

## Delay Tolerant Networking routing as a Game Theory problem – An Overview

**Laveen Sundararaj**

*Honeywell Research Scholar,  
Department of Computer Science and Engineering,  
Alagappa University, Tamil Nadu, Karaikudi 630003, India.*

laveen.sundararaj@honeywell.com

**Dr. Palanisamy Vellaiyan**

*Head of the Department,  
Department of Computer Science and Engineering,  
Alagappa University, Tamil Nadu, Karaikudi 630003, India.*

vpazhanisamy@yahoo.co.in

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### Abstract

This paper explores the theoretical approach to improve existing Delay and Disruption Tolerant Networking routing algorithms using Game Theory. Game Theory is a systematic study of strategic interaction among rational individuals. DTN deals with networks in challenged environment. DTN focuses on deep space to a broader class of heterogeneous networks that may suffer disruptions, affected by design decisions such as naming and addressing, message formats, data encoding methods, routing, congestion management and security. DTN is part of the Inter Planetary Internet with primary application being deep space networks. The hypothesis behind modeling DTN routing as a game is based on understanding that routing is also a strategic interaction between the DTN nodes. This brings cognitive abilities leading to automated routing decisions.

**Keywords:** DTN - Delay and Disruption Tolerant Networking, BRG – Bundle Routing Game, PRoPHET – Probabilistic Routing Protocol using History of Encounters and Transitivity, Game Theory, Nash Equilibrium, Kakutani's Theorem, Backward Induction.

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### 1. INTRODUCTION

An era of new and cheap wireless networking solutions has created opportunities for networking in new situations, and for exciting new applications that use the network. The advent of technologies such as Wi-Fi, Wi-Max, Bluetooth, and other radio solutions (e.g. low power radios designed for use in sensor networks), it has become viable to equip almost any device with wireless networking capabilities. Due to the ubiquity of such networking enabled devices, situations where communication is desirable can occur at any time and any place, even where no networking infrastructure is available. Also over the past 3 decades, deep space communication has evolved towards frame-oriented communications. These are a class of communication protocols that include packet switching and store-and-forward communication that have driven the internet to global prominence. But even the internet protocols (sometimes called the TCP/IP protocol suite) have their limitations [8]. In the presence of frequent disruption or long and uncertain delays from transmission to reception, the internet protocols are not always adequately robust.

One area that have received much attention recently and that remedies many of the situations where no infrastructure is available is that of ad hoc networking. In an ad hoc network, all nodes participate in the routing and forwarding of packets, so if two nodes can not communicate directly, intermediate nodes aid in forwarding the packet between them. One of the most basic requirements for "traditional" networking, which also holds for ad hoc networking, is that there must exist a fully connected path between communication endpoints for communication to be possible. There are however a number of scenarios where this is not the case (thus rendering the use of ad hoc networking protocols impossible), but where it still is desirable to allow communication between nodes. Such scenarios include communication between villages and summer camps of the Saami population of reindeer herders in the north of Sweden, living in locations where no fixed infrastructure is available. Similar problems exist between rural villages in India and other poor regions. DTN based water monitoring in Indian context [6] is another such application, which is still in nascent stages as part of the research by the authors. (This shall also serve as test bed [1] for experimentation of DTN enhancements)

Other fields where this kind of communication scenarios may occur are satellite communication, military and disaster recovery operations, sensor networking and monitoring. For example, experiments have been done with attaching sensors to seals and whales to be able to get a large number of sensor readings from the oceans. To allow scientists to analyze the collected data, it must somehow be transferred to a data sink, even though connectivity among the seals and whales is very sparse and intermittent, so the mobility of the animals must be relied upon for successful data delivery. Yet another example concerns weather monitoring of large areas such as a national park, where a number of electronic display boards showing weather reports from other parts of the park have been installed. By equipping hikers with small networked devices, their mobility through the park can be used to spread the weather information throughout the entire park.

The Delay-Tolerant Networking (DTN) architecture [2] defines architecture for communication in environments where traditional communication protocols can not be used due to excessive delays, link outages and other extreme conditions. The intermittently connected networks considered here are a subset of those covered by the DTN architecture. The DTN architecture [4] defines routes to be computed based on a collection of 'contacts' indicating the start time, duration, endpoints, forwarding capacity and latency of a link in the topology graph. These contacts may be deterministic, or may be derived from estimates. The architecture defines some different types of intermittent contacts. The ones called opportunistic and predicted are the ones addressed by this protocol. Opportunistic contacts are those that are not scheduled, but rather present themselves unexpectedly and frequently arise due to node mobility. Predicted contacts are like opportunistic contacts, but based on some information, it might be possible to draw some statistical conclusion on if a contact will be present soon. The DTN architecture [11] also defines the bundle protocol [5], which provides a way for applications to 'bundle' an entire session, including both data and meta-data, into a single message, or bundle, that can be sent as a unit. The bundling protocol also provides end-to-end addressing and reliability. We build on the bundling protocol, using bundles as the basic data transfer unit.

The Probabilistic Routing Protocol using History of Encounters and Transitivity (PRoPHET) algorithm [13] is one of the most prominently used routing algorithms for DTN routing. The PRoPHET algorithm enables communication between participating nodes wishing to communicate in an intermittently connected network where at least some of the nodes are mobile. The protocol leverages the observations made on the non-randomness of human mobility to improve routing performance. Instead of only blindly flooding messages through the network, it applies 'probabilistic routing'.

