network 2 to route all of its external routing. Thus everybody has a piece of the pie and is happy. Routing agreements are sometimes conditional. An example of a conditional agreement is one that is made only if the costs of the routing agreed upon remains below the costs of taking an alternative route. The algorithm will allow some simple conditionals.
- C. Link Reliability: This defines the quality of the link, and can be measured in the percent of downtime or in the terms of bit error rate.
- D. Media Type: This identifies whether the link is fiber, copper, etc.
- E. Network Topology: The topology consists of nodes and links. In this case, local-area networks are represented as nodes, and the links are the actual physical media that interconnects these networks.
- F. Partial Information of Path: Given an origin-destination (OD) pair, a portion of the nodes contained within the path may be known.

1.3 Research Problem

The proposed problem was to create a path prediction model for international communications. Essentially, the goal was to determine what countries that a voice message would travel from destination to origin. As the data was gathered, it was realized that the data of traffic from country i to country j did not take into account any third country routing. After more investigation of the data, it was realized that there was much data on the revenue achieved by each country. It was then decided to create a model to investigate the possible coalition that a NSP may be a member.

This research seeks to use multi-criteria gaming theory to design an incentive and coalition likelihood prediction tool to be used by the DoD. This tool will be specific to the needs of DoD and their NSP. This may address the issue of what NSP can best meet the reliability and vulnerability needs of the DoD.

1.3.1 Assumptions

This research has multiple assumptions. The first is that partial data on specific PSTN networks will be provided by DoD. The networks will be of the estimated public telecommunications networks. Two constraints that are to be considered are security vulnerability and coalition's revenue. This research will look at the security vulnerability of the nodes.

In addition, each node in itself is assumed to be a network where the links are the actual mediums through which the message travels. It will be assumed that local NSP's will have control of the nodes (sub-networks). Likewise, the physical links are controlled and

owned by the individual NSP. Examples of the physical links connecting the nodes are copper cable, satellites, and fiber optics.

It is assumed that there are adversaries of the DoD. The adversary's goal will be to inflict damage on the network that voice messages are sent. Each foreign NSP is assumed to be a neutral participant in the network. This disallows an adversary's NSP to be added to the network accidentally due to its financial capabilities.

It is also assumed that one NSP can belong to more than one coalition. For example, different coalitions can possibly be based on geographic locations. Each coalition still needs to be applied to the model to determine the best defensive/offensive and incentive allocation strategy. Although the gaming theory is played numerous times and the percentage of time that a NSP is attacked is calculated, it is still assumed that the adversary can only attack one NSP at a time.

1.3.2 Objectives

The primary objective is to create a family of models that will help DoD determine a defensive strategy for defense of their global voice communications. This research will concentrate on the feasibility of integrating circuit-switching formulation into an interactive linear and non-linear solving software package. This integration will be specific to the networks that are or may be utilized by DoD to be used as a coalition prediction/incentive tool. The following are the objectives supporting this thesis:

1. Identify the formulation and limitations of the current multi-criteria non-linear methodology

2. Identify and gather all data and assumptions for integrating a circuit-switching network into a multi-criteria non-linear formulation
3. Integrate the circuit-switching network into a multi-criteria non-linear formulation
4. Examine the usefulness of the circuit-switching network within multi-criteria non-linear formulation
5. Try to determine the actual path that a message may be sent within the coalition.

1.4 Methodology

The first objective is to get a good understanding of multi-criteria practices. LINGO can provide an interactive method to help solve the multi-criteria problem. It is an interactive computer-software package that can be used to solve linear, integer, and non-linear programming problems.

The second objective is to continue the literature review. The literature review is a never-ending process to establish if any new relative information becomes available. It will also prevent the reinvention of the wheel by finding what work has already been accomplished in this area of concern. The bulk of the focus will be on network coalitions and vulnerability.

The third objective is to gather all data and assumptions. These will be the basis that will be needed to predict a network coalition's revenue. The fourth objective will be to take this information and transform it into a format that can be inputted into the nonlinear formulation. Using this formulation, the data will give accurate data output to analyze.

The fifth objective is performed when the non-linear formulation is complete. Experimental runs will be conducted and output data collected. The following categories below outline the steps needed to complete this project:

Evaluate Network Model:

- A. Determine possible coalitions
- B. Determine revenue from node i to node j within the coalitions

Apply Multi-Criteria Methods:

- A. Formulate nonlinear problem using revenues
- B. Solve multi-criteria nonlinear problem using computer software
- C. Evaluate and interpret output data

Chapter 2. Literature Review

2.1 Introduction

In 1844, Samuel Morse invented the telegraph to transmit messages. Thirty-three years later Alexander Graham Bell invented the telephone. Not long afterwards, it was realized that telephone to telephone connections had to converge at a common point, a switchboard, to be connected. Initially these switches were handled manually. It was not until 1889 when Almond Stromger invented the two-motion systematic electro-magnetic switch that the direct connection of two telephones was accomplished by the user's dial pulses. This is commonly known today as circuit switching. Circuit switching is well tended for delay-sensitive services such as voice communication. Some current day networks can exceed 500 million telephone sets [Saadawi, 1994:399].

The more information that an organization can get about a given network, the better they can evaluate the voice communication performance. An accurate prediction of the telecommunication coalition that their verbal message travels will provide the decision maker (DM) with a tool to use for security and incentive evaluation decisions. Such a vulnerability prediction tool can give the DM a quantitative means to justify their communication usage decisions. By using multi-criteria non-linear methods combined with current telecommunication revenues, a network vulnerability prediction tool can be created.

This chapter will discuss the structure of telecommunication networks.

2.2 Telecommunication Networks

Three main components make up a telecommunication network. They are the customer premise equipment (CPE), transmission facilities, and switching facilities. The CPE is the actual equipment located at the customer's location. They may include telephone, modem, and answering machines [Saadawi, 1994:22].

The transmission facilities can be further broken down to local loops and trunk lines. Local loops are the connections between the CPE's and the local telecommunication company's switching station. Local loops are also commonly referred to as zones [Tayi, 1999:19] and clusters [Tsai, 1989:1059]. Local loops are made up of a group of nodes. Nodes can be thought of as CPE's. Local loops can be connected by wire or fiber optics cables.

Each local loop has one or more nodes that have links to other loop nodes called gates or switching stations. These gates are connected by trunks. Whereas the local loops are dedicated for the individual customers, the trunk carries messages from many customers. Trunks can range in length from one mile to thousands of miles. Trunks use a wider resource of media to transmit its messages. These can include wire cables, radio, satellites, and fiber optics.

2.2.1 Third Country Routing

Although most calls are routed from the originating country to the terminating country, it is common for a telephone call to be routed through a third country. In a circuit switched system, it can be more efficient to use a third country path. Country *A* can route a call through Country *B* to terminate in Country *C* during busy hours between Country *A* and

C. This is usually the case between three NSPs, which are all in a different time zone, thus each having a different peak time. This helps to prevent all the circuits from Country *A* to *C* to be in use at any given time [van den Nouweland, 1996: 298].

Staple [1997] explains Home Country Beyond and callback services add to the creation of third country calls. A home country beyond call may originate in Country *A*, be billed to Country *B* via a calling card, and terminate in Country *C*. This allows Country *B* to receive the call's revenue although the telephone call does not directly go through that country. Callback service is similar. A caller in Country *A* calls a callback service in Country *B* and hangs up after the first ring. Country *B* calls Country *A* and a call is placed to Country *C* from Country *B*. Hence, the subscriber is in Country *A*, but the call originates in Country *B* and terminates in Country *C*. In both cases, Country *B* gets the revenue while Country *A* loses the revenue although the subscriber is in Country *A*. On the other hand, the subscriber usually gets a lower rate for their call. There are both moral and legal ramifications of these methods.

The use of third country calling is usually limited to two link paths. There are two major reasons for this two-path link limit. The first is to prevent a telephone call to route back to the originating country. It is theoretically possible that a telephone call can get into a loop depending on the routing algorithms used unless a rerouted call cannot be rerouted again. The other reason is to prevent the congestion of the entire international telephone network. Since only two path links are used, this limits the NSPs to three at the most, a NSP in the originating country, a transit NSP, and an NSP in the terminating country.

2.2.2 Vulnerability of Commercial Telecommunication Systems

Commercial telecommunications companies have been involved with vulnerability of their networks since the civil war when military messages were sent via telegraph, sometimes directly to the President himself. During World War II, Bell Telephone employees reestablished telecommunications in Germany and France so that military commanders would have a reliable system to transmit messages. AT&T, during the cold war, routed much of their telephone lines around major cities to prevent the physical damage that may be caused by an adversary's nuclear strike.

Today, the physical damage is not as important as it was in the past. We must now worry about the "intentional translation of a single digit in a million lines of computer code, which, without instant remedy, can easily deny service to much of the national telecommunication system" [Campen, 1995: 27]. This would not be that hard of a task if there was only one NSP. Unfortunately, in an international telecommunication system, there are many NSPs. Even a single country may have more than one NSP to handle its service.

Cohen in *Protection and Security on the Information Highway* wrote, "any system designed purely for financial efficiency under normal operating conditions is highly susceptible to intentional disruption." In order for the NSPs to consider vulnerability in their networks, they must have some type of incentive in the way of revenue. Campen [1995: 27] feels that it should come from the government. "The security differential should come from the federal treasury if we are to have an information service that can operate in an inherently unsafe environment."

2.3 Game Theoretic Approach

Game Theory is two players involved in a competitive game. The first player is trying to maximize his or her own payoff while the second player is trying to minimize the first player's payoff.

In a two-person zero-sum game, the amount player one loses is also the identical amount that player two wins. These winnings are based on the strategies that each player chooses [Winston, 1994: 837]. Linear programming can be used to find the value and optimal strategies for two-person zero-sum games. Linear programming and the simplex method, developed by Dantzig in 1947, has been used to solve gaming theory problems within both the military and industry.

Gaming theory has also been extended to n -person games. The payoff of each player is based on the Shapley Value. The Shapley Value implies that player i 's reward should be the expected amount that player i adds to the coalition made up of all the n players.

2.3.1 Cooperative Game Theoretic Approach

Cooperative game theory can be applied to telecommunication problems. Two areas that cooperative game theory have been applied to are Terrestrial Flight Telephone System (TFTS) and the rerouting of international telephone calls. TFTS is a system where multiple agents have to cooperate to guarantee a profit. When a telephone call is made from an airborne plane, it is received by a receiver on the ground. In Europe, this means that it may be received in any one of a number of countries. Obviously, the company who routes the call gets the profit. In addition, the more receivers on the ground, the more of a chance that that area will receive the incoming call.

The rerouting of international calls is also a situation where multiple agents have to cooperate to share the profits. During busy hours, calls can be rerouted through quieter circuits. For example, at the prime time to call between America and Europe, a voice message may be rerouted through Australia to guarantee that the America-Europe path is not overloaded. This enables carriers to use their circuits more efficiently and to reduce the cost of their networks. In order to generate profits through rerouting international calls, there are three agents involved. They are the carriers in the originating country, the transit carrier, and the carrier in the destination country.

When modeling the game theoretic approach, one is forced to recognize the underlying structure. This approach not only concerns itself with individual players, but with coalitions of players. This allows all players to see what their outcome will be dependent upon the decision that is made. Their outcome is based on the coalition worth. The worth is derived from the revenue that a player could make if he was part of a particular coalition. Each player's revenue then would be some sort of division of the coalition worth. One such division would be proportional to the investment that a player made. This would insure appropriate payback based on the amount of revenue gambled. This division is denoted as Proportional Investment (*PI*). It is possible in telecommunication coalitions that a player may actually lose revenue, thus would not want to be part of that particular coalition.

Common among many game theoretic problems, a division known as Shapley's Value (*SV*) is commonly used. *SV* deals with the marginal contributions of players of a particular coalition [van der Nouweland, 1996:301]. Players are assigned an average of their contributions. In other words, the player receives the expected marginal contribution.

2.3.2 Non-cooperative Gaming Theory

Schavland [1998] defines non-cooperative gaming theory as a Blue network defender versus a Red network attacker. A player has to be on one side or the other, thus a two-person game. As the game is played, Blue's loss is Red's gain. In Schavland's example, if Red's attack on Blue's network results in reliability dropping from 0.75 from 0.90, Blue's loss of 0.15 units is exactly Red's gain. Red is opposed to Blue's interest. Thus, the name of non-cooperative game is applied.

Lyle et al. [1999] uses a non-cooperative gaming approach to determine the effects of an adversary on a stochastic communication network-network. He examined the reliability damage that an adversary inflicted upon his network. The non-cooperative gaming model was ran to determine damage on the network with and without hardening strategies. He was able to go one step further and determine the value of hardening.

