Characterizing and Mitigating Communication Challenges in Wireless and Mobile Networks

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Characterizing and Mitigating Communication Challenges in Wireless and Mobile Networks

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To my parents,

for their support and encouragement.

To my wife Yan Shen,

for her love and sacrifice.

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SUMMARY

Wireless and Mobile (WAM) networks have been evolving and extending their reach to more aspects of human activity for years. As such, networks have been deployed in wider and broader physical range and circumstances, so that end-to-end contemporaneous connectivity is no longer guaranteed. To address this connectivity challenge, recent research work on Disruption Tolerant Network (DTN) paradigm uses intermediate nodes to store data while waiting for transfer opportunities towards the destination. However, this work differs from conventional research work in WAM, e.g., Mobile Ad hoc Network (MANET) routing, since the connectivity assumptions are so different.

In this thesis, we present the WAM Continuum framework which aims to provide a unified treatment of wireless and mobile networks. The framework is based on the construction of a WAM continuum that defines the space of networks and a corresponding formalism by which one can group related WAMs into classes that map into design and operational regimes. We show a specific instantiation of this framework that classifies networks according to their path properties and apply it to networks described by traces from both real platforms and synthesized mobility models. Effect of introducing controllable node mobility, e.g., message ferrying, is quantitatively evaluated in our study. We extend this framework in a manner that enables the classification of a WAM's energy "sufficiency" depending on a combination of the network connectivity properties, available energy, and power management scheme. As another extension under the same WAM continuum framework, this thesis studies the interaction of mobile computation collaboration and underlying network connectivity characteristics.

Classification results from our framework indicate that heterogeneous connectivity may exist in WAM networks. In such cases, protocols from different routing paradigms need to work together to provide effective data communication. We focus on integration of MANET routing and message ferrying in clustered DTNs. A hybrid routing approach is developed in

which both MANET routing and message ferrying are used to explore available connectivity in clusters via gateway nodes. Different data aggregation as well as transmission scheduling algorithms are proposed. To achieve better performance, we also study the ferry route design problem in the clustered DTNs and develop three route design algorithms.

This thesis work also includes our experience to address challenges associated with new data communication requirements in oil field operations at remote areas. Backed up by a comprehensive measurement study of long range data links provided by satellite and cellular services, we develop a WAM network where multiple data links are jointly used to achieve an effective data communication solution in the challenged environment.

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CHAPTER I

INTRODUCTION

1.1 Conventional Wireless and Mobile Network

Wireless and Mobile (WAM) networks have been evolving and extending their reach to more aspects of human activity than ever before. The advent of wireless portable devices has enabled a broad range of new applications from social media on hand held devices to wild life tracking with sensors and from location based services to mobile computation.

Wireless and mobile networks can be divided into two broad categories based on how the network is constructed and what is the underlying architecture. There are *infrastructure-based* networks with designated access points or base stations serving as gateways to voice/data backbones, which normally are wired networks with fixed infrastructure. Mobile nodes establish direct connections with those gateways following a managed signaling sequence. Among this type of networks, mobile cellular phone networks have had tremendous success with nearly 400 million end user devices sold in 2011 Q2 according to IDC report [49]. Wireless LANs [58] operating in infrastructure mode have also gained significant popularity as a cost effective and license-free way to provide data access in a local area.

In the meanwhile, other wireless and mobile networks fall into the *infrastructure-less (ad hoc)* category in which the network is formed with cooperation of an arbitrary set of nodes, none of which have a specific infrastructure designation. Infrastructure-less wireless networks with mobile nodes, frequently called Mobile Ad Hoc Networks (MANETs) [33], have been the subject of extensive research for at least three decades. Interest in such networks is almost as old as the Internet [57].

In both infrastructured and infrastructureless wireless networks, a wireless link forms between a node pair when their communication interfaces are both active and within radio range of each other. Wireless networks are fundamentally different from wired networks as the connectivity in these networks may keep changing throughout their operation as a wireless link goes up or down when nodes are in or out of communication range due to reasons such as mobility. In keeping with the literature, we call such communication opportunities between node pairs *contacts*.

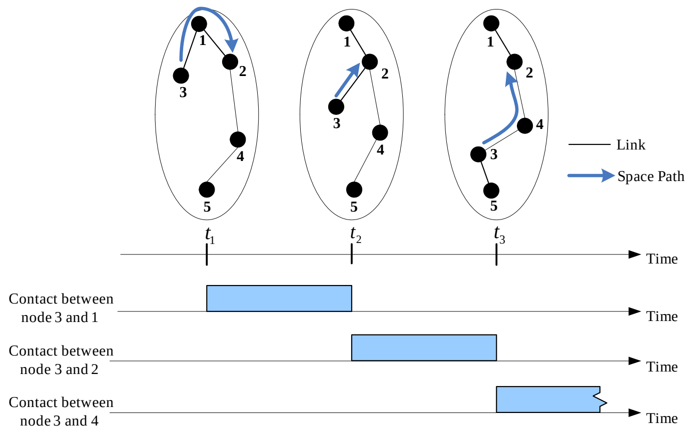


Figure 1: MANET Routing and Space Path

In conventional wireless and mobile networks, such dynamics of link status along end-to-end paths is assumed to be transient and the same or alternate paths can be restored relatively quickly. In MANET, nodes are recruited to serve as intermediate routers which relay data packets between two hosts that are not in direct contact. *Space path* formed by a set of contacts that exist contemporaneously is discovered in the *routing* process. Figure 1 shows snapshots of a MANET over time as the connectivity among nodes changes. Space paths between node 2 and 3 are also illustrated. Various approaches, e.g., proactive ones such as DSDV and OLSR protocols [32, 78] or reactive ones such as such as AODV and DSR protocols [53, 79], have been developed with different design considerations. In the meanwhile, interruptions on data communication between mobile nodes and base stations in infrastructured wireless networks are handled by specific signalling. As nodes moves from one base station's coverage to another, a procedure called the *handoff* is triggered [47, 70] to ensure the stability of data communication between these mobile nodes and backbones via these base stations.

1.2 *Delay Tolerant Network*

Regardless of the specifics of the MANET routing protocol or the handoff signalling, an end-to-end contemporaneous path is always assumed between the source and the destination. However, as wireless and mobile networks have been deployed in wider and broader physical range and circumstances, the end-to-end contemporaneous path assumption may not be always valid. Recently, research has focused on these challenged wireless and mobile network and the ways to transit data in such networks. These challenged networks go by various names: delay-tolerant, disruption-tolerant, opportunistic or intermittently-connected networks [39, 64, 91, 99]. We will use the "DTN" acronym to refer to this class of networks.