We model DTN Bundle routing as a Game Theory problem [14] and go on to improvise DTN routing [3] based on the findings

## 2. GAME THEORY

### 2.1 Overview of Game Theory

Humans cannot survive without interacting with other humans, and ironically, it sometimes seems that we have survived despite those interactions. Production and exchange require cooperation between individuals at some level but the same interactions may also lead to disastrous confrontations. Human history is as much a history of fights and wars as it is a history of successful cooperation. Many human interactions carry the potentials of cooperation and harmony as well as conflict and disaster. Examples are abounding: relationships among couples, siblings, countries, management and labor unions, neighbors, students and professors, and so on. One can argue that the increasingly complex technologies, institutions, and cultural norms that have existed in human societies have been there in order to facilitate and regulate these interactions. For example, internet technology greatly facilitates buyer-seller transactions, but also complicates them further by increasing opportunities for cheating and fraud. Workers and managers have usually opposing interests when it comes to wages and working conditions, and labor unions as well as labor law provide channels and rules through which any potential conflict between them can be addressed. Similarly, several cultural and religious norms, such as altruism or reciprocity, bring some order to potentially dangerous interactions between individuals. All these norms and institutions constantly evolve as the nature of the underlying interactions keep changing. In this sense, understanding human behavior in its social and institutional context requires a proper understanding of human interaction. Economics, sociology, psychology, and political science are all devoted to studying human behavior in different realms of social life. However, in many instances they treat individuals in isolation, for convenience if not for anything else. In other words, they assume that to understand one individual's behavior it is safe to assume that her behavior does not have a significant effect on other individuals. In some cases, and depending upon the question one is asking, this assumption may be warranted. For example, what a small farmer in a local market, say in Montana, and charges for wheat is not likely to have an effect on the world wheat prices. Similarly, the probability that my vote will change the outcome of the U.S. presidential elections is negligibly small. So, if we are interested in the world wheat price or the result of the presidential elections, we may safely assume that one individual acts as if her behavior will not affect the outcome.

In many cases, however, this assumption may lead to wrong conclusions. For example, how much our farmer in Montana charges, compared to the other farmers in Montana, certainly affects how much she and other farmers make? If our farmer sets a price that is lower than the prices set by the other farmers in the local market, she would sell more than the others, and vice versa. Therefore, if we assume that they determine their prices without taking this effect into account, we are not likely to get anywhere near understanding their behavior. Similarly, the vote of one individual may radically change the outcome of voting in small committees and assuming that they vote in ignorance of that fact is likely to be misleading. The subject matter of game theory is exactly those interactions within a group of individuals (or governments, firms, etc.) where the actions of each individual have an effect on the outcome that is of interest to all. Yet, this is not enough for a situation to be a proper subject of game theory: The Game theory [10] studies strategic interactions way that individuals act has to be strategic, i.e., they should be aware of the fact that their actions affect others. The fact that my actions have an effect on the outcome does not necessitate strategic behavior, if I am not aware of that fact. Therefore, we say that game theory studies strategic interaction within a group of individuals. By strategic interaction we mean that individuals know that their actions will have an effect on the outcome and act accordingly. Like any other theory, the objective of game theory is to organize our knowledge and increase our understanding of the outside world. A scientific theory tries to abstract the most essential aspects of a given situation, analyze them using certain assumptions and procedures, and at the end derive some general principles and predictions that can be applied to individual instances. For it to have any predictive power, game theory has to postulate some rules according to which individuals act. If we do not describe how individuals behave, what their objectives are and how rules of the game they try to achieve those objectives we cannot derive any predictions at all in a

given situation. The most important, and maybe one of the most controversial, assumption of game theory which brings about this discipline is that individuals are rational.

An individual is rational if she has well-defined objectives (or preferences) over the set of possible outcomes and she implements the best available strategy to pursue them. Rationality implies that individuals know the strategies available to each individual, have complete and consistent preferences over possible outcomes, and they are aware of those preferences. Furthermore, they can determine the best strategy for themselves and flawlessly implement it. If taken literally, the assumption of rationality is certainly an unrealistic one, and if applied to particular cases it may produce results that are at odds with reality. We should first note that game theorists are aware of the limitations imposed by this assumption and there is an active research area studying the implications of less demanding forms of rationality, called bounded rationality. The term strategic interaction is actually more loaded than it is alluded to above. It is not enough that I know that my actions, as well as yours, affect the outcome, but I must also know that you know this fact. Take the example of two wheat farmers. Suppose both farmer A and B know that their respective choices of prices will affect their profits for the day. But suppose, A does not know that B knows this. Now, from the perspective of farmer A, farmer B is completely ignorant of what is going on in the market and hence farmer B might set any price. This makes farmer A's decision quite uninteresting itself. To model the situation more realistically, we then have to assume that they both know that they know that their prices will affect their profits. One actually has to continue in this fashion and assume that the rules of the game, including how actions affect the participants and individuals' rationality, are common knowledge. A fact X is common knowledge if everybody knows it, if everybody knows that everybody knows it and so on. This has some philosophical implications and is subject to a lot of controversy, but for the most part we will avoid those discussions and take it as given.

In sum, we may define game theory as follows: Game theory is a systematic study of strategic interaction among rational individuals. Its limitations aside, game theory has been fruitfully applied to many situations in the realm of economics, political science, biology, law, etc. This paper attempts to apply game theory to computer science too.