Using Lyle as a basis, Schavland [1999] applied Lyle's non-cooperative game theoretic approach to create an improvement strategy for a probabilistic network. Reliability damage as well as flow damage was used to measure vulnerability. Using vulnerability, he was able to create an improvement strategy to minimize Red's negative impact upon the network. It was assumed that the game was being played multiple times.

Both Lyle and Schavland were able to determine the percentage of time that Blue should harden a link and determine the percentage of time that Red would tamper with a particular link. These percentages help determine the amount of improvement that a link should receive if a budget was allocated to link improvement.

2.4 Multicriteria Stochastic-Network Optimization

In telecommunication networks, reliability and throughput have been used as measures of effectiveness. Chan [1996] and Schavland [1999] use multicriteria methods to combine both reliability and throughput as a measure of effectiveness. This optimization has been used to both improve a network and to design telecommunication networks that are less vulnerable to tampering.

The optimization problem is reduced to a linear programming problem. The reliability of each arc is reduced to the reliability of each path with series-arc and parallel-arc reductions. These provide three linear constraints to consider: reliability, throughput, and budget-constraints. It is shown that varying the cost differences between the two criteria affects the efficient frontier or tradeoff region [Chan, 1996:13]. A full-scale multicriteria-optimization (MCO) model was used. This provided a means to explore the efficient frontier as well as the varying effects of the cost-budget. It also provided the tradeoffs between capacity versus reliability improvement.

With this method, there is no optimal solution. Where there are numerous alternatives to choose from, the identification of the ideal is not an easy task. Korhonen [1988] suggests a visual interactive method for identifying efficient solutions without actually needing to know the utility function. This is a heuristic iterating procedure, in which a reference direction toward the ideal is chosen at each iteration. This direction maximally minimizes the objective currently under consideration. The procedure terminates when the objective under consideration reaches a local minimum over the non-dominated set.

2.5 Summary

This chapter outlined the three parts of telecommunication networks, then discussed each part in more detail. This discussion was used to give a broad background into telecommunication networks. This review illustrated that there may not be one optimal solution given multiple criteria. Vulnerability prediction and coalition incentive methodology will be explored more thoroughly in Chapter 3.

Chapter 3. Models and Methodology

3.1 Notation

B_R	Budget available for improving coalition's revenue
B_S	Budget available for improving NSP A 's revenue
B_{tot}	Total budget available for improvement and/or hardening
c_{ij}	Cost of increasing retail charge of country i to country j by one unit
\mathbf{c}	Vector of c_{ij} 's, including all countries in the coalition
t_{ij}	Telephone traffic from country i to country j
\mathbf{t}	Vector of t_{ij} 's, including all countries in the coalition
I_{ij}	Incentive denoting the revenue improvement from country i to country j
\mathbf{I}	Vector of I_{ij} 's, including all countries in the coalition
$\underline{\mathbf{I}}$	Vector \mathbf{I} excluding $\sum_j (I_{ij} + I_{ji})$
y_i	Game-theoretic decision-variable (continuous) denoting the percentage of hardening effort at country i for the DoD (defensive) team decision maker
\mathbf{y}	Vector of y_i 's, including all countries in the coalition
z_i	Game-theoretic decision-variable (continuous) denoting the percentage of tampering effort at country i for the adversary (offensive) team decision maker
\mathbf{z}	Vector of z_i 's, including all countries in the coalition
n	Number of countries in the coalition
s	Constant varying from the largest value such that W_1 is at it's maximum without the W_2 constraint; all the way to W_2 's maximum
r_{ij}	Telephone call revenue from country i to country j
\mathbf{r}	Vector of r_{ij} 's for all communication links in coalition
$\underline{\mathbf{r}}$	Vector \mathbf{r} excluding $\sum_j (r_{ij} + r_{ji})$
\mathbf{r}_0	Initial vector \mathbf{r} (before incentive)
\mathbf{r}^*	Vector \mathbf{r} after incentive and before tampering
\mathbf{r}'_i	Vector \mathbf{r} after an adversarial tampering has removed country i
\mathbf{y}_i	Vector \mathbf{y} where the decision was to harden
$R(\mathbf{r}_0)$	The current revenue worth of the coalition
$R(\mathbf{r}^*)$	The final revenue worth of the coalition
$R(\mathbf{r}'_i)$	The final revenue worth of the coalition after a successful tampering has removed country i from the coalition
$S(\mathbf{r}_0)$	The current revenue for NSP A
$S(\mathbf{r}^*)$	The final revenue for NSP A
$S(\mathbf{r}'_i)$	The final revenue for NSP A after a successful tampering has removed country i from the coalition

- $W_1(\mathbf{r}_0, \mathbf{y}_i)$ The amount of damage caused to the coalition's worth by a given strategy \mathbf{y}_i (on country i)
- W_1 The coalition worth (in dollars) derived using a game theoretic approach
- $W_2(\mathbf{r}_0, \mathbf{y}_i)$ The amount of damage caused to NSP A 's revenue by a given strategy \mathbf{y}_i (on country i)
- W_2 NSP A 's revenue (in dollars) derived using a game theoretic approach

3.2 NSP Coalitions

Voice network topology is made up as switching nodes and links. Switching nodes are often referred to as International Switching Centers (ISC). With respect to this study, the ISCs are controlled by the local NSP networks. Inter-ISC groups (coalitions) are where a traffic relation exists due to a *bilateral agreement* among certain NSPs. The bilateral agreement is modified usually on a monthly or annual basis. This modification is usually due to changes in routing plans, ISCs, or traffic flow. It was common for traffic relations to be based on geographical location and bonds between countries and former colonies. Today's world trade has added new considerations to traffic relations. Some examples would be economic, political, and trade considerations.

3.3 Coalition Determination

Cooperative gaming theory will be used to determine what the best coalition of NSPs that maximizes the parent country's revenue. This method has been applied to telecommunication problems such as billing long distance calls and rerouting international telephone calls. A coalition game consists of a player set $N := \{1, 2, \dots, n\}$ and a characteristic function v that assigns to each coalition $S \subseteq N$ of players a real $v(S)$ that is to be interpreted as the maximal revenues that that the members in the coalition can achieve when they cooperate [van den Nouweland, 1996].

3.3.1 NSPs' Investments

Here N is defined as the set of countries (NSPs) in the derived network. It is assumed that each NSP invests in the operation and maintenance of their respective transit/switching exchanges and transmission links (satellite, radio, and cable). NTI's International Facilities Analysis tables for each node provides the data needed broken up by the node's respective NSPs. This data will be in tabular form illustrated in Table 3.1. The rows are the countries and the column is their respective number of switching stations and telecommunication links.

NSP	#OF SWITCHING STATIONS	# OF EARTH STATIONS
<i>A</i>	4	6
<i>B</i>	1	1
<i>C</i>	6	8
<i>D</i>	3	4

Table 3-1 - Number of Stations

The number of stations of each NSP will be used later to help determine the division of revenues for a given coalition.

3.3.2 NSPs' Revenues

The revenues of each NSP consist of two parts. The first part is the revenue created by providing a telephone call from country i to country j . This will be calculated by using TeleGeography's data on the telephone traffic from country i to country j . All traffic is based on millions of minutes. All dollars in this methodology are in millions of U.S. dollars. Once the number of calls is realized, a cost per telephone call from country i that can be assigned to the number of calls made to determine country i 's revenue. Since the scope of this project is focused on the global, international network, it will be assumed that a telephone call from country i to itself will provide revenue of \$0.0. Local network traffic is not modeled in this

study. Since local calls are not usually switched through international NSPs, there is little risk of a local call being rerouted through another country than the origin. There are some exceptions such as with U.S. and Canadian NSPs. Some local calls may be routed from the U.S. through Canada and then back into the U.S. Since all the data is derived international calls from the origin to destination, the issue of local calls is a mute point.

The second source of revenue is based on agreements among each pair of countries known as accounting or terminating rates. This agreement is used to maintain a balance of telephone calls between country i and country j . If one country has fewer incoming calls than the other country, the difference of the number of calls is taken into account. This difference is divided equally and multiplied by a prearranged compensation cost. This creates a compensation value that is then paid by the country with a higher number of incoming calls to the country with fewer incoming calls. Ideally, country i would route the exact number of calls to country j that country j is routing to country i . Unfortunately, since a global telecommunication network can be very complex, this is not realistic. This revenue will be either a positive or a negative value. For example, if country i has to compensate country j \$100, country i and country j 's revenues will be -\$100 and \$100 respectively.

This compensatory revenue can be calculated with the revenue of actually routing a call from country i to country j to create overall revenue. A revenue table can be created to illustrate these overall revenues. The table represents the traffic flow revenue from country i (row) to country j (column). Each element r_{ij} is the revenue country i earns when a call is routed to country j . An example is illustrated in Table 3.2.

NSP	A	B	C	D
A	\$0	\$52.00	\$77.60	\$48.20
B	\$60.60	\$0	\$3.20	\$0
C	\$44.00	\$30	\$0	\$30
D	\$38.70	\$0	\$.70	\$0

Table 3-2 – Revenues from Country *i* to Country *j* Based on Telephone Traffic

3.3.3 Coalition's Revenue

With the data now available, the revenue that a coalition *S* of countries can jointly realize within the cooperation of the countries can be calculated. It is assumed that the countries of the network will cooperate among each other. This allows the revenue that the members of coalition *S* can jointly realize with their coalition as the sum of revenues generated by the countries of that coalition. Van den Nouweland [1996] simplifies it to

$$v(S) = \sum_i a_{ii} + \sum_i \sum_j a_{ij} \quad (1)$$

In simpler terms, the worth of the coalition of countries can be determined by summing up all the revenues when the rows and columns not corresponding to the coalition countries are crossed out.

In theory, all combinations of coalition groups can be generated. A sample of the coalitions of interest and their joint revenues are as listed in Table 3.3. All values are in millions of dollars.

COALITION	WORTH
<i>AB</i>	\$112.57
<i>AC</i>	\$121.56
<i>AD</i>	\$86.92
<i>ABC</i>	\$237.61
<i>ABD</i>	\$199.49
<i>ACD</i>	\$209.47
<i>ABCD</i>	\$325.51

Table 3-3 – Coalitions' Worth

3.3.4 Division of Revenues

The revenue of the coalition by them does not determine what coalition is most advantageous to the parent country. Some type of division of revenues must be applied. Two different methods will be used to determine the division of revenues. The first division of revenue is based on the number of stations (percentage of investment) that each country made to the coalition. The percentages will be calculated using Table 3.1. Once the percentages are determined, the overall revenues will be split proportionally to the investments of the countries. This division will be denoted as Proportional Investment (*PI*).

The second method of division to be used is the Shapley Value (*SV*). With Shapley Value, each countries receives their revenue based on their marginal contributions. The general formula for division of revenue is

$$S_i = \sum_i \frac{(s-1)! * (n-s)!}{n!} * (V(s) - V(s-i)) \quad (2)$$

n = total number of players

s = the number of players in coalition S

For the case of telecommunications network coalitions, van den Nouweland [1996] was able to reduce the Shapley Value to

$$a_{ii} + \frac{1}{2} * \sum_{j \neq i} (a_{ij} + a_{ji}) \quad (3)$$

Once the revenues for the parent country are calculated for each method, the best coalition for the origin node to be part of will be determined. Multi-criteria decision making will determine what coalition is the most preferred from the U.S. NSP perspective. Table 3.4 illustrates monetarily a sample of the revenue for Country *A* to be a member of a particular coalition using the three methods of revenue division listed above.

REVENUE FOR NSP <i>A</i>	<i>PI</i>	<i>SV</i>
<i>AB</i>	\$93.43	\$56.29
<i>AC</i>	\$49.84	\$60.78
<i>AD</i>	\$50.41	\$43.46
<i>ABC</i>	\$90.29	\$117.07
<i>ABD</i>	\$103.74	\$99.75
<i>ACD</i>	\$67.03	\$104.24
<i>ABCD</i>	\$97.65	\$160.53
MAX REVENUE FOR NSP <i>A</i>	\$103.74	\$160.53

Table 3-4 – Revenue Division

When a graph is made of all of the optimal solutions in the *x-y* plane with the *x*-axis score being the score on the *PI* objective and the *y*-axis score being the score on the *SV* objective, the graph is called the efficient frontier of tradeoff curve for the proposed division of revenue. Using the data in Table 3.4, the efficient frontier can be created to find the most preferred coalitions through the evaluation of the efficient points. All other points will be eliminated since they are considered to be dominated.

The most preferred coalition can now be chosen by using the standard *l-norms* (one, two, and infinity). This is in essence measuring the distance from the efficient point to the ideal point. The ideal point would be both the *PI* and *SV* values are at each of their maximum amount. In this case, the point (\$160.53, \$103.74) is the ideal point. Each norm represents a different approach by the DM to chose the most preferred coalition. The one-norm is known as the *totally compensatory*. It measures the distance from the ideal point given that criterion affects the distance. The infinity norm is known as the *totally non-compensatory*. It measures the distance from the ideal point given that only the criterion furthest from the ideal point affects the distance. Regret is the deviation between the ideal point and the efficient point that is being evaluated. Each norm has a different type of regret. The one-norm minimizes the sum of regrets, while the infinity-norm minimizes the “maximize” regret from the ideal.