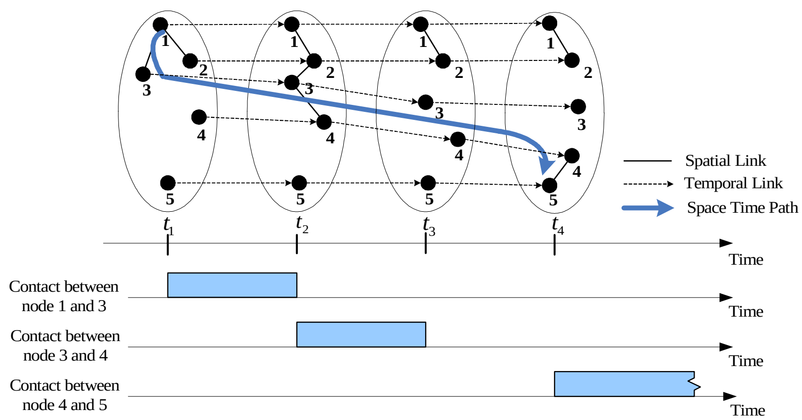


Figure 2: Space Time Path

DTNs differ from conventional wireless and mobile networks on the assumption of end-to-end connectivity. Figure 2 shows snapshots of a DTN over time. Conventional MANET routing protocols are not able to deliver data packets between node 1 and 5 as network partitions persist. However, asynchronous messaging of data bundles [39] provides meaningful communication in a *store-carry-and-forward* paradigm. Data is forwarded by being transmitted when link exists and then being stored at the intermediate node awaiting the next communication opportunity.

In Figure 2's example, data bundles can be forwarded from node 1 to 3 at time t_1. And they are stored on node 3 until t_2 when they are forwarded again to node 4. Node 4 stores those bundles and eventually forwards data to node 5 at t_4 when the link between node 4 and 5 forms. Assuming there are temporal links between the same node in consecutive snapshots in addition to physical links, i.e., spatial links, among different nodes in the same snapshot, those data bundles are forwarded along a *space-time path*.

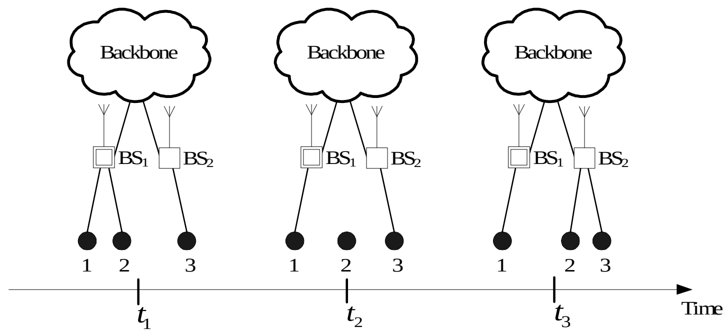


Figure 3: Path interruption in Infrastructured WAM

The end-to-end path from source to destination may also experience interruptions in infrastructured wireless and mobile network. More extensive usage of mobile devices and higher node mobility create challenges on the coverage of Wireless LAN, cellular system and even satellite network. In Figure 3's example, node 2 is able to access the backbone at t_1 via base station 1. Data bundles from node 2 to the backbone must be stored from t_2 to t_3 which is the duration of disconnection between node 2 and base stations. Note that the node 2 may access a distinct or even different type base station at t_3 when it regains the access to the backbone.

Examples of WAM networks in the DTN category include but are not limited to the following:

- Sensor Networks [7, 46, 65]: Sensor networks consist of spatially distributed nodes to cooperatively monitor physical or environmental conditions. These sensors are small in size and have limited communication range, implying a connected path may not always be established back to base stations.

- Human and Vehicular Networks [13, 48, 61]: Short-range wireless communication devices can be carried by humans or vehicles for various data services from activity monitoring to web access. Contacts between nodes are sporadic due to carriers' movements.

- Data collection at remote areas [29, 75]: Operations such as oil field activities may be conducted at remote locations under harsh working conditions. A satellite link may be disconnected from time to time.

- Deep Space/Deep Sea Communication [22, 77]: Wireless communication extends its reach to interplanetary or under-water data transmission. However, links in these types of network are associated with intermittent connectivity, long delay and high link loss.

- Disaster Recovery/Military Deployment [17, 97]: In these scenarios, data communication is essential for the success of missions. But frequent network partitions are expected due to natural factors such as difficult terrain or hostile actions.

Various DTN routing algorithms have been proposed which choose forwarding paths based on knowledge about network status [23,52,64], apply flooding to propagate messages to all nodes in the networks [99], or make forwarding decision based on certain expectation of the delivery performance [11]. When there is little or no contact opportunities in DTNs, data delivery is difficult with any of those DTN routing protocols. In this case, additional *assistance* is required to enable data delivery. Deploying inexpensive wireless nodes with storage are shown to improve data delivery by providing more relay opportunities [111]. Different types of infrastructures, including base stations and wireless mesh, are compared in [15]. Controllable mobility such as message ferrying [93, 108, 109] is another type of assistance available for data delivery in DTNs.

1.3 WAM Continuum and Network Classification Framework

In previous research work, studies of conventional wireless and mobile network is separated from or in contrast to those for DTNs. Therefore, protocols developed for MANETs generally do not work in DTNs and vice versa, since the connectivity assumptions are different.

In both cases, durations and intervals of contacts among wireless nodes determine characteristics of communication opportunities and consequently the performance of data delivery. Therefore, research work has been done on measuring and characterizing contacts in various scenarios from recording people's encounters by bluetooth devices [87] to tracking buses' communication opportunities via open Wireless LANs [21].

In this thesis, we make the simple but powerful observation that MANETs and DTNs fit into a continuum that generalizes these two previously distinct categories. Building on this observation, we develop a WAM continuum framework that goes further to scope the entire space of Wireless and Mobile networks so that a network can be characterized by its position in this continuum. Certain network equivalence classes can be defined over subsets of this WAM continuum and this classification can be used to determine network design and operation.

We develop our quantitative classification formally and present a specific instantiation of our framework based on connectivity in WAM networks. Unlike these empirical studies of DTNs at the contact level, we characterize wireless and mobile networks on the path level in this framework. The goal is to have a path classification usable to determine the most appropriate operation of the network. Unlike previous approaches [19], this classification admits granularity at the level of node-pairs, thus accommodating classification of portions of the network as well as the network as a whole. Once per node pair results are generated, they can be generalized into a network level classification.

Conventional MANETs and infrastructured wireless networks are characterized by the availability of space paths. We use the term *Space-Path Networks (SPNs)* [19] to denote networks where a space path can be found among all node pairs. Note that a wireless and mobile network's characterization not only decides which suite of protocols can be used but also whether assistance is required. If certain assistance such as message ferrying is required to provide effective data delivery in a DTN, such network is classified as *"Assitance-needed DTN or A-DTN*. Otherwise, the term *"Unassisted" DTN or U-DTN* is used to describe networks which is neither *SPN* nor *A-DTN* where data is deliverable using a DTN routing protocol without any "assistance".

By applying our framework to networks described by traces from real platforms and mobility models, we show that it can be used as a systematic and formal descriptive and evaluative tool. Furthermore, our classification results indicate that the boundary between different classes of networks is not rigid. More importantly, by providing necessary "assistance", e.g., using message ferrying, a WAM's classification can be changed due to transformation of path level characteristic. In other words, data communication challenges in such networks can be mitigated by allocating more resources and using them properly.