**2.2 Game Forms**

The Games are analyzed along 2 different dimensions: 1.Order of Moves 2.Information. This leads to 4 general forms of game namely 1. Strategic Form Games with Complete Information and Simultaneous moves 2. Bayesian Games with Incomplete Information and Simultaneous moves 3.Extensive form Games with Complete Information and Sequential Moves 4. Extensive form Games with Incomplete Information and Sequential Moves. The success of this problem description lies with the seamless co-relation of the DTN node behavior to the players of the Game. It is perfectly acceptable to have a game based on machine or automated decisions as well. Such a game fits into one of the 4 game forms depending on the parameters that are considered to make the routing decision. In the following paragraphs, a brief treatment of DTN routing with each of the Game forms is discussed.

		Information	
		Complete	Incomplete
Moves	Simultaneous	Strategic Form Games with Complete Information	Bayesian Games
	Sequential	Extensive Form Games with Complete Information	Extensive Form Games with Incomplete Information

**TABLE 1:** Game Forms.

### 2.3 Nash Equilibrium

The most commonly used solution concept in game theory is that of Nash equilibrium. This notion captures a steady state of the play of a strategic game in which each player holds the correct expectation about the other players' behavior and acts rationally. It does not attempt to examine the process by which a steady state is reached. The solution (routing decision) of the game (of forwarding bundles) in this case is based on Nash Equilibrium. The solution theory has 2 components.

1. Each Node chooses its action according to the model of rational choice, given its belief about the other Nodes' actions.
2. Every Nodes' belief about the other Node's action is incorrect.

These 2 components are embodied in the following definition: A Nash equilibrium is an action profile  $a^*$  with the property that no player  $i$  can do better by choosing an action different from  $a_i^*$ , given that every other player  $j$  adheres to  $a_j^*$ . In other words, the players (Nodes) act in accordance with the theory of rational choice (of forwarding), given their beliefs about the other players (Nodes) actions, and these beliefs are correct. In the idealized setting in which the players (Nodes) in any given play (of forwarding bundles) are drawn from a collection of population (of Nodes), a Nash Equilibrium corresponds to a steady state. If, whenever the game is played, the action profile is the same Nash equilibrium  $a^*$ , then no player has a reason to choose any action different from its component of  $a^*$ ; there is no pressure on the action profile to change. Expressed differently, a Nash equilibrium embodies a stable "social norm": if everyone else adheres to it, no individual wishes to deviate from it.

The second component of the theory of Nash Equilibrium – that the players' beliefs about each other's actions are correct – implies, in particular, that the two players' belief about a third player's action is the same. For this reason, the condition is sometime referred to as the requirement that the player's "expectations are coordinated". The situations to which Nash Equilibrium is applied may not apply to idealized scenario only. Nash Equilibrium depends on the Best Response Function of the Game. The Best Response function of a Game in which each player (Node) has only a few actions (Transmit, Receive or Drop the Bundle being forwarded) is found by examining each action profile in turn to see if it indeed satisfied the conditions for equilibrium. In more complicated Games (Routing decisions), it have been observed to be better to work with the players' (Nodes') "Best response functions". All games need not necessarily have Nash equilibrium. Example is matching penny which does not have Nash Equilibrium. Such scenario must be carefully eliminated. The Nash Equilibrium is based on Kakutani's Fixed Point theorem.

### 2.4 Kakutani's Fixed Point Theorem

Not every strategic game has a Nash equilibrium [12]. One such an example is the game of Matching Pennies. The condition under which the set of Nash equilibria of a game is nonempty has been investigated extensively. An existence of result has two purposes.

1. If a game satisfied the hypothesis of the result, then there are bright hopes that the efforts are indeed worth-while to find equilibrium successfully.
2. The existence of an equilibrium shows that the game is consistent with a steady state solution.

Also the existence of equilibria for a family of games (Routing) allows the researcher to study properties of these equilibria (by using, for example, "comparative static" techniques) without finding them explicitly and without taking the risk that empty set(s) are being investigated.

To show that a game has a Nash equilibrium it suffices to show that there is a profile  $a^*$  of actions such that  $a_i^* \in B_i(a_{-i}^*)$  for all  $i \in N$ . Defined the set-valued function  $B: A \rightarrow A$  by  $B(a) = \prod_{i \in N} B_i(a_{-i})$ . This can be written in vector form simply as  $a^* \in B(a^*)$ . Fixed point theorems give conditions on  $B$  under which there indeed exists a value of  $a$ , for which  $a^* \in B(a^*)$ . The Kakutani's Fixed point gives the condition in this case.

Theorem: Let  $X$  be a compact convex subset of  $R^n$  and let  $f: X \rightarrow X$  be a set-valued function for which:

1. For all  $x \in X$  the set  $f(x)$  is nonempty and convex
2. The graph of  $f$  is closed (i.e. for all sequences  $\{x_n\}$  and  $\{y_n\}$  such that  $y_n \in f(x_n)$  for all  $n$ ,  $x_n \rightarrow x$ , and  $y_n \rightarrow y$ , we have  $y \in f(x)$ ).

Then there exists  $x^* \in X$  such that  $x^* \in f(x^*)$ .

### 3. DTN ROUTING

As DTN as a piece of infrastructure is relatively fragile, protocols needs to be cautious in how they consume the network resources. Here is where we bring in the analogy to economics. If consumption of resources or wealth can be determined by game theory in economics, so can the usage of resources such a Node can be determined by Game theory in the world of Delay Tolerant Networks. The paper presents an introduction to comparison of DTN routing to various game forms.