Ideally, one efficient point would be best for both the one-, two-, and infinity-norm. If this were not the case, then the DM would have to decide whether they want to minimize or maximize their regrets and chose the most preferred coalition accordingly.

3.4 Coalition Network

Once the most likely coalition is chosen, the international telecommunication network can be illustrated with the data in Table 3.2. Each remaining country in the most preferred coalition is in itself a node representing a particular nation's NSP. The links themselves are the revenue that country *i* makes when they switch a telephone call to country *j*. There are theoretically two links between set of countries. This is only possible if there exists no circuits between country *i* and country *j*. For example, using Table 3.2 we can see that the

link from Country *A* to Country *B* is \$52.00 while the link from Country *B* to Country *A* is \$60.60. There is no source or sink. This is because we are not concerned with flow, but instead of revenue of the entire coalition and each country NSP.

3.5 Models

3.5.1 Model 1: Maximize f_I

Since $\mathbf{r}' = \mathbf{r} + \mathbf{I}$, let $f_I = R(\mathbf{r}')$. This single criteria problem maximizes the revenue of the preferred coalition. The linear formulation is illustrated below.

$$\begin{aligned}
 &\text{Max } f_I = R(\mathbf{r}') && (4) \\
 &\text{s.t.} \\
 &\mathbf{r}' \leq \mathbf{r} + \mathbf{I} \\
 &\sum_i \sum_j I_{ij} \leq B_{tot} \\
 &\mathbf{ct} = \mathbf{I}
 \end{aligned}$$

LINGO is an interactive computer-software package that can be used to solve linear and non-linear programming problems. It is written by LINDO Systems. A free evaluation copy can be downloaded at <http://www.lindo.com>. LINGO will be used to solve all of the models represented here within this thesis. LINGO model formulation and optimized output are available in the appendices.

It was assumed that differing amounts of incentive funds from DoD may be available. Funds can be usually thought of as strictly dollars. In reality, incentive funds can come in the form of international loans, wheat, or reduction in cost on military and economic aid. The model was optimized at different levels of B_{tot} . Obviously, when $B_{tot} = \$0$, the coalition's maximum revenue was the same as its initial revenue. The value of B_{tot} was

varied from \$0 to \$10,000.00. Since the value of the coalition's revenue is just the summation of all of the countries revenue, it is irrelevant at this point what country received an incentive from any of the other countries. There are multiple optimal solutions because no matter what part of the pot the incentive money goes into, it is all in the pot regardless.

3.5.2 Model 2: Maximize f_i without Hardening

We let $f_i = W$ where $\mathbf{r}'_i = \mathbf{r} - \mathbf{I}$. The optimal solution to this model will give the results from the maximization of coalition worth damage utility without hardening. The linear formulation to Model 2 is given:

$$\begin{aligned}
 & \text{Max } f_i = W_i & (5) \\
 & \text{s.t.} \\
 & W_i \leq R(\mathbf{r}'_i) \text{ (attack on NSP } i) \\
 & \mathbf{r}' \leq \mathbf{r} + \mathbf{I} \\
 & \sum_i \sum_j I_{ij} \leq B_{tot} \\
 & \mathbf{ct} = \mathbf{I}
 \end{aligned}$$

The coalition damage utility is based on gaming theory. This can be thought as of a two-player game where the players are Blue and Red. Blue owns the network and has the capability to improve the networks revenue worth with incentives. Red on the other hand plans to tamper with the network and inflict the maximum amount of damage by removing a country from the coalition. Blue must take into account Red's intentions when considering what incentives to give to what countries. This leads to Model 2 distributing its incentive over more countries.

This new thought process of Blue is a classic example of Game Theory. Red's goal is to attack the country that results in the maximum damage to the coalition worth when a

country is withdrawn from the coalition. The maximum damage is $R(\mathbf{r}') - R(\mathbf{r}'_i)$ where i is the country that Red convinced to withdraw from the coalition. This model was evaluated for various values of B_{tot} ranging from \$0 to \$10,000.

3.5.3 Model 3: Maximize f_1 with Hardening

In Model 2, Blue did not have the option to harden. Hardening can provide a more stable, robust network for DoD to send messages over. In Model 3, Blue has the option to harden. It is assumed that the more diplomatic effort Blue spends on country i , the harder it is for Red to convince country i to withdraw from the coalition.

Model 3's non-linear formulation is shown below.

$$\begin{aligned}
 \text{Max } f_1 &= W_1 & (6) \\
 \text{s.t.} & \\
 W_1 &\leq [R(\mathbf{r}'_i)][1-y] \\
 \mathbf{r}' &\leq \mathbf{r} + \mathbf{I} \\
 \sum_i \sum_j I_{ij} &\leq B_{tot} \\
 \mathbf{ct} &= \mathbf{I} \\
 \sum_i y_i &= 1
 \end{aligned}$$

It is also assumed that Red and Blue are repeatedly playing against each other; Blue trying to maximize revenue while Red is trying to maximize damage. If the game were to be played once, if Blue decides to harden country i , $y_i = 1$, all other y_j 's = 0. Likewise, if Red attacks country i , $z_i = 1$, all other z_j 's = 0. Gaming theory is formulated such that Blue must chose 1 of m strategies. Simultaneously, Red must chose one of n strategies [Winston, 1994:824] Since it is assumed that this game will be played repeatedly, y_i 's and z_i 's will no longer be 0-1 values. Instead they will be the percentage of times that Blue defends and Red

attacks country i . The damage utility of each hardening/attack strategy intersection can be shown in the Table 3.5. Each row denotes Blue's strategy to harden a particular country. Each column is Red's strategy to attack a particular country.

	A	B	C	D	E
A	$R(r')$	$R(r'_B)$	$R(r'_C)$	$R(r'_D)$	$R(r'_E)$
B	$R(r'_A)$	$R(r')$	$R(r'_C)$	$R(r'_D)$	$R(r'_E)$
C	$R(r'_A)$	$R(r'_B)$	$R(r')$	$R(r'_D)$	$R(r'_E)$
D	$R(r'_A)$	$R(r'_B)$	$R(r'_C)$	$R(r')$	$R(r'_E)$
E	$R(r'_A)$	$R(r'_B)$	$R(r'_C)$	$R(r'_D)$	$R(r')$

Table 3-5 –Game Theory Matrix

It is shown that in one round of the game, Blue hardens country i and red attacks country i , there is no damage to the revenue of the coalition. On the other hand, if Blue hardens country i and red attacks country j , there is some form of revenue damage. Each cell in the table is the expected payoff dependent on what country Blue defends and what country Red attacks. Over the life span of the game, the expected value to Blue is dependent on what strategy z Red attempts. The overall expected value to Blue is the sum of expected payoffs based on strategy y and strategy z . Obviously, Red will choose to tamper with the country that will result in the minimum payoff to Blue. Again, this model will be using a range of \$0 to \$10,000 for B_{tot} .

3.5.4 Model 4: Multi-Criteria with Hardening

The single-criteria models above were run to show how non-cooperative gaming and improvement goals can be handled simultaneously. Now that this is established, a multi-criteria optimization (MCO) model can be created. It is observed that the separate objective functions are linked by revenue between country i and country j and DoD's incentive budget.

The second objective function f_2 is the revenue that the U.S. NSP would receive from the coalition when the Shapley value is applied. This allows the DoD to show some level of loyalty to the U.S. NSP by giving a determined amount of preference to them.

$$\begin{aligned}
 & \text{Max } f_1 = W_1 & (7) \\
 & \text{Max } f_2 = W_2 \\
 & \text{s.t.} \\
 & W_2 \leq [S(\mathbf{r}')][\mathbf{y}] + [S(\mathbf{r}'_i)][1-\mathbf{y}] \\
 & W_1 \leq [R(\mathbf{r}'_i)][1-\mathbf{y}] \\
 & \mathbf{r}' \leq \mathbf{r} + \mathbf{I} \\
 & \sum_i \sum_j I_{ij} - \sum_j (I_{Aj} + I_{jA}) \leq B_R \\
 & \sum_j (I_{Aj} + I_{jA}) \leq B_S \\
 & B_R + B_S = B_{tot} \\
 & \mathbf{ct} = \mathbf{I} \\
 & \sum_i y_i = 1
 \end{aligned}$$

In a perfect world, both objective functions would be maximized. This usually is not the case though. Hence the objective of $\text{Max } f_2 = W_2$ is replaced with $f_2 = W_2 \geq s$.

$$\begin{aligned}
 & \text{Max } f_1 = W_1 & (8) \\
 & \text{s.t.} \\
 & f_2 = W_2 \geq s \\
 & W_2 \leq [S(\mathbf{r}')][\mathbf{y}] + [S(\mathbf{r}'_i)][1-\mathbf{y}] \\
 & W_1 \leq [R(\mathbf{r}'_i)][1-\mathbf{y}] \\
 & \mathbf{r}' \leq \mathbf{r} + \mathbf{I} \\
 & \sum_i \sum_j I_{ij} - \sum_j (I_{Aj} + I_{jA}) \leq B_R \\
 & \sum_j (I_{Aj} + I_{jA}) \leq B_S \\
 & B_R + B_S = B_{tot} \\
 & \mathbf{ct} = \mathbf{I} \\
 & \sum_i y_i = 1
 \end{aligned}$$

Now the problem can be solved using a constraint reduced feasible region approach. Model 4 will not find a single answer. Instead, it will find the maximum W_1 over the range

of s . Schavland [25:1999] shows that by parametrically varying the constant, s , from its largest value such that W_1 is at its maximum without the W_2 constraint – all the way to W_2 's maximum value, a frontier of non-inferior (efficient, non-dominated, Pareto-optimal) solutions may be found.

To ensure linear independence between the two objective functions, the orthogonality of the two objective vectors was investigated. It was concluded that the two objective functions are indeed linearly independent.

3.5.5 Model 5: Entire NSPs' Shapley Value with Hardening

Model 5 is a adaptation of Model 4. Instead of the criteria being the entire coalition's revenue and the US NSP's Shapley Value, there are n number of objectives. Each objective is to maximize the revenue of each NSP in the coalition.

$$\begin{aligned}
 & \text{Max } f_1 = W_1 & (9) \\
 & \text{s.t.} \\
 & f_k = W_k \geq s \\
 & W_k \leq [S(\mathbf{r}^*)][\mathbf{y}] + [S(\mathbf{r}'_i)][1-\mathbf{y}] \\
 & W_1 \leq [S(\mathbf{r}^*)][\mathbf{y}] + [S(\mathbf{r}'_i)][1-\mathbf{y}] \\
 & \mathbf{r}' \leq \mathbf{r} + \mathbf{I} \\
 & \sum_i \sum_j I_{ij} - \sum_j (I_{Aj} + I_{jA}) \leq B_R \\
 & \sum_j (I_{Aj} + I_{jA}) \leq B_S \\
 & B_R + B_S = B_{tot} \\
 & \mathbf{ct} = \mathbf{I} \\
 & \sum_i y_i = 1 \\
 & k = 1, 2, \dots
 \end{aligned}$$

This formulation models a coalition who jointly try to maximize their individual NSPs' Shapley Value within the coalition. There will be the same number, n , of objectives to maximize as there are NSPs within the coalition network. Now there is a cooperative

game played among the NSPs while a non-cooperative game is taking place between the entire coalition and an adversary.

LINGO can not easily handle more than two objective functions. It uses a multi-objective revised simplex method. To solve Model 5, ADBASE will be applied. ADBASE is a FORTRAN program for enumerating efficient extreme points and unbounded efficient edges. It was written by Dr. Ralph Steuer at the University of Georgia. A free evaluation copy was obtained for this thesis. ADBASE will be used to solve all of the Model 5 formulations represented here within this thesis. ADBASE model formulation and optimized output are available in the appendices.

3.6 Summary

This chapter discussed the methodology developed to predict a coalition that an NSP may choose to send a voice message and then to decide the vulnerability of that coalition's network and where any incentive to a country could be useful to serve the needs of DoD. An overview was provided to explain to the reader how the sections are inter-related. A section was devoted to a circuit switching telecommunication network. Coalition Determination section covered the methodology that will determine the best coalition within a global telecommunications network and how it is formulated.

In Chapter 4, Example Analysis on Sample Network, a set of test NSPs will be analyzed using gaming theory.

Chapter 4. Example Analysis on Sample NSPs

4.1 Determination of Sample Coalition

Three sample NSPs (AT&T, MCI, and Sprint) were used to test the proposed methodology. Each NSP was used separately to determine the most likely coalition that each NSP would join based on revenue.