1.4 Network Classification Framework Extensions

Besides challenges on path connectivity in wireless and mobile networks, another category of challenges in these networks is the power supply and management. Since the nodes of a WAM network are usually small and powered by battery, energy management is a critical issue for deployment and operation in those networks. Various power management schemes have been proposed for MANET [28, 101, 103], infrastructured WAM [6] and DTN contexts [16, 55, 100]. The principle is reducing energy consumption rate by turning off communication interfaces from time to time. Related research work focuses on various objectives from increasing nodes' lifetime to keeping a area covered by a sensor network [102]. However, an important yet practical question is always not answered: whether a certain amount of energy provision in a WAM network is enough for its operation.

In our work, we characterize this category of challenges in WAM by first extending our instantiation of the connectivity based classification framework. We start with the understanding that a network's classification from energy perspective is jointly determined by many factors, including its network connectivity properties, available energy, and power management scheme. These last two factors affect network connectivity and possibly alter the connectivity based classification results. Since power management schemes always intentionally turns of radio interfaces and thus reduces communication opportunities, certain level of "downgrading" is expected if power management scheme is used in a WAM network since limited energy is provided. By quantifying such "downgrading", we are able to determine to what level the communication between a node pair is affected by the energy supply and the power management scheme used. Results from node pairs are generalized into a network classification on whether such network has "sufficient" energy for its operation. We also evaluate the "downgrading" on traffic handling capacity by energy provisioning and power management schemes. Characterization of traces from real platform and certain mobility model using our classification framework provides useful insight on WAM operation from energy management point of view.

Today's mobile devices, e.g., smart phones, are equipped with processing capability and storage capacity to handle computational tasks beyond simple voice/data communication. In the meanwhile, advanced techniques such as application partitioning [31] and code offloading [34] are developed for mobile applications. These two factors make computational collaboration possible between mobile nodes and infrastructure [31, 34] or among mobile nodes [89]. In other words, a resource-intensive and time-consuming application can be divided into a number of tasks, which are distributed in the WAM network. After their executions, results of these tasks are returned to the node initiating the application. Therefore, functionalities such as media processing and data analysis can be provided beyond the resource limitation of a single mobile node. More importantly, the computational task can be finished faster or with less energy consumption on mobile nodes with support from resource inside the infrastructure or on other nodes.

In WAM networks where space-time path might exist between node pair, initiation and coordination of the computational collaboration among mobile nodes become a challenging task [89]. After computational tasks are distributed, results of these task may not be returned to the task initiator in time. We characterize such challenge in WAM networks with the extension of our connectivity based classification framework. The process of computational collaboration associated with each task is divided into a sequence of stages with different time constraints. A "round trip" with these time constraints satisfied must exist from the task initiator and the task executor to make such collaboration meaningful. By counting the number of these "round trips" from a node to its peers, we are able to determine whether it is "advantageous", i.e., finishing computational task faster, to initiate a computational collaboration at this node. Results from nodes are generalized into the network classification. In this thesis, we use such classification result to quantify the level of "worthwhile" for computational collaboration in WAM networks described by real traces and various mobility models.

1.5 Hybrid Routing in Clustered DTN

Heterogeneous spatial node distributions and concentration points of high node density exist in many practical settings [84]. Nodes in sensor networks [8] could be deployed in clusters to provide necessary sensing coverage and communication reliability. Connectivity based classification results over different mobile traces also show that different path types may exist among node pairs in the same WAM network. Therefore, to achieve efficient data delivery in such a network, different classes of routing protocols may co-exist and collaborate. In this thesis, we use message ferrying as the assistance among clusters of nodes. While a MANET protocol is able to handle data communication in each cluster, we evaluate its integration and interaction with a DTN routing protocol.

With extensive simulation results, we show that the integration of protocols from different routing paradigms requires careful evaluation of their interactions. The MANET protocol has to aggregate traffic to efficiently utilize the intermittent communication opportunities with the ferry. In the meanwhile, ferry route decision is greatly affect by MANET traffic in each cluster.

1.6 Mitigating Real Communication Challenges

In this thesis, we also report our experience of mitigating challenges in building a wireless and mobile platform used in oil field operations. While most of research work related to contact characteristics in wireless and mobile network focus on short-range and cost free radios such as bluetooth and Wireless LAN, we evaluate long range data links including cellular and satellite services in an outdoor challenged network where the connection between field locations and the data center cannot catch up with the new data communication requirement.

In the development of this platform, we first identify connectivity challenges in this infrastructured network from application's bandwidth and latency requirements. Solutions are provided correspondingly. Due to regulation policy, we are not able to use controllable mobility as assistance for additional communication opportunities to our systems located at remote areas. In this piece of work, we first conduct a large scale measurement study comparing cellular and satellite links side-by-side cross three states in US. We mitigate challenges in this network by integrating new data links into existing system. Performance measurements of such an infrastructured WAM network show that various access technologies have to be jointly used for an efficient yet cost-effective network solution in oil field operations.

1.7 Outline

The rest of the thesis is organized as follows. Chapter 2 discusses existing work related to the topics in our work. The WAM classification framework is defined in Chapter 3. We present classification results of contact traces from real systems and mobility models in this chapter as well. Our classification framework is extended to evaluate energy sufficiency of WAM networks in Chapter 4. And it is used as the foundation to evaluate the decision on computational collaboration in WAM networks considering connectivity characteristics. Chapter 5 studies the challenge of conducting hybrid routing in clustered DTNs. Experience of building a WAM system to mitigating communication challenges in remote areas is given in Chapter 6 with comprehensive measurement results collected during the development. We conclude this thesis and point out future research topics in Chapter 7.

CHAPTER II

RELATED WORK

This chapter provides an overview of the related work on routing in WAM networks, followed by a review of network characterization approaches. Recent research work on outdoor wireless link evaluation are presented together with resource management in WAM network.

2.1 Routing in Wireless and Mobile Networks

MANET routing protocols normally assume an contemporaneous end-to-end path can be found. On the other hand, DTN routing protocols generally assume completely isolated nodes and focus on the one-hop data exchange. When the connectivity in the network is heterogeneous and data delivery may go through multiple routing paradigms, Recent work [71, 104] extended MANET routing to overcome network partitions by utilizing multiple data duplications. Nain et.al introduced a message relay layer beneath DSDV protocol [71]. Local flooding duplicates data at the immediate neighbors, which send the duplicate to the destination once a route is found. ASOS [104] used a similar approach but duplicates were made at some designated storage-abundant nodes.

Authors of [74] extended AODV to enable it to discover nearby DTN routers during route search and obtain routing hints from them. AODV is used as a vehicle to locate DTN routers in case no end-to-end path can be determined. On the other hand, based on the path information provided by AODV, DTN-based hop-by-hop communication might be utilized instead of using an end-to-end path to improve the throughput.