One of the requirement of the DTN protocols (Bundle protocol) and its implementations is to support mechanisms for policy based routing [7]. The DTN protocol specification [5] is expected to state the security relevant policy variables based upon which it is a reasonable expectation to have an implementation that is capable of making routing and forwarding decisions. Forwarding of every single bundle results in consumption of network resources. Hence every single DTN node must implicitly incorporate some element of policy-based routing. It is generally not expected that every single DTN node would be able to handle complex policy decisions. In fact a DTN node might quite reasonable be programmed to forward all bundles received in a deterministic way, such as flooding which is implicitly a routing policy. Though all nodes are required to implement some policy, it could be very simple. Some DTN nodes may be on the boundaries of various sorts such as network topology related, administrative, networking technology related. The current view is that all nodes are policy routers with varying degrees of complexity in policy. The policy based routing, though important must be deployed carefully. If not, it may inadvertently create bundle sink holes. We are proposing a Game theory based routing decision where, the solution is based on the Nash equilibrium which is going to ensure that all the Nodes as players do what is the best for themselves and others.

#### 3.1 Classification of DTN routing protocols

Some of the DTN routing protocols [9] and their categories are as follows:

##### A. Deterministic case

1. Space time routing
2. Tree approach
3. Modified shortest path approaches

##### B. Stochastic case

1. Epidemic/random spray
2. History or predication-based approach
  - Per contact routing based on one-hop information
  - Per contact routing based on end-to-end information
3. Model-based
4. Control movement
5. Coding-based approaches

#### 3.2 Open Issues in DTN protocol

The following are some of the open issues [9] in DTN routing protocols:

1. What is the proper objective function in designing a protocol in DTNs: short delay or high throughput?
2. Methods to determine how many nodes to forward should be developed.
3. When multiple copies of the packets are in the network, duplication of packets occurs and such duplication requires a method of eliminating unnecessary copies to reduce the buffer occupancy. Where the duplication reduction should be done?
4. Scheduling becomes much more complex in DTNs than in IP-centric networks, because connections in DTNs are intermittent while in normal IP networks they are not.
5. Whenever possible, information about node location and future movement should be utilized in designing the protocols.

6. New security mechanisms must be developed, as techniques that rely on access to a centralized service cannot be used, or the assumption that all intermediate nodes are trusted is not valid.
7. Open spectrum allows secondary users to opportunistically explore unused licensed band on a non-interfering basis.
8. Transmissions in networks with directional antennas are often pre-scheduled and may result in intermittent connectivity. Therefore, scheduling transmissions with directional antennas and power management should be considered.
9. To use the capability of a directional antenna to transmit over longer distances, but to adaptively use this capability only when necessary for selected packets.
10. Self-learning and automation algorithms should be developed so the underlying network is cognitive and thus intelligent decisions on scheduling and forwarding can be made automatically.

#### 4. APPLICATION OF GAME THEORY ON ROUTING

Game theory based DTN routing is construed as a step towards a Self-learning and automation algorithm so as to make the network cognitive, and hence make intelligent decisions on scheduling and forwarding in an automatic fashion. The following part of the paper tries to explore fitting the various game forms into DTN routing decisions.

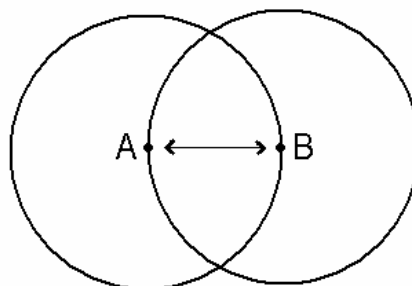
##### 4.1 DTN routing as a Strategic Game

A Strategic Game is a model of interacting decision-makers. In recognition of the interaction, the decision makers are referred as players. Each player has a set of possible actions. The model captures interaction between the players by allowing each player to be affected by the actions of all players, not only its own action.

In our case, the interacting decision makers are the DTN nodes. The DTN strategic game consists of

1. A Set of players (Nodes A and B)
2. For each player (node), a set of actions (Transmit, Receive or Drop)
3. For each player (node), preferences over the set of action profiles. (Receive > Transmit > Drop)

The Nash equilibrium of a game in which each player has only a few actions can be found by examining each action profile in turn to see if it satisfied the conditions for equilibrium. In more complicated games, it is recommended to use the “Best response functions” of the player. Consider Node A as a player. For various actions of the players (nodes) other than Node A, Node A actions yields various payoff in its mission of bundle routing. The focus is on best actions that yield the highest payoff (successful bundle forwarding).



**FIGURE 1:** Bundle Routing Game: Two Nodes, Node A and Node B are coming into radio contact of each other. This is the starting point for the strategic interacting decision making.

In Bundle Routing Game (BRG), Transmit is the best action for Node A if Node B chooses Receive, Receive is the best action for Node A if Node B chooses Transmit. In particular, in BRG Node A has a single best action for each action of Node B.

The action profile  $a^*$  is a Nash equilibrium of a strategic game with ordinal preferences if and only if every player's action is a best response to the other players' actions:  $a_i^*$  is in  $Bi(a_{-i}^*)$  for every player (Node)  $i$ . If each player  $i$  has a single best response to each list  $a_{-i}$  of the other players' actions, then the above equation is applicable.  $a_i^* = b_i(a_{-i}^*)$  for every player  $i$  is applicable for a collection of  $n$  equations in the  $n$  unknowns  $a_i^*$ , where  $n$  is the number of players in the game. In BRG with 2 nodes A and B, the equations are

$$a_1^* = b_1(a_2^*)$$

$$a_2^* = b_2(a_1^*)$$

In a 2 Node game in which each Node has a single best response to every action of the other Node ( $a_1^*, a_2^*$ ) is a Nash equilibrium if and only if Node A's action  $a_1^*$  is its best response to Node B's action  $a_2^*$  and Node B's action  $a_2^*$  is the best response to Node A's action  $a_1^*$ .