Six additional country's NSPs were used as possible coalition members. The countries are Australia (*AU*), France (*FR*), Germany (*GE*), Japan (*JA*), United Kingdom (*UK*), and India (*IN*). Not only are the countries major NSPs in the international market, adequate data is available to properly analyze the traffic in MiTT, retail cost per minute, and accounting rates. Using these six countries and the appropriate U.S. NSP in the models, there are 63 possible coalitions that the U.S. NSP may prefer to be a member. This was calculated using the sum of the number of combinations of six objects taken r ($r = 1 \dots 6$) times. The proposed methodology will be demonstrated with the U.S. NSP of AT&T.

4.1.1 NSP's Investment

NTI was used to determine the number of transit exchanges and earth stations that each NSP owns. This, in addition to each coalition's worth, was used to determine the most likely coalition that an U.S. NSP would join based on their proportional investment (*PI*). The number of transit exchange and earth stations are illustrated in Table 4.1.

NSP	# OF EARTH STATIONS	# OF SWITCHING STATIONS
<i>ATT</i>	10	10
<i>AU</i>	7	9
<i>FR</i>	12	9
<i>GE</i>	18	7
<i>JA</i>	11	12
<i>UK</i>	12	8
<i>IN</i>	4	4

Table 4-1 – Number of Stations of Sample Network

4.1.2 NSPs' Revenue

Using TeleGeography's 1996 data on MiTT, retail cost, and accounting rates, a revenue table from country *i* to country *j* was developed for AT&T in Table 4.2.

NSP	<i>ATT</i>	<i>AU</i>	<i>FR</i>	<i>GE</i>	<i>JA</i>	<i>UK</i>	<i>IN</i>
<i>ATT</i>	-	\$107.85	\$115.96	\$209.73	\$238.67	\$396.96	\$.78
<i>AU</i>	\$75.13	-	\$.12	\$28.08	\$42.29	\$155.16	\$.18
<i>FR</i>	\$33.44	\$.09	-	\$116.37	\$7.19	\$110.46	\$2.11
<i>GE</i>	\$107.95	\$.11	\$165.51	-	\$14.18	\$164.22	\$.18
<i>JA</i>	\$226.20	\$66.45	\$35.09	\$43.26	-	\$80.13	\$2.56
<i>UK</i>	\$138.83	\$108.67	\$130.33	\$139.76	\$35.07	-	\$97.13
<i>IN</i>	\$125.44	\$9.80	\$132.31	\$23.10	\$9.70	\$44.63	-

Table 4-2 – Revenue from Country *i* to Country *j* per Call of Sample Network

Table 4.2 helps to illustrate the political and geographical relationships between countries and their international telephone networks. Looking at India's column, its revenue is fairly low except with the United Kingdom. This may be because India was at one time a colony of the United Kingdom. Similarly, Australia has a higher revenue with the United Kingdom. Geographically, Australia also has higher revenue with Japan possibly due to their proximity to each other in Asia.

4.1.3 Coalition Worth

Table 4.2 was then used to determine the coalition's worth. Table 4.3 gives the value to a sample of the possible 61 coalitions that AT&T may consider to be a member.

COALITION	WORTH
<i>ATT-AU</i>	\$182.98
<i>ATT-FR</i>	\$149.39
<i>ATT-FR-IN</i>	\$410.04
<i>ATT-JA-IN</i>	\$603.34
<i>ATT-AU-FR-GE</i>	\$960.32
<i>ATT-AU-FR-JA</i>	\$948.48
<i>ATT-AU-FR-UK</i>	\$1,372.99
<i>ATT-FR-GE-JA-IN</i>	\$1,609.70
<i>ATT-FR-GE-UK-IN</i>	\$2,255.18
<i>ATT-FR-JA-UK-IN</i>	\$1,962.99
<i>ATT-GE-JA-UK-IN</i>	\$2,098.46
<i>ATT-AU-FR-GE-JA-IN</i>	\$1,939.80
<i>ATT-AU-GE-JA-UK-IN</i>	\$2,857.68
<i>ATT-AU-FR-GE-UK-IN</i>	\$2,740.36
<i>ATT-AU-FR-GE-JA-UK-IN</i>	\$3,541.15

Table 4-3 – Coalitions' Worth of Sample Network

It is obvious that unless there is a negative revenue from country *i* to country *j*, the coalition with the maximize revenue would be the largest coalition.

4.1.4 Division's of Revenue

The revenue that AT&T can achieve from each coalition can now be computed. Table 4.1 and 4.3 will be used to determine the Proportional Investment (*PI*) that AT&T will receive, where as Table 4.2 will determine AT&T's revenue per coalition using the Shapely Value (*SV*) formula. AT&T's revenue per coalition is listed in Table 4.4. Once again, only a sample of the coalitions are shown.

REVENUE FOR ATT	<i>PI</i>	<i>SV</i>
<i>ATT-AU</i>	\$101.66	\$91.49
<i>ATT-FR</i>	\$72.87	\$74.70
<i>ATT-FR-IN</i>	\$167.36	\$137.81
<i>ATT-JA-IN</i>	\$236.61	\$295.55
<i>ATT-AU-FR-GE</i>	\$234.22	\$325.02
<i>ATT-AU-FR-JA</i>	\$237.12	\$398.62
<i>ATT-AU-FR-UK</i>	\$356.62	\$434.08
<i>ATT-FR-GE-JA-IN</i>	\$279.95	\$529.08
<i>ATT-FR-GE-UK-IN</i>	\$479.83	\$564.54
<i>ATT-FR-JA-UK-IN</i>	\$426.74	\$638.14
<i>ATT-GE-JA-UK-IN</i>	\$437.18	\$722.18
<i>ATT-AU-FR-GE-JA-IN</i>	\$343.33	\$620.57
<i>ATT-AU-GE-JA-UK-IN</i>	\$510.30	\$813.77
<i>ATT-AU-FR-GE-UK-IN</i>	\$498.25	\$656.03
<i>ATT-AU-FR-GE-JA-UK-IN</i>	\$532.50	\$888.47

Table 4-4 - Revenue Division of Sample Network

In this case, no multi-criteria methods need to be applied. The best coalition for AT&T to become a member of based on revenue is *ATT-AU-FR-GE-JA-UK-IN*. This is because the maximum revenue for AT&T based on both *PI* and *SV* is from the largest coalition. This does not imply that we should always pick the largest coalition. Nor does it imply that that the same coalition is the most preferred for the Proportional and Shapley Value division of revenues. This output is unique to this U.S. NSP and the other international NSPs that were chosen to evaluate this model. Other runs on different U.S. NSPs reinforces that any of these possible coalitions are possible candidates.

The ideal point would be at the point that both the *PI* and *SV* revenue were maximized. In this case, it would be the point (\$532.50, \$888.47). All the other points are dominated by this ideal point; thus, the *l-norm* does not need to be investigated. This is a unique situation. It is not always guaranteed that the largest coalition will always be the most

preferred. Nor would the *PI* and *SV* methods always choose the same coalition as the most financially preferred.

4.2 ATT-AU-FR-GE-JA-UK-IN Sample Network

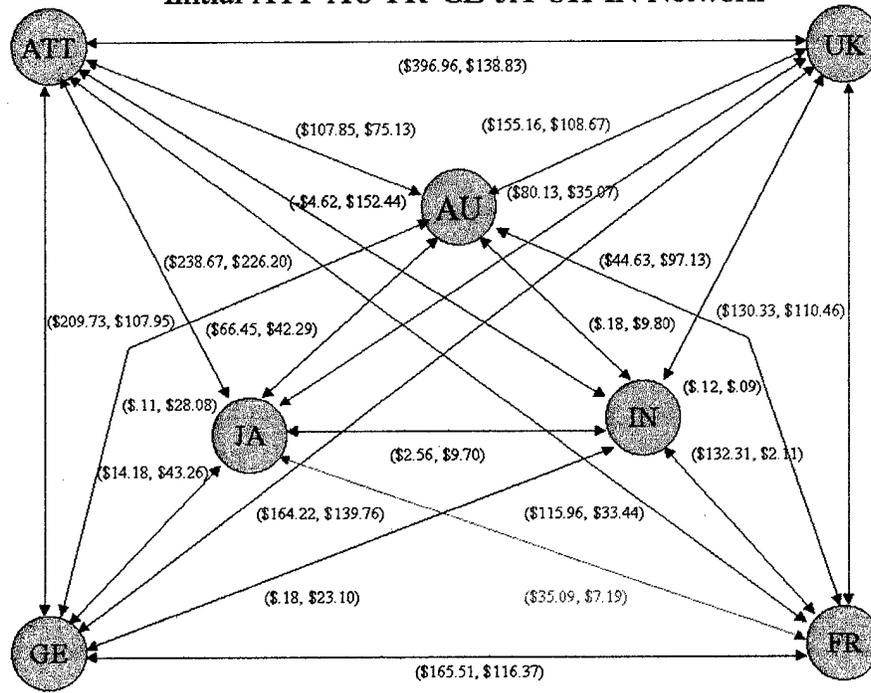
Now that the most preferred coalition is chosen, it can be represented graphically. This is illustrated in Figure 4-1. Using the data in Table 4.2, the coalition can be expressed as a network. Each arc is the revenue made for country *i* by sending traffic to country *j*. The arcs are multi-directional to account for the revenue made from country *j* to country *i*.

Each arc represents the revenue made from traffic that originated from country *i* and terminates in country *j*. The data supplied by TeleGeography is based solely on where the traffic originated from and its final destination. Since it does not take into account that the call made have been routed through another country's NSP, this network is not a strictly physical network.

4.3 Application of Single-Criteria Models to Sample Network

Models 1-3 above were applied to the sample network derived for AT&T. LINGO was used for all calculations. LINGO was well adapted for these purposes since it solves both linear and non-linear mathematical problems. The appendices show that the LINGO input files are linear for Models 1-2, but becomes non-linear for Models 3-4. This is due to the ability to harden in Models 3-4.

Initial ATT-AU-FR-GE-JA-UK-IN Network



ATT	AT&T
FR	France
GE	Germany
JA	Japan
UK	United Kingdom
IN	India
AU	Australia
(x, y)	(revenue from country <i>i</i> to country <i>j</i> , revenue from country <i>j</i> to country <i>i</i>)
↔	OD link between country <i>i</i> and country <i>j</i>

Figure 4-1 – Graphic Representation of Telecommunication Network

All input files for Models 1-4 are included in the appendix. All formats are in LINGO and should be self-explanatory in nature.

Each model allocated its incentive resources differently. Maximizing the coalition revenue (Model 1) is not the same as maximizing the coalition's revenue after a worst case node tampering (Model 2). In Model 1, all resources (\$10) were allocated to one arc, India to Australia. In reality, the incentive could have been allocated anywhere within the coalition since the only concern is to maximize the coalition. In Model 2, where a NSP may be convinced to withdraw from the coalition, the incentive of \$10 is best spent on the arc AT&T to India. This enforces that neither AT&T or India is a NSP that the adversary would have high interest to convince to withdraw from the coalition.

The artificial break point is when the budget to spend on incentive is over \$1000 for Model 2. This spreads the incentive out over multiple arcs. This is in anticipation of a NSP being removed from the coalition. This makes it harder for the adversary to determine where to tamper. Both Model 1 and 2 give a global optimal answer.

Model 3 allows the capability to harden as well as giving incentives to selected NSPs. Hardening could be the physical act of improving a network, or it could be diplomatic efforts to convince a NSP to be faithful to the coalition and be a strong member. All of the \$10 incentive should be spent on the arc India to Australia because the adversary has no desire to try and remove these NSPs from the network. Thus, there is no financial risk of losing the incentive added to the coalition's revenue. This is shown in Table 4.5 with the z_i column why the India to Australia arc was chosen.

	y_i	z_i
<i>ATT</i>		
<i>AU</i>		
<i>FR</i>	.13	.29
<i>GE</i>	.27	.24
<i>JA</i>	.06	.31
<i>UK</i>	.54	.16
<i>IN</i>		

Table 4-5 – Decision Variables at $B_{tot} = \$100$

It is assumed that the U.S. NSP, AT&T in this example, is loyal to the DoD's cause, so there will be no hardening or tampering with that node. The adversaries attack strategy, z_i , is derived from the dual of the model. They indicate the most likely places where the adversary will tamper. It can be shown that the dual of the DoD's maximization of revenue model is the adversary's minimization of the revenue model. Both the DoD and adversary's models have an optimal solution W_i . Thus, using the Dual Theorem, the DoD's maximization of revenue equals the adversary's minimization of revenue. Complementary slackness is used to simultaneously solve the DoD and adversary's model. There is a stable equilibrium because neither the DoD and the adversary can improve their situation by a unilateral change in strategy. The z_i column shows that the adversary has no interest in tampering with India or Australia, so it is logical that the *IN-AU* arc would be the best place to expend the incentive since there is little financial risk involved with losing that arc.