The probability based routing protocol in [64] was extended in [94] which considered disconnected networks where nodes move in groups. MANET routing, i.e., DSDV, was used to keep the membership information in each group and update the probability of successful delivery to other groups. Routing was first done among groups. Once messages arrived at the group containing the destination node, they are delivered via MANET routing.

Although applications in DTNs should be tolerant to long delay and high loss rate, better delivery performance, i.e., shorter delay and higher delivery ratios, is always desirable. In DTNs, intermittent data exchange happens during nodes' contacts. Since the inter-contact time may be heavy tailed [26], forwarding copies of message along multiple path is widely used in DTN routing protocols to reduce the end-to-end delay. Many DTN routing protocols are proposed on how to make message copies and forward them, which can be a simple and aggressive approach like epidemic routing [99] or based on certain expectation of the delivery performance [11]. With different level of knowledge of the network, a suite of unicast routing protocols are developed and evaluated in [52].

2.2 Mobility Control in Wireless and Mobile Network

In MANETs, although the end-to-end connectivity is guaranteed due to dense node deployment, controllable node movement is used to adjust network topology to improve certain metrics. [42] considers moving intermediate nodes along a end-to-end path so that distances between node pairs are minimized so that lower energy is used to cover a shorter distance. Other than energy consumption, survivability of end-to-end path is considered in [18, 97]. Algorithms are proposed in [18] to transform a *non-biconnected* network configuration to a *biconnected* one by making certain nodes to move to new positions. Therefore, a single node failure won't create network paritions. Controlling a team of robots' movement based on signal strength on wireless links so that not network partitioning occurs is also discussed in [97].

In DTNs, controllable mobility normally is used as "assistance" to provide additional contact opportunities. In [63], mobile nodes modify their trajectories to move into communication range of each other and delivery message over network partitions. Moving special nodes called *message ferries* along designated routes introduces more intermittent yet regular encounters with nodes. The ferry route can be designed so that traffic load from stationary node can be satisfied [109]. This work has been extended to handle traffic from mobile nodes [93] or in multiple ferries cases [110].

The movement of ferry or similar agent can be adjusted in real time as well. A control function considering a variety of network performance metrics is given in [24]. Special order is given to resolve the conflicts in agent's trajectory adjustments towards satisfying different metrics. In [108], ferry's movement can be adjusted based on communication requests from nodes. Furthermore, nodes are able to intentionally move towards the ferry when the communication request outweighs the interruption to their routine operation.

Mobility helps energy conservation in WAM networks as well. A mobile base station was also used in [66] to increase network lifetime. Their technique leads to a more uniform distribution of energy consumption by repeatedly relocating the base station, which changes the bottleneck nodes which are closest to the base station and results in load-sharing the burden of relaying.

Reducing number of intermediate hops equals to fewer times of forwarding for each messages. Therefore, the energy consumption during communication can be reduced by using nodes' mobility to provide end-to-end path with fewer number of hops. However, the tradeoff is longer latency in message delivery [56, 90].

Opportunistic scheduling between nodes and gateway is proposed for a ferry-based network in [45]. The contact time between ferry and gateways are sufficiently long to finish all data exchange. Therefore, the objective is to minimize the delivery latency given the information about ferry schedules.

2.3 Connectivity Characterization of Wireless and Mobile Network

In MANETs, data packets are forwarded along an end-to-end contemporaneous path. Also, one essential function of numerous routing protocols developed for MANETs is route maintenance between source/destination pairs with link dynamics. Information related to end-to-end paths can be used to characterize MANETs from a routing perspective. As an end-to-end path consists of hop-by-hop links, statistical property of link availability, i.e, how long will two nodes remain connected, is shown to affect the performance of routing protocols [68]. On the other hand, path duration statistics is modeled across a set of mobility models in [9], which can be used to predict the general trends for reactive MANET routing protocols.

In a DTN, end-to-end connectivity is the exception instead of normal. Bundle/message forwarding is along the space-time path which consists of contact opportunities between node pairs. Therefore, a DTN is specified by the contacts between its nodes as well as properties of each contact. Statistics of inter-contact time, i.e., the time interval between two contacts, is studied in [26]. Inter-contact time determines the frequency of data exchange opportunities and has the most significant impact on the feasibility of opportunistic networking. Studies of four different contact traces from human movements show that distribution of inter-contact times in those DTNs follows an approximate power law, which is not consistent with exponential decay predicted by mobility models used in MANET studies.

Chaintreau *et al.* characterized opportunistic wireless networks by a parameter called diameter, which is the number of intermediate hops to find a space-time path between node pairs given a time constraint [38]. A "small-world" phenomenon is observed that the diameter grows very slowly as the network size increases. However, the diameter is affected by the delay constraint on the space-time path.

Empirical study and analytical result of human movement traces in [27] show the "path explosion" phenomenon, meaning the delay of the optimal path between a node pair may be long but there normally exists a large number of sub-optimal paths with similar delay. Besides their unique routing decision making policies, a few typical routing protocols developed for DTNs surprisingly have similar performance in light of this phenomenon. However, heterogeneous contact rates between different node pairs affect how fast the "path explosion" begins.

The author of [82] used a different approach to describe WAM. A framework for routing formalizing is provided. With this formalism and three abstract constraints and three types of pre-defined WAM networks, solvability for different WAM types is given with enumeration of those constraints.

2.4 Outdoor Wireless Link Utilization and Evaluation

A big portion of studies of outdoor data access focus on connectivity provided via open WiFi Access Points (APs) [13, 25]. Due to the limited communication range of those APs and their uncoordinated coverage, handoffs with predictive methods and using pre-fetching improved downloading are discussed in [36]. Cellular data service is also considered as a good source for outdoor data access due to its better coverage and less frequent service interruptions. Using tools from information theory, the work in [105] shows certain level of predicability of bandwidth on 3G links in a metro area. Most recently, performance comparison between WiFi and 3G connectivity are conducted in urban areas. Although these two types of data links have different characteristics, they can be good supplementary to each other based on studies in [12, 35].

Cellular data service providers normally apply sophisticated control/scheduling method in their networks. The configuration can be highly customizable from location to location due to Quality of Service (QoS) and business concerns [92]. Empirical study of of transport layer performance over those managed cellular data links are reported in [60, 67, 81].

Satellite networks are under strict regulation and management due to the expensive and limited bandwidth over the links. Research work over satellite links focus on measuring TCP's performance over those links and "tuning" the TCP protocol stack to fit the link characteristics such as long end-to-end latency [30, 50, 107].

Modern oil field operations from exploration to production requires significant amount of interactions between software and hardware as well as collaboration among field personnel. Providing data communication at field locations is not only essential but critical. Wireless technology has been well adopted since most of oil field operations are conducted at locations where a conventional wired network infrastructure is physically or financially impractical. Wireless LAN (WLAN) and two-way radio are common equipments of field crews with high mobility nowadays. And wireless communication technology continues extending its reaches at oil field operations [80, 85, 106].