		Node B		
		(T)ransmit	(R)eceive	(D)rop
Node A	(T)ransmit	1,1	1*,2*	1,-1
	(R)eceive	2*,1*	0,0	2*,-1
	(D)rop	-1,1	-1,2*	-1,-1

**TABLE 2:** Bundle Routing – Strategic Game.

The Nash equilibrium for the BRG is determined as follows:

1. Find the best response function of each Node.
2. Find the action profile that satisfies if each Node has a single best response to each list of the other Nodes' actions.

Accordingly in this case, find the best response of Node A to each action of Node B. If Node B chooses T, then Node A's best response is R (2 is the highest payoff for Node A in this column); indicate the best response by attaching star to Node A's payoff to (R,T). If Node B chooses R, then Node A's best response is T, indicated by the star attached to Node A's payoff to (T,R). And if Node B chooses D, then R is the best response for Node A, which is indicated by star. Next the best response of Node B to each action of Node A is found. These best responses are indicated by attaching star to Node B's payoffs. Finally, boxes in which both Nodes' payoffs are starred is found. Each such box is a Nash equilibrium: the star on Node A's payoff means that Node A's action is a best response to Node B's action, and the star on Node B's payoff means that Node B's action is a best response to Node A's action. The BRG is concluded with finding of 2 Nash equilibria: (T,R) and (R,T).

#### 4.2 DTN routing as an Extensive Game with perfect information

The BRG is analyzed as a possible Extensive game with perfect information. Appropriate changes are made to BRG suit the analysis.

An Extensive game with perfect information consists of

1. A set of players.
2. A set of sequences (terminal histories) with the property that no sequence is a proper sub-history of any other sequence.
3. A function (the player function) that assigns a player to every sequence that is a proper sub-history of some terminal history.
4. For each player, preferences over the set of terminal histories.

The set of terminal histories is the set of all sequences of actions that may occur; The player assigned by the player function to any history  $h$  is the player who takes an action after  $h$ . As for a strategic game, the player's preference may be specified by a payoff function that represents it. In some situations an outcome is associated with each terminal history, and the players' preferences are naturally defined over these outcomes, rather than directly over the terminal histories. For example, if we are modeling firms choosing prices, then we may think about each firm caring about its profit – the outcome of a profile of prices, then we may think in terms of each firm's caring about its profit – the outcome of a profile of prices – rather than directly about the profile of prices. However, any preferences over outcomes may be translated into preferences



over terminal histories (eg sequence of prices). In the general definition, outcomes are conveniently identified with terminal histories and preferences are defined directly over these histories, avoiding the need for an additional element in the specification of the game.

1. Node A receives when Node B transmits. Worst case is Node A drops when Node B transmits.
2. Node B receives when Node A transmits. Worst case is Node B drops when Node A transmits.

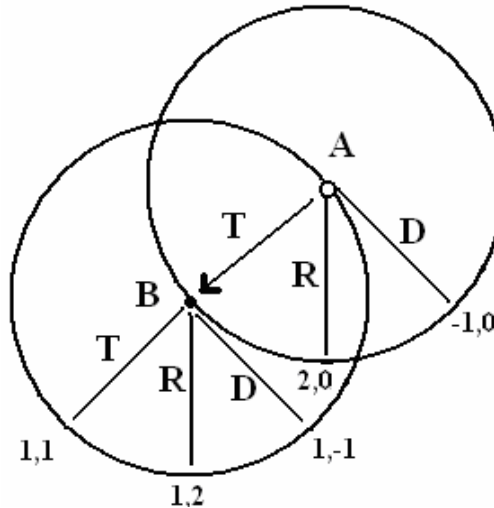
The situation may be modeled as the following extensive game with perfect information.

Players: Node A and Node B

Terminal histories: (T,T), (T,R), (T,D), (R,T), (R,R), (R,D) and D.

Player function:  $P(\Phi) = \text{Node A}$  and  $P(B) = \text{Node B}$ .

Preferences: The Node A's preferences are represented by the payoff function  $u_1$  for which  $u_1(T,T) = 1$ ,  $u_1(T,R) = 1$ ,  $u_1(T,D) = 1$ ,  $u_1(R) = 2$  and  $u_1(D) = -1$ . Node B's preferences are represented by payoff function  $u_2$  for which  $u_2(T,T) = 1$ ,  $u_2(T,R) = 2$ ,  $u_2(T,D) = -1$ . The game is illustrated in the diagram. The small circle at the top of the Fig 2 represents the empty history. The label above the circle indicates that Node A chooses an action at the start of the game ( $P(\Phi) = \text{Node A}$ ). The 3 branches labeled T(ransmit), R(eceive) and D(rop) represent's Node A's choices. The branch labeled T(ransmit) leads to a small black disk, the label beside which indicates that the Node B takes an action after the history T (that is,  $P(B)=B$ ). The 3 branches emanating from the disk represent the Node B's choices, T(ransmit), R(eceive) and D(rop). The pair of numbers beneath each terminal history gives the players (Nodes) payoffs to that history with the Node A's payoff listed first. (The Nodes' payoffs are given in order in which they move in well-defined manner). These sets are deduced from a set of terminal histories and the player function.