Similarly, y_i is the DoD's hardening strategy. It is derived from the game-theoretic decision-variable denoting the percentage of hardening effort at country i . A majority of the hardening, 54%, would be expended on the United Kingdom to maximize the coalitions revenue. The logic of this can be derived from the coalition network, besides AT&T, there are no other NSPs whose arcs contribute as much revenue as the United Kingdoms. Thus, it

is natural that the most effort should be spent on the United Kingdom to stay in the coalition. Likewise, 27% of the effort should be spent on Germany due to their next highest revenue contribution to the coalition.

The amount of incentive determines the amount of hardening for each NSP. Figure 4.2 shows how the recommended hardening percentage changes for the United Kingdom as the budget is increased.

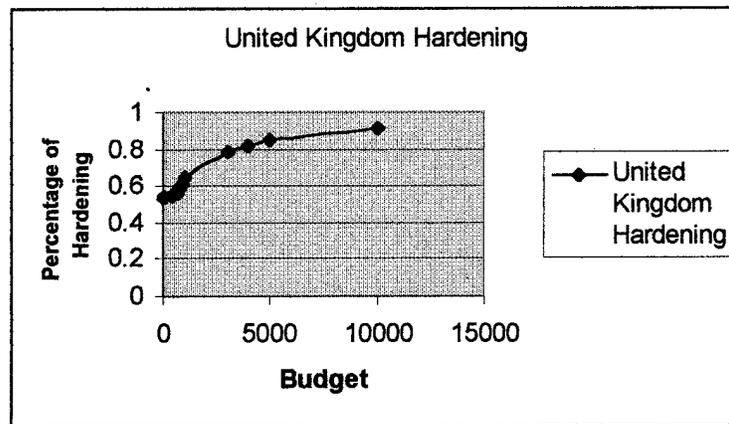


Figure 4-2 – Relationship between UK Hardening and Budget

Although the incentive money is given to over six arcs, the percentage of hardening for the United Kingdom NSP continuously goes up. This is of interest if the DoD wanted to maximize its hardening effort. Any amount of incentive over \$10 to the coalition ensures that a majority of the hardening will be placed on one NSP, the United Kingdom. Since these models are discrete in nature and specific to each individual network, there are no error probabilities.

4.4 Application of Multi-Criteria Model to Sample Network

Model 4 is an adaptation of Model 3. Besides the addition of a second objective function, an additional constraint is added to model. The constraint is $B_R + B_S = B_{tot}$. This will allow the DoD to determine the division of funds to the coalition versus AT&T to ensure that the coalition revenue is maximized subject to AT&T receiving their share of revenue.

Model 4 was investigated with the $B_{tot} = \$100$. To determine the range of s , the model was changed to maximize f_1 only. This provided the lower bound on s . Then the model was changed to maximize f_2 without regards to f_1 . This determined the upper bound on s . Any value larger than the upper bound resulted in an unfeasible solution for Model 4. Then analysis was conducted to find the value of f_1 over the range of s . Figure 4.3 shows the relationship between the coalition revenue worth and AT&T's Shapley revenue worth.

The DM has several choices at this point. They may chose to maximize the coalition's revenue. If that is the case, the coalition would make \$2898. AT&T would earn \$722 of that revenue. On the other hand, DoD may want to maximize AT&T's revenue to exhibit patriotism. This would maximize AT&T's revenue with \$798 out of the \$2751 that the coalition would earn. The value of the coalition's revenue went down since the optimum strategy of where to spend the incentive could not be applied. This was to ensure that AT&T's revenue was maximized first, then the coalition worth was maximized. Each case has it's own specific hardening strategy to ensure that these values are met.

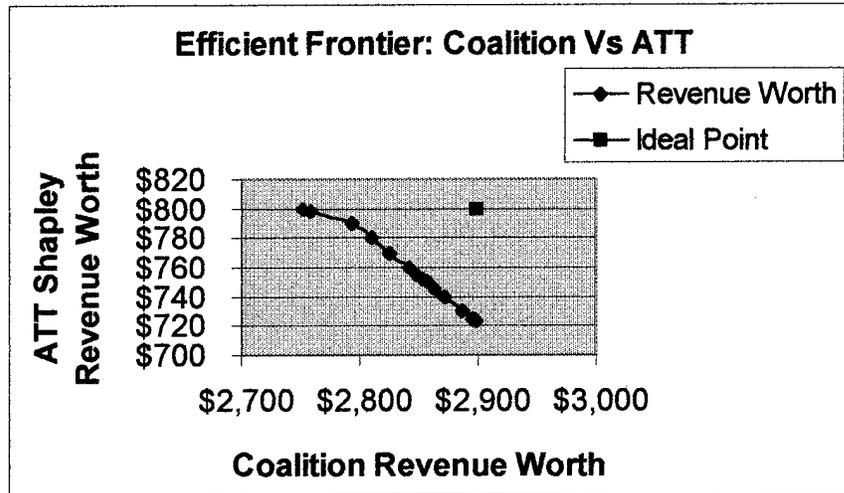


Figure 4-3 – Tradeoff Between ATT and Coalition Revenue Worth

Compromise programming can be applied to the efficient frontier if no satisfactory solution exists [Chan, 1999:5-13]. In this case, the ideal point ($\max f_1 | f_2 > 0, \max f_1 | f_2 > 0$) is not achievable. The distance from the ideal point is a function of the metric parameter, the deviation metric. The Manhattan and Euclidean deviation metrics can be accommodated with the L_p -norm. The norm assumes the function:

$$L_p = y' - y'^*_{p,w} = \left[\sum_i w_i^p |y'_i - y_i'^*|^p \right]^{1/p} \quad (10)$$

w^p = range of weights

p = metric parameter, $p \in (\{1, 2, \dots\} \cup \{\infty\})$

It is assumed that $w'_i = 1$ for all i 's unless otherwise specified. The L_1 or Manhattan metric is a *totally compensatory* tradeoff altitude by the DM. The DM treats the contributions of each criterion equally. The L_2 or Euclidean is based on its geometric properties. The L_∞ or Tchebycheff metric corresponds to a *totally non-compensatory*

tradeoff. The DM wants to minimize their maximum deviation from the ideal. It can simply be expressed as $\max_i (w'_i d'_i)$. The results of the *l-norms* on the sample network are summarized in Figure 4.4.

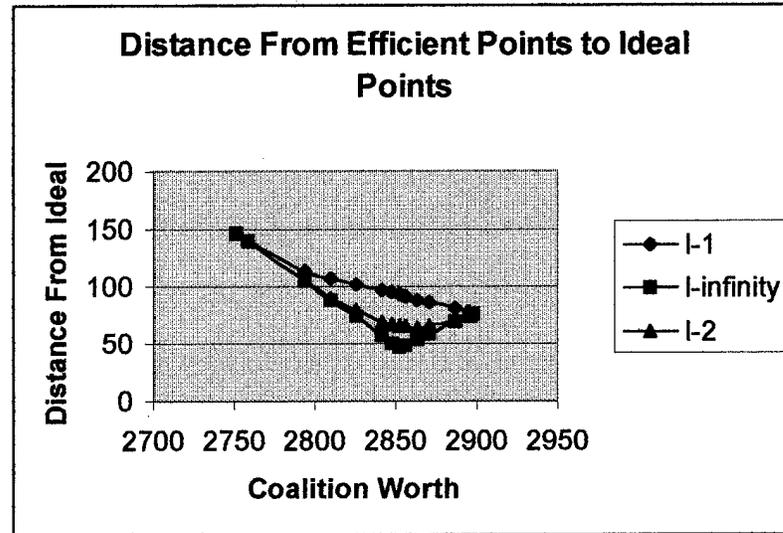


Figure 4-4 – Sample Network *l-Norm* Distances

The most preferred points for each *l-norm* are listed in Table 4.6.

<i>l-norm</i>	f_1 – Coalition Revenue	f_2 – AT&T Revenue
L_1	\$2898	\$723
L_2	\$2864	\$745
L_∞	\$2853	\$752

Table 4-6 – Preferred Efficient Points for Each *l-Norm*

The most obvious preferred efficient point to select graphically is for L_1 . Since this *l-norm* chooses the best efficient point based on the criteria's contributions, it is natural that this point would maximize the coalition revenue worth. This is because the entire coalition

contributes more to the model than just AT&T alone. Both L_2 and L_∞ picked an efficient point between the maximum of the coalition and AT&T's revenue worth. Table 4.7 summarizes the hardening strategy that the DM should accept given that they chose a *totally non-compensatory* tradeoff.

	y_i	z_i
<i>ATT</i>		
<i>AU</i>		
<i>FR</i>	.07	.42
<i>GE</i>	.22	.35
<i>JA</i>	.20	
<i>UK</i>	.51	.23
<i>IN</i>		

Table 4-7 – Decision Variables at $B_{tot} = \$100$ and L_∞

Figure 4-5 shows the results from Model 4 with the budget set at \$100 and using the L_1 norm. Between the two objective functions, it is shown that all of the incentive is spent on the AT&T – Australia arc. Since the adversary has no interest in tampering with these arcs, it is the natural choice to guarantee that the incentive spent will not be tampered with. The United Kingdom gets a majority of the hardening since it becomes the natural target of exploitation. Australia and India get no hardening.

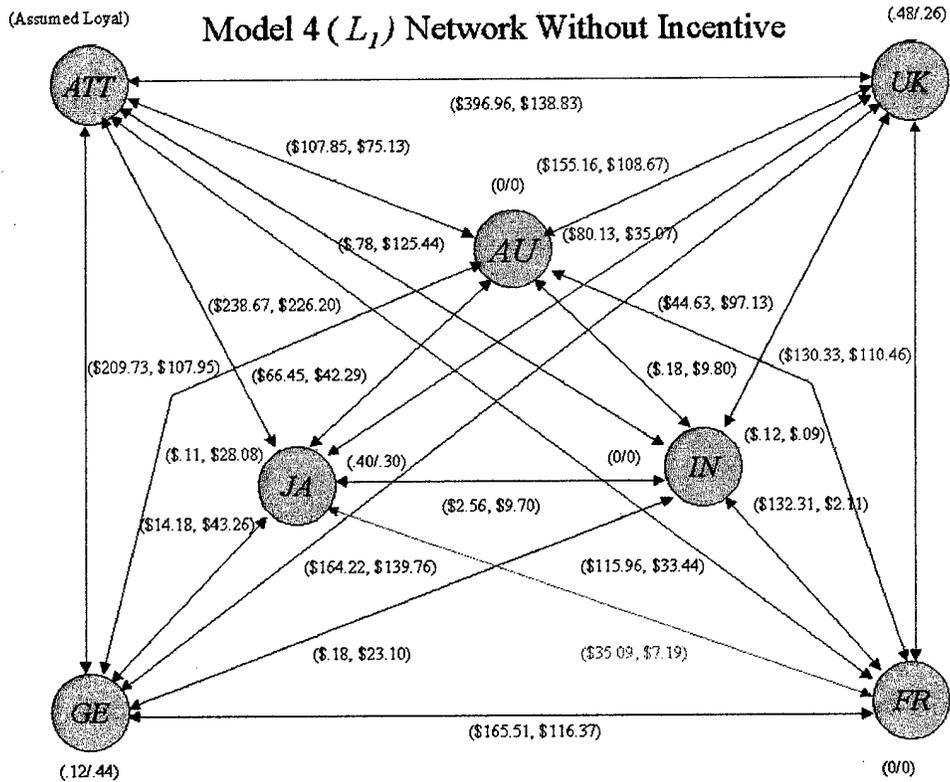


Figure 4-6 – Results from Model 4 (L_1) without Incentive

An incentive is not needed to run Model 4. The results will still provide a hardening as well as a tampering strategy that will be helpful in the defense of the coalition. Figure 4-6 represents these results. The similarities can be seen with Model 4 with and without an incentive.

Model 5 was to be ran using ADBASE. Unfortunately, ADBASE is not “user friendly.” It is difficult and very easy to set up the data files. In addition, the documentation was not clear or unavailable. It was not possible to run the seven objective game in ADBASE.

It was possible though to run all possible pairs of NSPs in LINGO to maximizes their Shapley Value worth’s. After the models were ran and the data analyzed, the distance of efficient frontier to the ideal solution were calculated.