[76].

2.5 Power Management in Wireless and Mobile Networks

There are two complementary approaches to optimize the energy consumption in WAM Networks: 1) Minimizing energy consumption between data communication; 2) Minimizing energy consumption during data communication.

Wireless network interfaces consumes much less energy in their sleep mode. Keep those interfaces at sleep mode as much as possible extends the operation time of the network before any node depletes its energy. But those interfaces should be available when there is data communication requests. The straightforward approach is to make the network interface cycle between sleep and active mode. This mechanism can be synchronous or asynchronous. In former approaches such as 802.11 Power Saving Mode (PSM) [6], nodes wake up periodically together. Additional mechanism must be provided to keep clocks synchronous on those node. For the latter, special rules must be defined to make sure durations in which neighboring nodes in active mode overlap. For example, the BECA/AFECA protocol [103] is designed to be integrated with a reactive MANET routing protocol. Each node cycles between sleep state and listening/active states. Those cycle intervals can be adjusted according to information such as node density so that nodes sleep for longer time whenever there are more potential alternate routes available.

Topological and connectivity information is also used to determine the energy consumption mode of nodes. A special set, i.e., dominating set, of nodes are chosen to be in active mode so that a routing backbone is maintained and the network connectivity is kept [28,101]. On the other hand, geographic information is used to divide the deployment area into grids and one node in each grid is guaranteed to be in active mode. This approach [102] is intended for sensor networking scenarios so that the whole area is covered and data collection is possible through a connected network.

In MANETs, a node turns off its wireless interface whenever there is no traffic requests or its neighboring nodes provide alternate route in the network. In the context of DTN, nodes are sparsely distributed and the time when nodes are able to communicate is limited in intermittent contacts. Therefore, considerable amount of energy can be saved by aggressively turnning off radios between contacts. But it is challenging to determine when a node is able to communicate with other nodes and when it should stay in the sleep mode. Beacons or probes are used to search for potential contact opportunities among nodes [16, 55, 100]. In those schemes, nodes use certain timers to control their state transitions. They wake up from time to time and search surrounding with beacon signals. By responding to beacons, nodes mutually discover the contact opportunity between them.

In reality, if the beacon/probe is used too frequently, too much energy is wasted if there is long time period between node contacts; on the other hand, too few beacon/probe would miss a lot of contacts and thus the data delivery performance will suffer. Schemes controlling nodes' state transition based on the availability knowledge about network connectivity are proposed and evaluated in [55]. Results show that the level of knowledge on network connectivity affects both energy saving and data delivery performance. On the other hand, the tradeoff between missing a contact and the contact probing frequency is studied in [100]. This work also includes a framework for computing optimal probing interval as a function of the contact arrival rate.

Different hierarchical power management schemes with multi-radio platforms are used in DTNs [14, 54]. In [54], a short range, low power radio is used with a long range, high power radio. As the long range radio handles data transmission, the short range radio can be used to discover contact opportunities. If traffic load can be predicted, sleep/wake-up interval of those radios are tuned by approximation algorithm for maximum energy conservation while discovering enough contacts for the expected traffic load. As this approach is appropriate for relatively dense node deployment, a different usage of multi-tier radios is proposed in [14] for DTNs with sparse node deployment. A low power, long range radio searches and predicts contact opportunities with duty cycle. A high bandwidth radio can be waken up for the data communication. In addition, a token-bucket algorithm is developed to satisfy an average power consumption rate constraint.

Turning off wireless interfaces whenever possible minimizes energy consumption between data communication requests/opportunities. Various techniques are used to reduce energy consumption during data communication in WAM networks. How to route a sequence of messages so that the lifetime of a network, i.e., the earliest time a message cannot be sent, is optimized is discussed in [62] an online approximation algorithm is proposed. Utilizing nodes mobility to provide intermittent yet regular contact opportunities instead of setup contemporaneous multi-hop paths conserves energy [56, 88].

CHAPTER III

CLASSIFICATION FRAMEWORK AND WIRELESS AND MOBILE NETWORK CONTINUUM

For any particular network, the question of whether it is a MANET or a DTN (or equivalently a network with space paths or space-time paths) is critical to answer. Protocols developed for MANETs generally do not work in DTNs and vice versa, since the connectivity assumptions are so different; hence categorizing a network is critical to its effective operation. In practice, the question of network category is challenging to formulate and answer. Many networks will not fit neatly within a simple classification scheme and/or they may change their classification over time.

This chapter aims to take a fresh perspective on classifying wireless and mobile networks (WAMs) networks. We develop the WAM continuum framework which provides a unified treatment of wireless and mobile networks. We envision that each fully specified WAM represents a point in a multi-dimensional space that we call the *WAM continuum*. Figure 4 illustrates this concept with a two-dimensional space that uses the *average node density* and the *average node speed* as the two dimensions. A given WAM network will occupy a point in this two dimensional space based on its density and speed properties. Furthermore, We can group points on a WAM continuum into *classes* such that networks within a specific class possess equivalent properties. A qualitative classification over this two-dimensional WAM continuum results in three network categories mentioned in previous discussion: Class 1 is with reasonably persistent space paths with high node density with slow movements; Class 2 is with no paths among certain node pairs due to low density and low speed; and Class 3 is where space time paths can be created from nodes' movement.

Our characterization can apply to an entire network or can be different for different parts of the network (e.g., different node pairs). Certain *network equivalence classes* can be defined over subsets of this WAM continuum and such network classification can be used

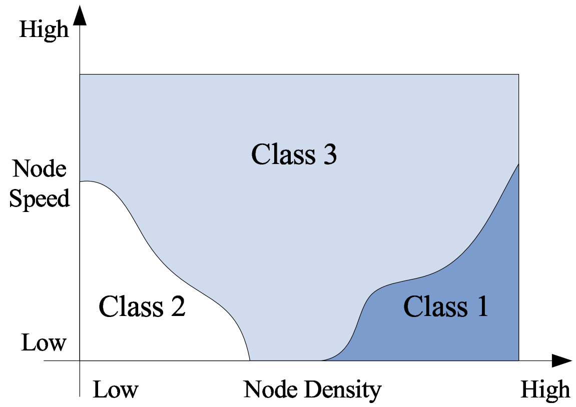


Figure 4: WAM Continuum Classification Example

to help guide WAM design and operation.

In this chapter, we develop a WAM classification framework based on the path type between node pairs. We start with node pair classifications and then provide the whole network classification from node pair classification results. The power of our classification framework is demonstrated on both real contact traces which is from WAM deployments and synthesized traces which have tunable parameters to highlight the interesting capability of our framework.