**FIGURE 2:** Bundle Routing Game: Node A moves into radio contact of Node B. creating radio contact with each other. This has been modeled as an Extensive game with perfect information. Node A's payoff's is the first number in each pair.

If for some non-terminal history  $h$ , the sequence  $(h,a)$  is a history, then  $a$  is one of the actions available to the player who moves after  $h$ . Thus the set of all actions available to player who moves after  $h$  is  $A(h) = \{a : (h,a) \text{ is a history}\}$

Accordingly the set of actions available to the player who moves at the start of the game namely the Node A is  $A(\Phi) = \{\text{Transmit, Receive, Drop}\}$  and the set of actions available to the player who moves after the history Transmit, namely the Node B is  $A(\text{Transmit}) = \{\text{Transmit, Receive, Drop}\}$ .

Solutions:

In the BRG in fig 2, it seems clear that Node A will Transmit and Node B will subsequently Receive. The Node A can reason that if it transmits, then Node B will receive, because doing so

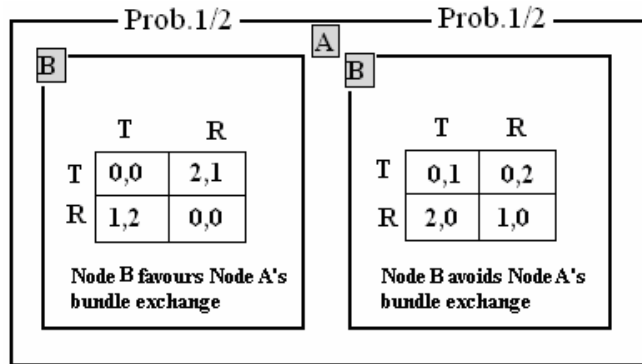
is better for the Node B than Transmitting or Dropping. Given that Node B will respond to Transmit this way, the Node A is better off transmitting. This process is called backward induction. Whenever the player (Node) has to forward a bundle, it deduces, for each of its possible actions, the actions that the players (nodes) including itself will subsequently take and choose the action that yields the terminal history it most prefers. While backward induction was applied in this case, it cannot be applied to every extensive game with perfect information.

**Nash Equilibrium:**

The strategy profile  $s^*$  in an extensive game with perfect information is a Nash equilibrium if, for every player  $I$  and every strategy  $r_i$  of player  $I$ , the terminal history  $O(s^*)$  generated by  $s^*$  is at least as good according to player  $i$ 's preferences as the terminal history  $O(r_i, s_{-i}^*)$  generated by the strategy profile  $(r_i, s_{-i}^*)$  in which player  $I$  chooses  $r_i$  while every other player  $j$  chooses  $s_j^*$ . Equivalently, for each player  $i$ ,  $u_i(O(s^*)) \geq u_i(O(r_i, s_{-i}^*))$  for every strategy  $r_i$  of the player  $i$ , where  $u_i$  is a payoff function that represents player  $i$ 's preferences and  $O$  is the outcome function of the game. One way to find the Nash equilibria of an extensive game in which each player has finitely many strategies is to list each player's strategies, find the outcome of each strategy profile, and analyze this information as for a strategic game. That is, we construct the following strategic game, known as the strategic form of the extensive game.

1. **Players:** The set of players in the extensive game.
2. **Actions:** Each player's set of actions is her set of strategies in the extensive game.
3. **Preferences:** Each player's payoff to each action profile is its payoff to the terminal history generated by that action profile in the extensive game.

The set of Nash equilibria of any extensive game with perfect information is the set of Nash equilibria of its strategic form. In the BRG in fig 2, Node A has 3 strategies, Transmit, Receive and Drop and the Node B has 3 strategies Transmit, Receive and Drop. The strategic form of the game is shown in Table 2. There are 2 Nash equilibria (T,R) and (R,T). The first equilibrium is the pattern of behavior isolated by backward induction. In the second equilibrium the Node A chooses Receive. This strategy is optimal given the Node B's strategy to Transmit in the event of Receive. Further the Node B's strategy to Transmit is optimal given the Node A's strategy: the Node A chooses Receive, so whether the incumbent plans to choose Receive or Transmit or Drop makes no difference to its payoff. Thus the Node can increase its payoff by choosing a different strategy given the other player's strategy.



**FIGURE 3:** Bundle Routing Game: Node A is unsure whether Node B wants to favor or avoid exchange of bundle. The frame labeled B enclosing each table indicates that Node B knows the relevant table. The frame labeled A enclosing both tables indicates that Node A does not know the relevant table; the probabilities it assigns to the 2 tables appear on the frame.

Analyzing the BRG, question arises about the Nash equilibrium (R,T) that does not arise in the strategic form: How does the Node A know that Node B will choose Receive when it transmits? It is interpreted that the strategic game to model a situation in which, whenever the Node A plays the game, it observes the Node B even if it chooses Receive or Drop. By contrast it is interpreted

in extensive game to model a situation in which a Node A that always chooses Receive or Drop never observes the Node B's action, because the Node B never acts. In strategic game the rationale for Nash equilibrium condition that each player's strategy be optimal given the other players' strategies is that in a steady state, each player's experience playing the game leads its belief about the other players' actions to be correct. This rationale does not apply to the Nash equilibrium (R,T) of the extensive BRG, because Node A who always chooses R or D never observes the Node B's action after history Transmit. This difficulty is overcome by interpreting a Nash equilibrium of an extensive game by considering a slightly perturbed steady state in which, on rare occasions, non equilibrium actions are taken (perhaps players make mistakes or deliberately experiment) and the perturbations allow each player eventually to observe every other player's action after every history. Given such perturbations, each player eventually learns the other players' entire strategy. Nash equilibrium (R,T) is interpreted as such a perturbed steady state. However these rare occasions will lead to others problems that are beyond the scope of this paper.