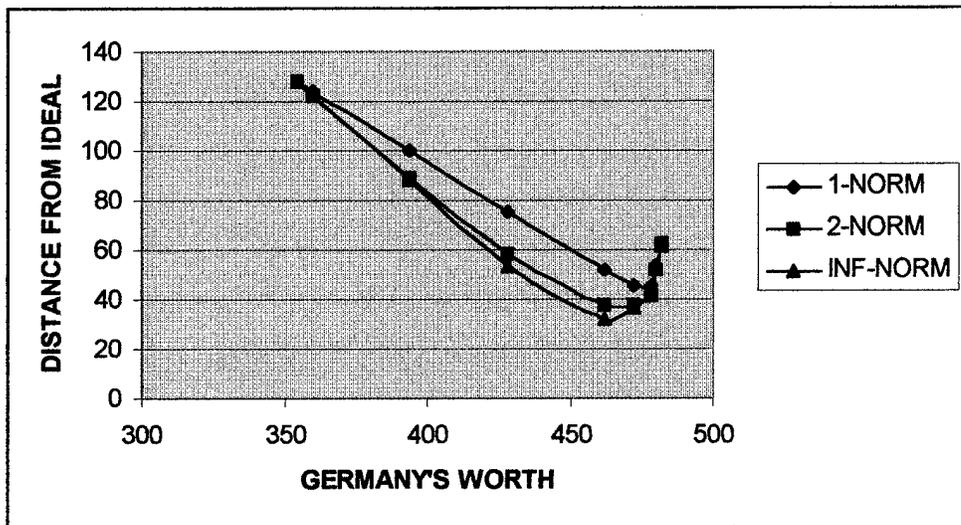


Figure 4-7 – Germany-U.K Distance from Ideal

In most case as in Figure 4-7, The L_2 and L_∞ had the same Shapley Value worth. Unfortunately, the L_1 was at a different value for each case. This observation only applies towards each set two NSPs. This observation was based on what set of NSPs were chosen to analyze. When the NSPs had a significant difference in the revenue that they provided, the L_1 was never the same as the L_2 and L_∞ . On the other hand, when the revenue was of each NSP had a smaller difference, the L_1 was closer to the L_2 and L_∞ if not the same value. Since

the L_1 is based on the contribution of the criterion, the closer the two NSPs are in value, the closer they will be to the L_2 and L_∞ . No conclusions could be made about sets of NSPs greater than three that want to all maximize their Shapley Value worth.

Even though a steady equilibrium of l-norms could not be reached, Model 5 does provide a hardening strategy, as well as a tampering strategy that can be used to form a stronger coalition where all NSPs cooperated among each other. This is of use not only to DoD, but also to the coalition regardless or not DoD has an incentive budget.

4.5 Value of Model without Revenue Improvement

It is not necessary for DoD to provide an incentive described in this modeling approach. It may also be that the DoD does not have or want to spend a large amount of money a coalition network. If this is the case, the DoD can still use the model to help determine the best hardening strategy without running the incentive portion of the model. Schavland represents this as a "descriptive" application of the models formulation. The results will not only give an optimal hardening strategy be given, but a optimal tampering strategy as well. The optimal tampering strategy is the shadow prices or dual variables at optimality.

Model 4 can be reduced to linear in nature compared to when it was non-linear with the budget. If the budget is set to \$0.0, then model four is as follows:

$$\begin{aligned}
& \text{Max } f_1 = W_1 && (11) \\
& \text{s.t.} \\
& f_2 = W_2 \geq s \\
& W_2 \leq [S(\mathbf{r}')][\mathbf{y}] + [S(\mathbf{r}'_i)][1-\mathbf{y}] \\
& W_1 \leq [R(\mathbf{r}'_i)][1-\mathbf{y}] \\
& \mathbf{r}' \leq \mathbf{r} + \mathbf{I} \\
& \sum_i \sum_j I_{ij} - \sum_j (I_{Aj} + I_{jA}) \leq B_R \\
& \sum_j (I_{Aj} + I_{jA}) \leq B_S \\
& B_R + B_S = \$0.0 \\
& \mathbf{ct} = \mathbf{I} \\
& \sum_i y_i = 1
\end{aligned}$$

With B_{tot} being equal to \$0.0 and B_R and B_S having to be positive because they are budgets, this implies that B_R and B_S are also equal to \$0.0. This reduces the model another step.

$$\begin{aligned}
& \text{Max } f_1 = W_1 && (12) \\
& \text{s.t.} \\
& f_2 = W_2 \geq s \\
& W_2 \leq [S(\mathbf{r}')][\mathbf{y}] + [S(\mathbf{r}'_i)][1-\mathbf{y}] \\
& W_1 \leq [R(\mathbf{r}'_i)][1-\mathbf{y}] \\
& \mathbf{r}' \leq \mathbf{r} + \mathbf{I} \\
& \sum_i \sum_j I_{ij} - \sum_j (I_{Aj} + I_{jA}) \leq \$0.0 \\
& \sum_j (I_{Aj} + I_{jA}) \leq \$0.0 \\
& \mathbf{ct} = \mathbf{I} \\
& \sum_i y_i = 1
\end{aligned}$$

Using the same logic with the incentive having to be positive but less than or equal to \$0.0, then it is implied that the incentive \mathbf{I} , is also \$0.0.

$$\begin{aligned}
& \text{Max } f_1 = W_1 && (13) \\
& \text{s.t.} \\
& f_2 = W_2 \geq s \\
& W_2 \leq [S(\mathbf{r}')][y] + [S(\mathbf{r}'_i)][1-y] \\
& W_1 \leq [R(\mathbf{r}'_i)][1-y] \\
& \mathbf{r}' \leq \mathbf{r} + \$0.0 \\
& \mathbf{ct} = \$0.0 \\
& \sum_i y_i = 1
\end{aligned}$$

If the traffic, t , is positive and \mathbf{ct} equals $\$0.0$, then \mathbf{c} must equal 0. Likewise, since \mathbf{r}' is the vector \mathbf{r} with incentive, then \mathbf{r}' must now equal \mathbf{r} since there is no incentive. The \mathbf{r} vector is just the revenue values from Table 4.2 instead of revenue as a function of \mathbf{I} .

$$\begin{aligned}
& \text{Max } f_1 = W_1 && (14) \\
& \text{s.t.} \\
& f_2 = W_2 \geq s \\
& W_2 \leq [S(\mathbf{r})][y] + [S(\mathbf{r}_i)][1-y] \\
& W_1 \leq [R(\mathbf{r}_i)][1-y] \\
& \sum_i y_i = 1
\end{aligned}$$

This model can be derived yet another way. Table 4-8 list the revenue of the entire coalition depending on what strategies DoD and the adversary uses. The diagonal cells $a_{i,i}$ are the coalition's revenue if DoD hardens NSP i and the adversary attacks NSP i . The cells $a_{i,j}$ are the revenue of the coalition if DoD hardens NSP i and the adversary attacks NSP j . Sample coalition revenues are given for the likely hood that either France, Japan, or the United Kingdom is attacked.

NSP	ATT	AU	FR	GE	JA	UK	IN
ATT	\$3,541.15		\$2,857.68		\$2,740.36	\$1,939.80	
AU		\$3,541.15	\$2,857.68		\$2,740.36	\$1,939.80	
FR			\$3,541.15		\$2,740.36	\$1,939.80	
GE			\$2,857.68	\$3,541.15	\$2,740.36	\$1,939.80	
JA			\$2,857.68		\$3,541.15	\$1,939.80	
UK			\$2,857.68		\$2,740.36	\$3,541.15	
IN			\$2,857.68		\$2,740.36	\$1,939.80	\$3,541.15

Table 4-8 – Coalition Revenue

Using linear programming to model optimal revenue for the coalition given there is an adversary attacking, the following formulation is derived:

$$\begin{aligned}
 & \text{Max } f_i = W_I && (15) \\
 & \text{s.t.} \\
 & W_I \leq \sum_i a_{i,j} y_i \\
 & \sum_i y_i = 1
 \end{aligned}$$

The same procedure can be applied for each NSP's Shapley Value. The diagonals would be the optimal revenue for each NSP based on the Shapley Value and no adversary. The other cells would be the revenue after an adversary successfully attacks a NSP. These models still allows for the objective values and hardening strategy. Both models without revenue improvement was analyzed to determine the best hardening and tampering strategy. Both models gave the same optimal solutions based on the same data in all cases. Table 4.9 lists the results. Besides giving a hardening strategy, these models also gave a globally optimal solution.

	y_i	z_i
<i>ATT</i>		
<i>AU</i>		
<i>FR</i>	.08	.42
<i>GE</i>	.23	.35
<i>JA</i>	.17	
<i>UK</i>	.51	.23
<i>IN</i>		

Table 4-9 - Decision Variables at L_2

Subsidy is not a necessity of the models in effecting a secure coalition. It is assumed that the defensive measure actually comes from the diplomatic efforts of DoD to keep all NSPs in the coalition. Unless the DoD specifies where the incentive money is to be

spent, the incentive is just a catalyst to help determine where and how much the DoD should spend its diplomatic effort.

Figure 4.2 illustrates this methodology. If the DoD has a historical advantage to use its diplomatic effort with an U.K. NSP, they can determine how much incentive they want to spend on the coalition. Any amount over \$5000 will guarantee a majority of the hardening with the U.K. NSP. In addition, whether they spend \$5000 or \$10000 on incentive, there is not a significant amount of change in the diplomatic effort that should be applied. This puts bounds on the amount of money that the DoD should optimally spend.

4.6 Optimality

Both Model 1 and 2 provided an global optimal solution based on LINGO's optimality determination function. This was not the case with Model 3 and 4. LINGO indicates when a solution is either a global or a local optimal solution. LINGO indicated that both Model 3 and 4 do not yield globally optimal solutions, but instead locally optimal. This indicates that the solution given by LINGO may not be the global optimal. A local optimum can possibly be the global optimal, but this would have to be investigated in all cases where the solution was deemed local optimal.

The Hessian of the objective functions was calculated to check for concavity and convexity. When the k th leading principle minors were analyzed, it was concluded that the objective functions are indeed neither concave nor convex.

Since the objective function is not convex, other optimal points had to be explored. This is common in LINGO when a model is non-linear. LINGO lets the modeler give initial values, guesses, in their INIT section to try to find other optimal points. When this was

applied, no other optimal points were found, suggesting that the optimum solution is indeed a global optimum.

When Models 4-5 had their incentives set to \$0.0, the models could be reduced to a linear format. When these formats were ran in LINGO, they provided a global optimum with the exact solutions as the non-linear models when the budget was set to \$0.0. This further reinforces that the answers given with the non-linear problems are more than likely global optimums.

Chapter 5. Conclusions and Recommendations

5.1 Summary

This thesis proposed a new, game-theoretic, revenue criterion, for coalition's revenue improvement and security. This methodology was demonstrated in a multi-criteria optimization model. The model was applied to a network derived from collected 1996 telecommunications data.

5.2 Conclusions

- The option to harden NSPs has measurable value whether or not an incentive is provided for the coalition.
- The adversary's tampering strategy is revealed in the *shadow prices* associated with the game constraints.
- The two objective functions, f_1 and f_2 , are different measures of effectiveness. A network optimized for one objective is more than likely not optimized for the other objective.
- Minimal DM participation is needed to obtain these results.
- There is no one "best" answer. There is only the most preferred answer that best meets the DM's needs.
- The L_2 and L_∞ had the same Shapley Value worth for Model 5.

5.3 Future Work

- This thesis assumed that there are adversaries outside of the coalition. This methodology can be inspected to see if a n -person zero sum game approach can be applied to Model 3 and 4. The players would be the NSPs. This may be of use to a NSP as a way to determine the best approach to compete financially with other NSPs within the international telecommunication community.
- Build upon this methodology to build a path prediction model. The data used in this thesis was the traffic switched from origin to the final destination. Investigation of whether data that shows the traffic from country i to country j regardless whether or not it is rerouted can be of great use. It may be combined with the coalition determination, cooperative gaming theory of this thesis to try to predict the NSPs that a voice communication may travel. A possibility could be to look at the trade balance of one country to another and try to predict what links may need more traffic to even out the trade of calls. The model could be ran at different time intervals. These outputs could be statistically investigated to try to determine the physical path that a voice message may travel.
- Apply a multi-objective revised simplex method such as ADBASE to Model 5 and analyze the output.