3.1 Network Classification based on Connectivity

We consider wireless and mobile network comprising a number of nodes equipped with wireless interfaces moving within a given space. Communication between two nodes is established when they are within radio range of each other. Contacts between nodes i and j are described by a link function $L_{ij}(t)$ as follows:

$$L_{ij}(t) = \begin{cases} 1 & \text{if nodes } i \text{ and } j \text{ are within radio range} \\ & \text{of each other} \\ 0 & \text{otherwise} \end{cases}$$

We call those time interval in which $L_{ij}(t) = 1$ *contacts* between node i and j. Data can be exchanged between nodes during those contact periods. Therefore, in terms of the data transfer opportunities, a WAM is fully specified by the sequence of contacts, $L_{ij}(t)$, between its nodes.

At any given time, a graph $G = (V, E)$ can be used to describe nodes and links. In order to accurately describe a general WAM with time-varying contacts, we use the model based on the concept of evolving graphs [40].

Definition 1. *Evolving Graph [40]: An evolving graph* $\mathcal{G} = (G, S_G, S_T)$ *comprises a graph* $G = (V, E)$*, the sequence of its* $\mathcal{T}$ *subgraphs* $S_G = G_1, G_2, ..., G_{\mathcal{T}}$ *and the sequence of its* $\mathcal{T} + 1$ *time instants* $S_T = t_0, t_1, t_2, ...t_{\mathcal{T}}$. G_k *is the subgraph in place during* $[t_{k-1}, t_k)$.

It is relatively straightforward to see how a wireless and mobile network can be described as an evolving graph. As nodes move they potentially acquire and shed neighbors, changing the shape of a graph. The exact nature of these neighbor changes is a function of the node mobility and can be captured by the specifics of graph evolution.

Our notion of space-time paths is captured by the definition of journeys as follows:

Definition 2. *JOURNEY [40]: A journey* $\mathcal{J} = (R, R_\delta)$ *in an evolving graph* $\mathcal{G}$ *is comprised of* $R = e_1, e_2, ..., e_k$ *the sequence of edges it traverses, and* $R_\delta = \delta_1, \delta_2, ..., \delta_k$ *the corresponding time instants of edge traversal.* R_δ *must be in accordance with* R *and* $\mathcal{G}$ [1].

Ferreira *et al.* [40] also define a *foremost journey* as one that has the earliest arrival time at a destination. Note that a space path is a special type of journey in which all the links in the journey exist in one of the graphs G_k describing the evolving graph over time period $[t_{k-1}, t_k)$. We use the terms "space-time path" and "journey" interchangeably in this thesis. Both are similar to definitions in [37, 51, 69].

3.2 Node Pair Classification

In this section, we first formally define "ideal" node pair classes by mapping the connectivity between them onto paths of certain properties without taking time consideration into account. This idealized classification is then extended to accommodate operational concerns, including time constraints.

[1] *That is, each edge traversed must be in the evolving graph at the time of traversal.*

3.2.1 An Idealized Node Pair Classification

For the following definitions we assume that an evolving graph $\mathcal{G}$ describes the WAM under consideration.

Definition 3. *Space-Path Pair (S-Pair): A pair of nodes i and j is called an S-Pair if a space path can always be found between them in $\mathcal{G}$.*

Data can still be transferred between node pairs which are not S-Pairs with the store-carry-forward paradigm. To capture the character of those node pairs, we have the following node pair definition:

Definition 4. *Space-Time-Path Pair (ST-Pair): A pair of nodes i and j is an ST-Pair if:*

- *$\forall t$, a journey exists in $\mathcal{G}$ between i and j at t.*

- *this pair is not an S-Pair.*

It is possible that no path can be found between particular node pairs after certain time point. Therefore, we introduce the last node pair class.

Definition 5. *No-Path Pair (N-Pair): A pair of nodes i and j is an N-Pair if $\exists t$ such that no journey can be found from i to j after t in $\mathcal{G}$.*

Finally, it is important to note that both the ST-Pair and the N-Pair definitions are not symmetric. That is if node-pair (i, j) is either an ST-pair or an N-Pair then node (j, i) might follow a different classification. Although there is a *space time path* from node 1 to node 5 at time t_k, there is *no path* from node 5 to node 1 from t_k to t_{k+3}. Note, however, that the S-Pair definition is symmetric.

3.2.2 A Practical Classification

We now augment our node-pair classification above to incorporate some degree of practical routing consideration. To understand the motivation, consider a network where connectivity changes rapidly but where a particular node pair is always connected through a space path. While a space path exists all the time, the actual links forming the path change in such a manner that no specific path persists for a long time. According to our definitions above, this pair will be classified as an S-Pair and one may reach the conclusion that a MANET routing protocol may be suitable for routing between the two nodes. However, such routing protocols need some time to discover a route and therefore require a certain amount of *route persistence*. In that case we need to modify our S-Pair definition to take this into account. To that end we define space path persistence as follows:

Definition 6. *Space Path Persistence Time: Let i and j be an S-Pair in an evolving graph $\mathcal{G}$. By definition, the node pair is always connected by a space path that may change over time. We denote the sequence of space paths connecting the two nodes over time as $p_1, p_2, p_3, \ldots$. The persistence time for path p_i is the time from when it is first formed in the network until the time it is replaced by a new path p_{i+1}.*

Assuming that routing protocols need at least δ time units to discover a new path, we define the following:

Definition 7. *(δ) S-Pair: A (δ) S-Pair is an S-Pair where all the paths have persistence time more than δ.*

Now consider node pairs classified as ST-Pair. For such pairs, the important consideration is the duration of the journey providing the space-time path. While such journeys are usable if some form of DTN routing is used, such networks often impose a lifetime beyond which data is not usable. This leads to the following definition.

Definition 8. *(γ) ST-Pair: A (γ) ST-Pair is an ST-pair where the journeys according to Definition 4 are always less than or equal to γ in duration.*

3.2.3 Classifying Node Pairs Over Time

The previous classification provides a rather strict categorization of node pairs. For example, if a node-pair that is connected through a space path, losing connectivity even for a brief period of time make it not an S-Pair.

To address this issue we propose to classify network over time. Time is broken up into *epochs* during which the network connectivity (or graph in an evolving graph) does not change. Our goal is to provide a classification *for each node pair in each epoch* according to the following criteria for given δ and γ:

- A node-pair is classified as an S-Pair during epoch k represented by subgraph G_k (one of the series of subgraphs in the evolving graph) if the node pair is in the same connected component of G_k and either the epoch lasts for at least δ or the path connecting the node pair does not change for at least δ time units and this period consists of one or multiple epochs including epoch k.

- A node-pair (i, j) is classified as an ST-Pair during epoch k if it is not classified as an S-Pair in this epoch and one can find a journey from i to j of duration no more than γ starting form the beginning of this epoch.

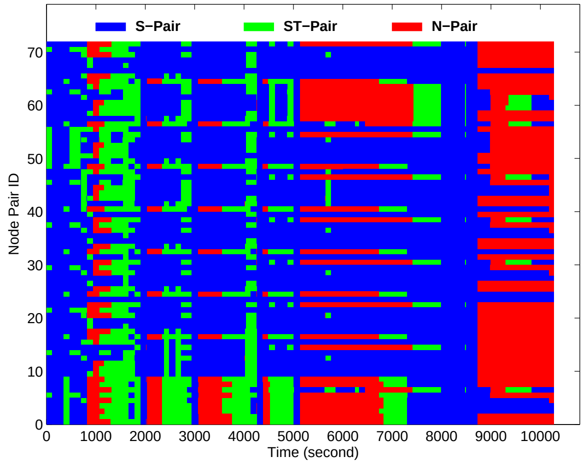
- A node-pair is classified as an N-Pair otherwise.