### 4.3 DTN routing as Bayesian Game

A strategic game with imperfect information is called a "Bayesian Game". As in a strategic game, the decision makers are called players, and each player is endowed with a set of actions. A key component in the specification of the imperfect information is the set of states. Each state is a complete description of one collection of the players' relevant characteristics, including both their preferences and their information. For every collection of characteristics that some player believes to be possible, there must be a state. For instance in the BRG in Fig 3, suppose Node B wishes to favor Node A. In this case, the reason for including in the model the state in which Node B wishes to avoid Node A is that Node A believes such a preference to be possible. At the start of the game a state is realized. The Players (Nodes) do not observe this state. Rather, each Player (Node) receives a signal that may give it some information about the state. Denote the signal player  $i$  receives in state  $\omega$  by  $\tau_i(\omega)$ . The function  $\tau_i$  is called player  $i$ 's signal function. (Note that the signal is a deterministic function of the state: for each state, a definite signal is received). The states that generate any given signal  $t_i$  are said to be consistent with  $t_i$ . The sizes of the sets of states consistent with each of player  $i$ 's signals reflect the quality of player  $i$ 's information. If, for example,  $\tau_i(\omega)$  is different for each value of  $\omega$ , then player  $i$  knows, given its signal the state that has occurred; after receiving its signal, it is perfectly informed about all the players' relevant characteristics. At the other extreme, if  $\tau_i(\omega)$  is the same for all states, then player  $i$ 's signal conveys no information about the state. If  $\tau_i(\omega)$  is constant over some subsets of the set of states, but is not the same for all states, then player  $i$ 's signal conveys partial information. For example, if there are three states  $\omega_1$ ,  $\omega_2$  and  $\omega_3$ , and  $\tau_i(\omega_1) \neq \tau_i(\omega_2) = \tau_i(\omega_3)$ , then when the state is  $\omega_1$  player  $i$  knows that it is  $\omega_1$ , whereas when it is either  $\omega_2$  or  $\omega_3$  she knows only that it is one of these two states. We refer to the player  $i$  in the event that she receives the signal  $t_i$  as type  $t_i$  of player  $i$ . Each type of each player holds a belief about the likelihood of the states consistent with her signal. If, for example  $t_i = \tau_i(\omega_1) = \tau_i(\omega_2)$ , the type  $t_i$  of player  $i$  assigns probabilities to  $\omega_1$  and  $\omega_2$ . (A player who receives a signal consistent with only one state naturally assigns a probability 1 to that state.)

Each player may care about the actions chosen by the other players, as in a strategic game with perfect information, and also about the state. The players may be uncertain about the state, so we need to specify their preferences regarding probability distributions over pairs  $(a, \omega)$  consisting of an action profile  $a$  and a state  $\omega$ . I assume that each player's preferences over such probability distributions are represented by the expected value of a Bernoulli payoff function. Thus each player  $i$ 's preference is specified by giving a Bernoulli payoff function  $u_i$  over pairs  $(a, \omega)$ .

The BRG is modeled for Bayesian form as follows.

1. Players: The pair of Nodes (A and B)
2. States: The set of states is {favor, avoid}
3. Actions: The set of actions of each player is {T,R}
4. Signals: Node A may receive a single signal, say  $z$ ; its signal function  $\tau_1$  satisfies  $\tau_1(\text{favors}) = \tau_1(\text{avoid}) = z$ . Node B receives one of two signals, say  $m$  and  $v$ ; its signal function  $\tau_2(\text{favor}) = m$  and  $\tau_2(\text{avoid}) = v$ .

5. Beliefs: Node A assigns probability  $\frac{1}{2}$  to each state after receiving the signal z. Node B assigns probability 1 to the state favor after receiving the signal m, and probability 1 to the state avoid after receiving the signal v.
6. Payoffs: The payoffs  $u_i(a_i, \text{favor})$  of each player i for all possible action pairs are given in the left panel of fig 3, and the payoffs  $u_i(a_i, \text{avoid})$  are given in the right panel.

**Nash Equilibrium:** In a strategic game, each player chooses an action. In a Bayesian game, each player chooses a collection of actions, one for each signal it may receive. That is, in a Bayesian game each type of each player chooses an action. In a Nash equilibrium of such a game, the action chosen by each type each player is optimal, given the actions chosen by every type of every other player. (In a steady state, each player's experience teaches its actions). Any given type of player i is not affected by the actions chosen by the other types of player i, so there is no harm in thinking that player i takes as given these actions, as well as those of the other players. Thus the Nash equilibrium of a Bayesian game may be defined as Nash equilibrium of a strategic game in which each player is one of the types of one of the players in the Bayesian game.