APPENDICES

Appendix 1 – LINGO Input Files for Sample Network

```
! MODEL 1 INPUT;
! MAX F1;
! ATT-AU-FR-GE-JA-UK-IN;
! Btot = 100;

MAX = F1;

W=F1;

! COALITION MAX WORTH;
W=rTF+rFT+rTG+rGT+rTJ+rJT+rTU+rUT+rTI+rIT+rFG+rGF+rFJ+rJF+rFU+rUF+
rFI+rIF+rGJ+rJG+rGU+rUG+rGI+rIG+rJU+rUJ+rJI+rIJ+rUI+rIU+rAT+rTA+
rAF+rFA+rAG+rGA+rAJ+rJA+rAU+rUA+rAI+rIA;

! REVENUE CONSTARINTS;
rTF<=115.96+ITF;
rFT<=33.44+IFT;
rTG<=209.73+ITG;
rGT<=107.95+IGT;
rTJ<=238.67+ITJ;
rJT<=226.20+IJT;
rTU<=396.96+ITU;
rUT<=138.83+IUT;
rTI<=.78+ITI;
rIT<=125.44+IIT;
rFG<=116.37+IFG;
rGF<=165.51+IGF;
rFJ<=7.19+IFJ;
rJF<=35.09+IJF;
rFU<=110.46+IFU;
rUF<=130.33+IUF;
rFI<=2.11+IFI;
rIF<=132.31+IIF;
rGJ<=14.18+IGJ;
rJG<=43.26+IJG;
rGU<=164.22+IGU;
rUG<=139.76+IUG;
```

$rGI \leq .18 + IGI;$
 $rIG \leq 23.10 + IIG;$
 $rJU \leq 80.13 + IJU;$
 $rUJ \leq 35.07 + IUJ;$
 $rJI \leq 2.56 + IJI;$
 $rIJ \leq 9.70 + IIJ;$
 $rUI \leq 97.13 + IUI;$
 $rIU \leq 44.63 + IIU;$
 $rAT \leq 75.13 + IAT;$
 $rTA \leq 107.85 + ITA;$
 $rAF \leq .12 + IAF;$
 $rFA \leq .09 + IFA;$
 $rAG \leq 28.08 + IAG;$
 $rGA \leq .11 + IGA;$
 $rAJ \leq 42.29 + IAJ;$
 $rJA \leq 66.45 + IJA;$
 $rAU \leq 155.16 + IAU;$
 $rUA \leq 108.67 + IUA;$
 $rAI \leq .18 + IAI;$
 $rIA \leq 9.80 + IIA;$

! INCENTIVE REVENUE;

$ITF = 87.86 * cTF;$
 $IFT = 82.72 * cFT;$
 $ITG = 168.81 * cTG;$
 $IGT = 157.62 * cGT;$
 $ITJ = 154.6 * cTJ;$
 $IJT = 186.1 * cJT;$
 $ITU = 370.58 * cTU;$
 $IUT = 332.89 * cUT;$
 $ITI = 109.12 * cTI;$
 $IIT = 22.69 * cIT;$
 $IFG = 325.9 * cFG;$
 $IGF = 389.8 * cGF;$
 $IFJ = .1 * cFJ;$
 $IJF = 21 * cJF;$
 $IFU = 317.7 * cFU;$
 $IUF = 360.8 * cUF;$
 $IFI = .1 * cFI;$
 $IIF = 5.8 * cIF;$
 $IGJ = .1 * cGJ;$
 $IJG = 25.9 * cJG;$
 $IGU = 365.1 * cGU;$

IUG=364.4*cUG;
 IGI=.1*cGI;
 IIG=13.2*cIG;
 IJU=48*cJU;
 IUJ=.1*cUJ;
 IJI=.1*cJI;
 IJJ=6.9*cIJ;
 IUI=55.5*cUI;
 IIU=25.5*cIU;
 IAT=85.67*cAT;
 ITA=68.04*cTA;
 IAF=.1*cAF;
 IFA=.1*cFA;
 IAG=24*cAG;
 IGA=.1*cGA;
 IAJ=34*cAJ;
 IJA=33.4*cJA;
 IAU=182*cAU;
 IUA=127.3*cUA;
 IAI=.1*cAI;
 IIA=5.6*cIA;

! BUDGET CONSTRAINTS;

87.86*cTF+82.72*cFT+168.81*cTG+157.62*cGT+154.6*cTJ+186.1*cJT+
 370.58*cTU+332.89*cUT+109.12*cTI+22.69*cIT+325.9*cFG+389.8*cGF+
 .1*cFJ+21*cJF+317.7*cFU+360.8*cUF+.1*cFI+5.8*cIF+
 .1*cGJ+25.9*cJG+365.1*cGU+364.4*cUG+.1*cGI+13.2*cIG+
 48*cJU+.1*cUJ+.1*cJI+6.9*cIJ+55.5*cUI+25.5*cIU+
 85.67*cAT+68.04*cTA+.1*cAF+.1*cFA+24*cAG+.1*cGA+
 34*cAJ+33.4*cJA+182*cAU+127.3*cUA+.1*cAI+5.6*cIA=Btot;

Btot=100;

END

! MODEL 2 INPUT;
! MAX F1 WITOUT HARDENING;
! ATT-AU-FR-GE-JA-UK-IN;
! Btot = 100;

MAX = F1;

! COALITION WORTH DAMAGE UTILITY;
F1<=W-rFT-rTF-rFG-rGF-rFJ-rJF-rFU-rUF-rFI-rIF-rFA-rAF;
F1<=W-rGT-rTG-rGF-rFG-rGJ-rJG-rGU-rUG-rGI-rIG-rGA-rAG;
F1<=W-rJT-rTJ-rJF-rFJ-rJG-rGJ-rJU-rUJ-rJI-rIJ-rJA-rAJ;
F1<=W-rUT-rTU-rUF-rFU-rUG-rGU-rUJ-rJU-rUI-rIU-rUA-rAU;
F1<=W-rIT-rTI-rIF-rFI-rIG-rGI-rIJ-rJI-rIU-rUI-rIA-rAI;
F1<=W-rAT-rTA-rAF-rFA-rAG-rGA-rAJ-rJA-rAU-rUA-rAI-rIA;

! COALITION MAX WORTH;
W=rTF+rFT+rTG+rGT+rTJ+rJT+rTU+rUT+rTI+rIT+rFG+rGF+rFJ+rJF+rFU+rUF+rFI+rIF+rGJ+rJG+rGU+rUG+rGI+rIG+rJU+rUJ+rJI+rIJ+rUI+rIU+rAT+rTA+rAF+rFA+rAG+rGA+rAJ+rJA+rAU+rUA+rAI+rIA;

! REVENUE CONSTARINTS;

rTF<=115.96+ITF;
rFT<=33.44+IFT;
rTG<=209.73+ITG;
rGT<=107.95+IGT;
rTJ<=238.67+ITJ;
rJT<=226.20+IJT;
rTU<=396.96+ITU;
rUT<=138.83+IUT;
rTI<=.78+ITI;
rIT<=125.44+IIT;
rFG<=116.37+IFG;
rGF<=165.51+IGF;
rFJ<=7.19+IFJ;
rJF<=35.09+IJF;
rFU<=110.46+IFU;
rUF<=130.33+IUF;
rFI<=2.11+IFI;
rIF<=132.31+IIF;
rGJ<=14.18+IGJ;
rJG<=43.26+IJG;
rGU<=164.22+IGU;
rUG<=139.76+IUG;

$rGI \leq .18 + IGI;$
 $rIG \leq 23.10 + IIG;$
 $rJU \leq 80.13 + IJU;$
 $rUJ \leq 35.07 + IUJ;$
 $rJI \leq 2.56 + IJI;$
 $rIJ \leq 9.70 + IJJ;$
 $rUI \leq 97.13 + IUI;$
 $rIU \leq 44.63 + IIU;$
 $rAT \leq 75.13 + IAT;$
 $rTA \leq 107.85 + ITA;$
 $rAF \leq .12 + IAF;$
 $rFA \leq .09 + IFA;$
 $rAG \leq 28.08 + IAG;$
 $rGA \leq .11 + IGA;$
 $rAJ \leq 42.29 + IAJ;$
 $rJA \leq 66.45 + IJA;$
 $rAU \leq 155.16 + IAU;$
 $rUA \leq 108.67 + IUA;$
 $rAI \leq .18 + IAI;$
 $rIA \leq 9.80 + IIA;$

! INCENTIVE REVENUE;

$ITF = 87.86 * cTF;$
 $IFT = 82.72 * cFT;$
 $ITG = 168.81 * cTG;$
 $IGT = 157.62 * cGT;$
 $ITJ = 154.6 * cTJ;$
 $IJT = 186.1 * cJT;$
 $ITU = 370.58 * cTU;$
 $IUT = 332.89 * cUT;$
 $ITI = 109.12 * cTI;$
 $IIT = 22.69 * cIT;$
 $IFG = 325.9 * cFG;$
 $IGF = 389.8 * cGF;$
 $IFJ = .1 * cFJ;$
 $IJF = 21 * cJF;$
 $IFU = 317.7 * cFU;$
 $IUF = 360.8 * cUF;$
 $IFI = .1 * cFI;$
 $IIF = 5.8 * cIF;$
 $IGJ = .1 * cGJ;$
 $IJG = 25.9 * cJG;$
 $IGU = 365.1 * cGU;$

IUG=364.4*cUG;
 IGI=.1*cGI;
 IIG=13.2*cIG;
 IJU=48*cJU;
 IUJ=.1*cUJ;
 IJI=.1*cJI;
 IJJ=6.9*cIJ;
 IUI=55.5*cUI;
 IJU=25.5*cIU;
 IAT=85.67*cAT;
 ITA=68.04*cTA;
 IAF=.1*cAF;
 IFA=.1*cFA;
 IAG=24*cAG;
 IGA=.1*cGA;
 IAJ=34*cAJ;
 IJA=33.4*cJA;
 IAU=182*cAU;
 IUA=127.3*cUA;
 IAI=.1*cAI;
 IIA=5.6*cIA;

! BUDGET CONSTRAINTS;

87.86*cTF+82.72*cFT+168.81*cTG+157.62*cGT+154.6*cTJ+186.1*cJT+
 370.58*cTU+332.89*cUT+109.12*cTI+22.69*cIT+325.9*cFG+389.8*cGF+
 .1*cFJ+21*cJF+317.7*cFU+360.8*cUF+.1*cFI+5.8*cIF+
 .1*cGJ+25.9*cJG+365.1*cGU+364.4*cUG+.1*cGI+13.2*cIG+
 48*cJU+.1*cUJ+.1*cJI+6.9*cIJ+55.5*cUI+25.5*cIU+
 85.67*cAT+68.04*cTA+.1*cAF+.1*cFA+24*cAG+.1*cGA+
 34*cAJ+33.4*cJA+182*cAU+127.3*cUA+.1*cAI+5.6*cIA=Btot;

Btot=100;

END

! MODEL 3 INPUT;
 ! MAX F1 WITH HARDENING;
 ! ATT-AU-FR-GE-JA-UK-IN;
 ! Btot = 100;

MAX = F1;

! COALITION WORTH DAMAGE UTILITY;
 $F1 \leq W - (r_{FT} + r_{TF} + r_{FG} + r_{GF} + r_{FJ} + r_{JF} + r_{FU} + r_{UF} + r_{FI} + r_{IF} + r_{FA} + r_{AF}) * (1 - y_F)$;
 $F1 \leq W - (r_{GT} + r_{TG} + r_{GF} + r_{FG} + r_{GJ} + r_{JG} + r_{GU} + r_{UG} + r_{GI} + r_{IG} + r_{GA} + r_{AG}) * (1 - y_G)$;
 $F1 \leq W - (r_{JT} + r_{TJ} + r_{JF} + r_{FJ} + r_{JG} + r_{GJ} + r_{JU} + r_{UJ} + r_{JI} + r_{IJ} + r_{JA} + r_{AJ}) * (1 - y_J)$;
 $F1 \leq W - (r_{UT} + r_{TU} + r_{UF} + r_{FU} + r_{UG} + r_{GU} + r_{UJ} + r_{JU} + r_{UI} + r_{IU} + r_{UA} + r_{AU}) * (1 - y_U)$;
 $F1 \leq W - (r_{IT} + r_{TI} + r_{IF} + r_{FI} + r_{IG} + r_{GI} + r_{IJ} + r_{JI} + r_{IU} + r_{UI} + r_{IA} + r_{AI}) * (1 - y_I)$;
 $F1 \leq W - (r_{AT} + r_{TA} + r_{AF} + r_{FA} + r_{AG} + r_{GA} + r_{AJ} + r_{JA} + r_{AU} + r_{UA} + r_{AI} + r_{IA}) * (1 - y_A)$;

! COALITION MAX WORTH;
 $W = r_{TF} + r_{FT} + r_{TG} + r_{GT} + r_{TJ} + r_{JT} + r_{TU} + r_{UT} + r_{TI} + r_{IT} + r_{FG} + r_{GF} + r_{FJ} + r_{JF} + r_{FU} + r_{UF} + r_{FI} + r_{IF} + r_{GJ} + r_{JG} + r_{GU} + r_{UG} + r_{GI} + r_{IG} + r_{JU} + r_{UJ} + r_{JI} + r_{IJ} + r_{UI} + r_{IU} + r_{AT} + r_{TA} + r_{AF} + r_{FA} + r_{AG} + r_{GA} + r_{AJ} + r_{JA} + r_{AU} + r_{UA} + r_{AI} + r_{IA}$;

! REVENUE CONSTARINTS;