Our procedure uses Dijkstra algorithm to compute space path and the algorithm described in [40] for computing foremost journeys.

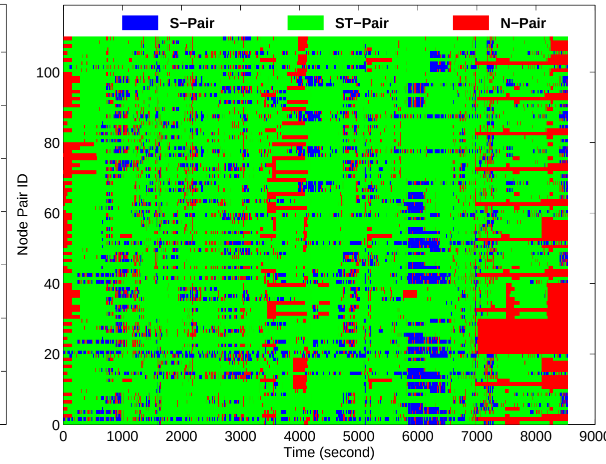
3.2.4 Examples of Node Pair Classification

We now illustrate our node-pair classification methodology by applying it to networks represented by two types of contact sequences: traces collected from real WAM deployment or experiment [41, 43, 87, 95] and synthesized ones from mobility models such as Random Way Point (RWP) and Levy Walk [83]. we consider the latter for their simplicity on tuning different parameters to highlight the interesting capability of our classification scheme. It should be clear that our goal in this illustration is to demonstrate the descriptive and evaluative power of our framework and not to compare various network operation strategies.

With $\delta = 2$ seconds and $\gamma = 600$ seconds, we first show epoch by epoch node pair classification of the first three hours portion of a 9 node trace [86] collected in the Haggle Project [87]. As a comparison, Figure 5a presents the classification results over a 11 node trace collected from participants in a rollerblading event [95]. Time is shown on the x-axis and node pairs are represented on the y-axis. Different node pair classification are represented with different colors as indicated by the legend. Note that each node pair



(a) Haggle Trace



(b) RollerNet Trace

Figure 5: Epoch by Epoch Node Pair Classification: Small Time Scale

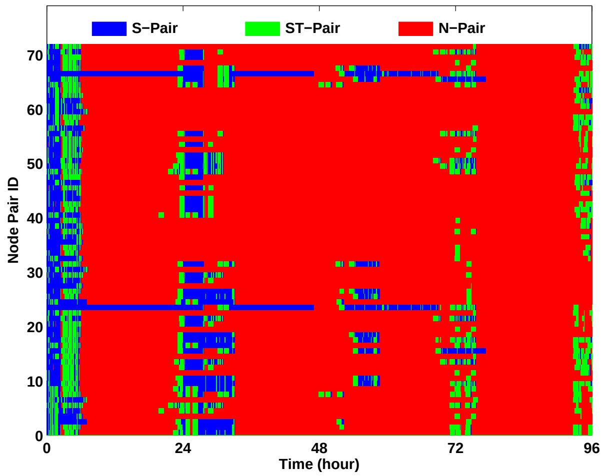
appears twice along the y-axis but in a reverse direction. The reason is that ST-Pair and N-Pair classification is not symmetric between each node pair as we pointed out earlier in Section 3.2.1.

Both traces are about 3 hours long and contain similar number of nodes. They all record encounters between human participants using bluetooth devices. However, the classification results presented in Figure 5 are quite different and the insight into properties of the trace achievable from this visualization of the outcome of our classification is evident. Node pairs in Haggle trace are mostly classified as S-Pair over time. On the contrary, node pairs in the RollerNet trace are mostly ST-Pair over time. Such difference roots from the connectivity characteristic of these two WAM network instances.

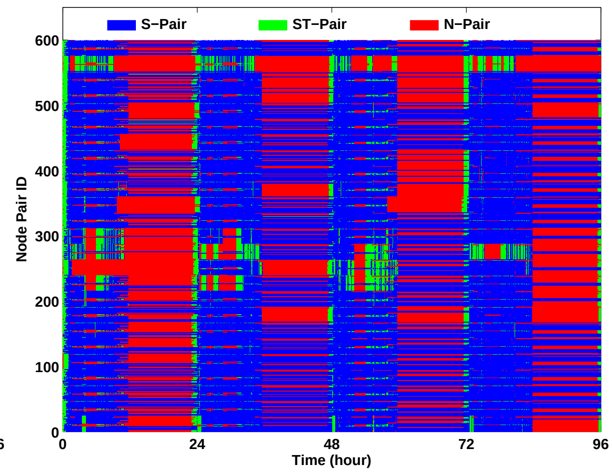
Haggle trace was collected in an office building environment where the distance between node pairs is short. In addition, node movement in such setting is limited and constrained. Abundant and stable physical links among nodes ensure that there are plenty space paths in this WAM network.

Nodes in the network presented by RollerNet trace move in an open space so that the physical distance between node pairs can be long. Furthermore, those nodes, i.e., rollerbladers, are in relatively fast movement all the time in the 3 hour period. Therefore, direct contacts between node pairs are sporadic and duration of these contacts are short.

Therefore, we can see space paths occur sparsely among node pairs and those paths generally do not last long. On the other hand, nodes movement creates plenty space time paths in this WAM network. Data communication is still feasible if the application can tolerate a delivery latency of 600 seconds.



(a) Haggle Trace

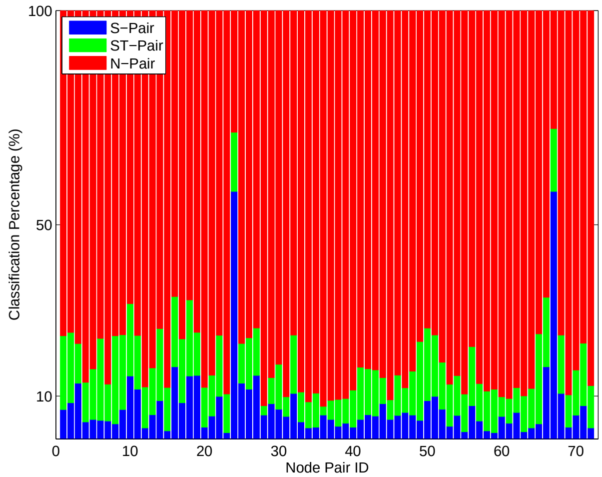


(b) Shopping Mall Trace

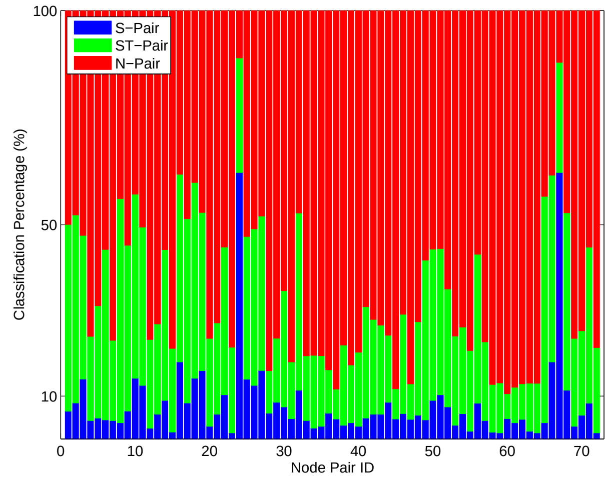
Figure 6: Epoch by Epoch Node Pair Classification: Big Time Scale