Consider type  $t_i$  of player i. For each state  $\omega$  she knows every other player's type (i.e., it knows the signal received by every other player). This information, together with its belief about the states, allows her to calculate its expected payoff for each of its actions and each collection of actions for various types of the other players. In the BRG in fig 3, Node A's belief is that the probability of each state is  $\frac{1}{2}$ , and it knows that Node B is type m in the state favor and type v in the state avoid. Thus if type m of Node B chooses R and type v of Node B chooses T, Node A thinks that if it chooses T, then its expected payoff is  $\frac{1}{2} u_1((T,R), \text{favor}) + \frac{1}{2} u_1((T,T), \text{avoid})$ , Where  $u_1$  is its payoff function in the Bayesian game. In a general game, denote the probability assigned by the belief of type  $t_i$  of player i to state  $\omega$  by  $\text{Pr}(\omega | t_i)$ . Denote the action taken by each type  $t_j$  of each player j by  $a_j(t_j)$ . Player j's signal in state  $\omega$  and each player j, let  $a_j(\omega) = a_j(t_j(\omega))$ . Then the expected payoff of type  $t_i$  when she chooses the action  $a_i$  is

$$\sum_{\omega \in \Omega} \text{Pr}(\omega | t_i) u_i((a_i, a_j(\omega)), \omega) \quad (1)$$

where  $\Omega$  is the set of states and  $(a_i, a_j(\omega))$  is the action profile in which player i chooses the action  $a_i$  and every other player j chooses  $a_j(\omega)$ . Based on these, the Nash equilibrium of a Bayesian game is defined as:

1. Players: The set of all pairs  $(i, t_i)$  in which i is a player in the Bayesian game and  $t_i$  is one of the signals that I may receive.
2. Actions: The set of actions of each player  $(i, t_i)$  is the set of actions of player i in the Bayesian game.
3. Preference: The Bernoulli payoff function of each player is given by equation (1).

#### 4.4 DTN routing as Extensive Games with imperfect information

The Extensive game with perfect information (as discussed in 4.2) was described by

1. Set of players
2. The set of terminal histories
3. The player function
4. Player's preferences.

To describe an extensive game with imperfect information, a single item needs to be added to the list: a specification of each player's information about the history at every point at which there is a move. Denoted by  $H_i$  are the set of histories after player i moves. We specify player i's information by partitioning (dividing up)  $H_i$  into a collection of information sets. This collection is called payer i's information partition. When making her decision, player i is informed of the information set that has occurred but not of which history within that set has occurred.

Suppose for example that player i moves after histories C,D and E (i.e.  $H_i = \{C, D, E\}$ ) and is informed only that the history is C, or that it is either D or E. That is, if the history C has occurred, then it (player) is informed that C has occurred, whereas if either D or E has occurred, then it (player) is informed only that either D or E has occurred and not C, it (player) is not informed whether the history that has occurred was D or E. Then player i's information partition consists of two information sets:  $\{C\}$  and  $\{D, E\}$ . If instead it (player) is not informed at all about which history has occurred, then its information partition consists of a single information set  $\{C, D, E\}$ , whereas if she is informed precisely about the history, then her information partition consists of 3

information sets,  $\{C\}, \{D\}$  and  $\{E\}$ . As before, denote the set of actions available to the player who moves after the history  $h$  by  $A(h)$ . We allow 2 histories  $h$  and  $h'$  to be in the same information set only if  $A(h) = A(h')$ . This is because the player who moves after any history must know the set of actions available after that history, so if  $h$  and  $h'$  are in the same information set and  $A(h) \neq A(h')$ , then the player who moves at this information set can deduce which of these 2 histories had occurred by looking at the actions available to it. Only  $A(h) = A(h')$  is the player's knowledge of the set of actions available to it consistent with its not knowing whether the history is  $h$  or  $h'$ . If the information set that contains  $h$  and  $h'$  is  $I_i$ , the common value of the  $A(h)$  and  $A(h')$  is denoted  $A(I_i)$ . That is,  $A(I_i)$  is the set of actions available to player  $I$  at its information set  $I_i$ . Many interesting extensive games with imperfect information contains a move of chance, so the definition of an extensive game, unlike the original definition of an extensive game with perfect information, allows for such moves. Given the presence of such moves, an outcome is a lottery over the set of terminal histories, so each player's preferences must be defined over such lotteries.

An extensive game (with imperfect information and chance moves) consists of

1. A set of players
2. A set of sequences (terminal histories) having the property that no sequence is a proper sub-history of any other sequence.
3. A function (the player function) that assigns either a player or "chance" to every sequence that is a proper sub histories of some terminal history.
4. A function that assigns to each history that the player function assigns to chance a probability distribution over the actions available after that history, with the property that each such probability distribution is independent of every other distribution.
5. For each player, a partition (the player's information partition) of the set of histories assigned to that player by the player function.
6. For each player, preferences over the set of lotteries over the terminal histories.

The simplest extensive games, in which each player moves once and no player, when moving, is informed of any other player's action, model situations that may alternatively be modeled as strategic games and can be demonstrated in BRG.

## 5. CONCLUSION AND FUTURE WORK

This paper theoretically explores the use of Game Theory as routing policy for DTN bundle routing. Being a theoretical overview, the paper does not discuss experimental treatment or results which may be beyond its scope. A Brief comparison of BRG with various game forms is introduced. Future scope of work includes,

1. Detailed analysis of DTN routing with respect to each game form. For instance, a node may have positive payoff on receiving a new bundle. However, the same node will suffer a negative payoff when it tries to receive the same bundle again as it is a duplicate.
2. Experimentation and subsequent implementation of the same in DTN bundles.
3. The implementation may require changes to the Bundles in way of maintaining history or signaling which may be necessitated by the Game theory itself.
4. Analysis of BRG using Gambit [15] to compute its Nash Equilibrium and other solutions.
5. Apply the solutions of Gambit to design Game Theory based routing scheme for AUDTWMN [16].
6. Simulate the Game Theory based routing using Alunivdtnsim [17] and analyze its performance in comparison to other existing and proposed [18] DTN routing schemes.

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