$r_{TF} \leq 115.96 + ITF$;
 $r_{FT} \leq 33.44 + IFT$;
 $r_{TG} \leq 209.73 + ITG$;
 $r_{GT} \leq 107.95 + IGT$;
 $r_{TJ} \leq 238.67 + ITJ$;
 $r_{JT} \leq 226.20 + IJT$;
 $r_{TU} \leq 396.96 + ITU$;
 $r_{UT} \leq 138.83 + IUT$;
 $r_{TI} \leq .78 + ITI$;
 $r_{IT} \leq 125.44 + IIT$;
 $r_{FG} \leq 116.37 + IFG$;
 $r_{GF} \leq 165.51 + IGF$;
 $r_{FJ} \leq 7.19 + IFJ$;
 $r_{JF} \leq 35.09 + IJF$;
 $r_{FU} \leq 110.46 + IFU$;
 $r_{UF} \leq 130.33 + IUF$;
 $r_{FI} \leq 2.11 + IFI$;
 $r_{IF} \leq 132.31 + IIF$;
 $r_{GJ} \leq 14.18 + IGJ$;
 $r_{JG} \leq 43.26 + IJG$;
 $r_{GU} \leq 164.22 + IGU$;

$rUG \leq 139.76 + IUG;$
 $rGI \leq .18 + IGI;$
 $rIG \leq 23.10 + IIG;$
 $rJU \leq 80.13 + IJU;$
 $rUJ \leq 35.07 + IUJ;$
 $rJI \leq 2.56 + IJI;$
 $rIJ \leq 9.70 + IJJ;$
 $rUI \leq 97.13 + IUI;$
 $rIU \leq 44.63 + IIU;$
 $rAT \leq 75.13 + IAT;$
 $rTA \leq 107.85 + ITA;$
 $rAF \leq .12 + IAF;$
 $rFA \leq .09 + IFA;$
 $rAG \leq 28.08 + IAG;$
 $rGA \leq .11 + IGA;$
 $rAJ \leq 42.29 + IAJ;$
 $rJA \leq 66.45 + IJA;$
 $rAU \leq 155.16 + IAU;$
 $rUA \leq 108.67 + IUA;$
 $rAI \leq .18 + IAI;$
 $rIA \leq 9.80 + IIA;$

! INCENTIVE REVENUE;

$ITF = 87.86 * cTF;$
 $IFT = 82.72 * cFT;$
 $ITG = 168.81 * cTG;$
 $IGT = 157.62 * cGT;$
 $ITJ = 154.6 * cTJ;$
 $IJT = 186.1 * cJT;$
 $ITU = 370.58 * cTU;$
 $IUT = 332.89 * cUT;$
 $ITI = 109.12 * cTI;$
 $IIT = 22.69 * cIT;$
 $IFG = 325.9 * cFG;$
 $IGF = 389.8 * cGF;$
 $IFJ = .1 * cFJ;$
 $IJF = 21 * cJF;$
 $IFU = 317.7 * cFU;$
 $IUF = 360.8 * cUF;$
 $IFI = .1 * cFI;$
 $IIF = 5.8 * cIF;$
 $IGJ = .1 * cGJ;$
 $IJG = 25.9 * cJG;$

IGU=365.1*cGU;
 IUG=364.4*cUG;
 IGI=.1*cGI;
 IIG=13.2*cIG;
 IJU=48*cJU;
 IUJ=.1*cUJ;
 IJI=.1*cJI;
 IJJ=6.9*cIJ;
 IUI=55.5*cUI;
 IIU=25.5*cIU;
 IAT=85.67*cAT;
 ITA=68.04*cTA;
 IAF=.1*cAF;
 IFA=.1*cFA;
 IAG=24*cAG;
 IGA=.1*cGA;
 IAJ=34*cAJ;
 IJA=33.4*cJA;
 IAU=182*cAU;
 IUA=127.3*cUA;
 IAI=.1*cAI;
 IIA=5.6*cIA;

! BUDGET CONSTRAINTS;

87.86*cTF+82.72*cFT+168.81*cTG+157.62*cGT+154.6*cTJ+186.1*cJT+
 370.58*cTU+332.89*cUT+109.12*cTI+22.69*cIT+325.9*cFG+389.8*cGF+
 .1*cFJ+21*cJF+317.7*cFU+360.8*cUF+.1*cFI+5.8*cIF+
 .1*cGJ+25.9*cJG+365.1*cGU+364.4*cUG+.1*cGI+13.2*cIG+
 48*cJU+.1*cUJ+.1*cJI+6.9*cIJ+55.5*cUI+25.5*cIU+
 85.67*cAT+68.04*cTA+.1*cAF+.1*cFA+24*cAG+.1*cGA+
 34*cAJ+33.4*cJA+182*cAU+127.3*cUA+.1*cAI+5.6*cIA=Btot;

Btot=100;

! GAME BUDGET;

yF+yG+yJ+yU+yI+yA=1;

END

! MODEL 4 INPUT;
 ! MULTI-CRITERIA WITH HARDENING;
 ! ATT-AU-FR-GE-JA-UK-IN;
 ! Btot = 100;
 ! S = 752, 1-INF;

MAX = F1;

F2 >= S;
 S = 752;

! ATT'S SHAPLEY WORTH DAMAGE UTILITY WITH GAME VARIABLES;
 $F2 \leq (R_o * y_F) + (R_F * (1 - y_F));$
 $F2 \leq (R_o * y_G) + (R_G * (1 - y_G));$
 $F2 \leq (R_o * y_J) + (R_J * (1 - y_J));$
 $F2 \leq (R_o * y_U) + (R_U * (1 - y_U));$
 $F2 \leq (R_o * y_I) + (R_I * (1 - y_I));$
 $F2 \leq (R_o * y_A) + (R_A * (1 - y_A));$

! ATT'S SHAPLEY WORTH WITH ALL NODES (R_o) AND WITH ONE EACH
 REMOVED FROM COALITION (R_i);

$R_o = (r_{TF} + r_{FT} + r_{TG} + r_{GT} + r_{TJ} + r_{JT} + r_{TU} + r_{UT} + r_{TI} + r_{IT} + r_{TA} + r_{AT}) * .5;$
 $R_F = R_o - ((r_{TF} + r_{FT}) * .5);$
 $R_G = R_o - ((r_{TG} + r_{GT}) * .5);$
 $R_J = R_o - ((r_{TJ} + r_{JT}) * .5);$
 $R_U = R_o - ((r_{TU} + r_{UT}) * .5);$
 $R_I = R_o - ((r_{TI} + r_{IT}) * .5);$
 $R_A = R_o - ((r_{TA} + r_{AT}) * .5);$

! COALITION WORTH DAMAGE UTILITY;

$F1 \leq W - (r_{FT} + r_{TF} + r_{FG} + r_{GF} + r_{FJ} + r_{JF} + r_{FU} + r_{UF} + r_{FI} + r_{IF} + r_{FA} + r_{AF}) * (1 - y_F);$
 $F1 \leq W - (r_{GT} + r_{TG} + r_{GF} + r_{FG} + r_{GJ} + r_{JG} + r_{GU} + r_{UG} + r_{GI} + r_{IG} + r_{GA} + r_{AG}) * (1 - y_G);$
 $F1 \leq W - (r_{JT} + r_{TJ} + r_{JF} + r_{FJ} + r_{JG} + r_{GJ} + r_{JU} + r_{UJ} + r_{JI} + r_{IJ} + r_{JA} + r_{AJ}) * (1 - y_J);$
 $F1 \leq W - (r_{UT} + r_{TU} + r_{UF} + r_{FU} + r_{UG} + r_{GU} + r_{UJ} + r_{JU} + r_{UI} + r_{IU} + r_{UA} + r_{AU}) * (1 - y_U);$
 $F1 \leq W - (r_{IT} + r_{TI} + r_{IF} + r_{FI} + r_{IG} + r_{GI} + r_{IJ} + r_{JI} + r_{IU} + r_{UI} + r_{IA} + r_{AI}) * (1 - y_I);$
 $F1 \leq W - (r_{AT} + r_{TA} + r_{AF} + r_{FA} + r_{AG} + r_{GA} + r_{AJ} + r_{JA} + r_{AU} + r_{UA} + r_{AI} + r_{IA}) * (1 - y_A);$

! COALITION MAX WORTH;

$W = r_{TF} + r_{FT} + r_{TG} + r_{GT} + r_{TJ} + r_{JT} + r_{TU} + r_{UT} + r_{TI} + r_{IT} + r_{FG} + r_{GF} + r_{FJ} + r_{JF} + r_{FU} + r_{UF} +$
 $r_{FI} + r_{IF} + r_{GJ} + r_{JG} + r_{GU} + r_{UG} + r_{GI} + r_{IG} + r_{JU} + r_{UJ} + r_{JI} + r_{IJ} + r_{UI} + r_{IU} + r_{AT} + r_{TA} +$
 $r_{AF} + r_{FA} + r_{AG} + r_{GA} + r_{AJ} + r_{JA} + r_{AU} + r_{UA} + r_{AI} + r_{IA};$

! REVENUE CONSTARINTS;

$rTF \leq 115.96 + ITF;$
 $rFT \leq 33.44 + IFT;$
 $rTG \leq 209.73 + ITG;$
 $rGT \leq 107.95 + IGT;$
 $rTJ \leq 238.67 + ITJ;$
 $rJT \leq 226.20 + IJT;$
 $rTU \leq 396.96 + ITU;$
 $rUT \leq 138.83 + IUT;$
 $rTI \leq .78 + ITI;$
 $rIT \leq 125.44 + IIT;$
 $rFG \leq 116.37 + IFG;$
 $rGF \leq 165.51 + IGF;$
 $rFJ \leq 7.19 + IFJ;$
 $rJF \leq 35.09 + IJF;$
 $rFU \leq 110.46 + IFU;$
 $rUF \leq 130.33 + IUF;$
 $rFI \leq 2.11 + IFI;$
 $rIF \leq 132.31 + IIF;$
 $rGJ \leq 14.18 + IGJ;$
 $rJG \leq 43.26 + IJG;$
 $rGU \leq 164.22 + IGU;$
 $rUG \leq 139.76 + IUG;$
 $rGI \leq .18 + IGI;$
 $rIG \leq 23.10 + IIG;$
 $rJU \leq 80.13 + IJU;$
 $rUJ \leq 35.07 + IUJ;$
 $rJI \leq 2.56 + IJI;$
 $rIJ \leq 9.70 + IIJ;$
 $rUI \leq 97.13 + IUI;$
 $rIU \leq 44.63 + IIU;$
 $rAT \leq 75.13 + (85.67 * cAT);$
 $rTA \leq 107.85 + (68.04 * cTA);$
 $rAF \leq .12 + (.1 * cAF);$
 $rFA \leq .09 + (.1 * cFA);$
 $rAG \leq 28.08 + (24 * cAG);$
 $rGA \leq .11 + (.1 * cGA);$
 $rAJ \leq 42.29 + (34 * cAJ);$
 $rJA \leq 66.45 + (33.4 * cJA);$
 $rAU \leq 155.16 + (182 * cAU);$
 $rUA \leq 108.67 + (127.3 * cUA);$
 $rAI \leq .18 + (.1 * cAI);$
 $rIA \leq 9.80 + (5.6 * cIA);$

! INCENTIVE REVENUE;

ITF=87.86*cTF;
IFT=82.72*cFT;
ITG=168.81*cTG;
IGT=157.62*cGT;
ITJ=154.6*cTJ;
IJT=186.1*cJT;
ITU=370.58*cTU;
IUT=332.89*cUT;
ITI=109.12*cTI;
IIT=22.69*cIT;
IFG=325.9*cFG;
IGF=389.8*cGF;
IFJ=.1*cFJ;
IJF=21*cJF;
IFU=317.7*cFU;
IUF=360.8*cUF;
IFI=.1*cFI;
IIF=5.8*cIF;
IGJ=.1*cGJ;
IJG=25.9*cJG;
IGU=365.1*cGU;
IUG=364.4*cUG;
IGI=.1*cGI;
IIG=13.2*cIG;
IJU=48*cJU;
IUJ=.1*cUJ;
IJI=.1*cJI;
IJJ=6.9*cIJ;
IUI=55.5*cUI;
IIU=25.5*cIU;

! BUDGET CONSTRAINTS;

82.72*cFT+157.62*cGT+186.1*cJT+332.89*cUT+22.69*cIT+325.9*cFG+
389.8*cGF+.1*cFJ+21*cJF+317.7*cFU+360.8*cUF+.1*cFI+
5.8*cIF+.1*cGJ+25.9*cJG+365.1*cGU+364.4*cUG+.1*cGI+
13.2*cIG+48*cJU+.1*cUJ+.1*cJI+6.9*cIJ+55.5*cUI+
25.5*cIU+85.67*cAT+.1*cAF+.1*cFA+24*cAG+.1*cGA+
34*cAJ+33.4*cJA+182*cAU+127.3*cUA+.1*cAI+5.6*cIA=BR;

87.86*cTF+168.81*cTG+154.6*cTJ+370.58*cTU+109.12*cTI+68.04*cTA=BS;

BR+BS<=Btot;
Btot=100;

! GAME BUDGET;
yF+yG+yJ+yU+yI+yA=1;

END

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