Figure 6 shows classification results in a much bigger time scale. With $\delta = 2$ seconds and $\gamma = 3600$, classification result of the entire trace of Haggle trace is illustrated in Figure 6a. Figure 6b presents the result of the trace from an experiment conduct in a shopping mall [41]. In this experiment, 25 mobile devices are distributed to sales in different stores and contacts among those devices are recorded in a 4 days period.

In both WAM networks, the interval of network characteristic changes follows human daily activity cycle, i.e., 24 hours. The long duration in which most of node pairs are N-Pair is the time when most participants leave the experiment settings, e.g., their working places, and carry those mobile devices with them. Beside heterogeneous classification results over time, Figure 6 also indicates the spatially heterogeneous character in both WAM networks. In Haggle trace, two nodes are in constant contact is represented by the two blue lines (actually representing the same node pair). In Shopping Mall trace, there are more node pairs classified as S-Pair most of the time during the 4 days experiment. And such classification result is not affected by the daily activity cycle. One possible explanation is that those



(a) $\gamma = 1$ hour, $\delta = 2$ seconds



(b) $\gamma = 8$ hour, $\delta = 2$ seconds

Figure 7: Node Pair Classification and Simulation Result of the Haggle Trace

mobile devices are left in the stores by the experiment participants.

To show the variation on node pair classification in the Haggle trace from a different perspective, we calculate percentage of time that each node pair belongs to each type of classification and present the result in Figure 7a. Note that overall the classification varies significantly among all node pairs. The impact of the parameters γ on the classification of node pairs in the Haggle trace is illustrated in Figure 7b. A larger γ value means more relaxed constraint on the allowed journey duration. A node pair classified as an N-Pair in some epochs may be reclassified as ST-Pair. We notice an increase in the ST-Pair percentage on most node pairs in Figure 7b when γ increases from 1 hour to 8 hours.

With the same contact trace, we run a simulation using the ONE simulator [59]. Simulation parameters are set as follows: TTL = 1 hour; traffic load is 1 kbps between each node pair with average message size of 100 KB; the buffer size on each node is 50MB and probabilistic routing [64] is used. The correlation between node classification results and message delivery ratio is given in Figure 8, which demonstrates how our classification can be used as a low cost performance prediction in certain instances.

The value of δ determines whether an end-to-end path can be classified as a space path. To show the role of this parameter plays in the classification, we use the trace from an outdoor MANET experiment [44] consists of 33 laptops carried by walking students on a

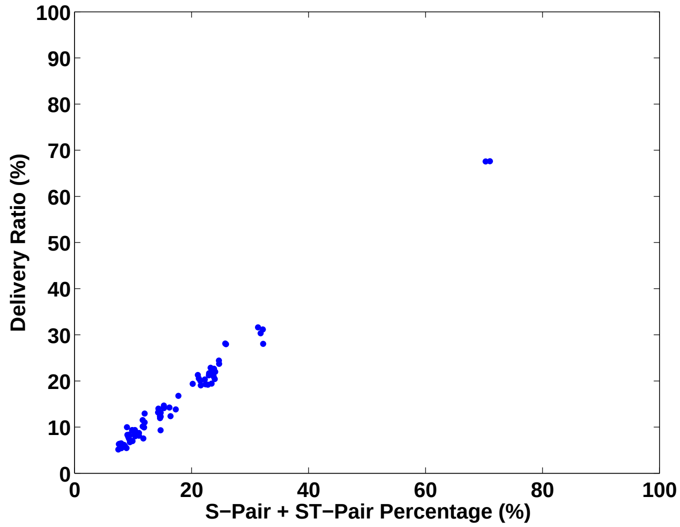


Figure 8: Correlation between Classification and Simulation Result

sports field. Different MANET routing protocols were evaluated in this experiment [43]. Among the 33 mobile nodes, we select 16 with good and continuous GPS logs. A 4000 second contact trace is generated from these GPS logs accordingly.

δ	S-Pair	ST-Pair	N-Pair
2	95%	4.8%	0.2%
4	93.6%	6.2%	0.2%
8	89.7%	10.1%	0.2%
16	79%	20.8%	0.2%

Table 1: Percentage of Node Pair Classifications

Averages of all node pair classification results with $\gamma = 60$ seconds and different δ values are shown in Table 1. As the value of δ increases, a tighter constraint is put on the stability of a space path, which leads to lower percentage of S-Pair classification. When the δ value is 16, the average S-Pair classification of all node pairs is lower than 80%. In the routing protocol implementations used in [43], intervals between basic operations such as neighbor probing are several seconds. Therefore, a multi-hop route discovery might take more than 10 seconds to finish. End-to-end contemporaneous paths that exist shorter than that period are not classified as space paths and the MANET protocol implementation is not able to use them. This provides one explanation of why the data delivery ratios with MANET protocols were low in the experiment reported in [43].

3.3 Whole Network Classification

We now show how the per-node-pair classification described above can be aggregated to classify whole networks. In [19], three categories of network are proposed: *Space Path Network (SPN)* in which MANET routing protocols can be applied among all nodes, *Unassisted-DTN (U-DTN)* in which DTN routing protocols (such as epidemic routing [99] or probabilistic routing [64]) are able to deliver data between all node pairs; and *Assistance-needed-DTN (A-DTN)* in which extra assistance (such as message ferrying [108]) is needed because no space/space-time path can be found between some node pairs.

While we use the same terminology for whole network classification as [19], the approach in this paper is different in that it builds the network classification from components of node-pair classifications. In addition, we allow some flexibility in the definition where for example a network can be classified as an SPN even if some of the node-pairs are ST- or N-pairs.

Specifically we define the following:

Definition 9. *x-SPN: A network is classified as an x-SPN in an epoch if at least $x\%$ of the node pairs are classified as S-Pairs during that epoch.*

Definition 10. *x-U-DTN: A network is classified as an x-U-DTN in an epoch if at least $x\%$ of the node pairs are classified as either S-Pairs or ST-Pairs and the network is not classified as x-SPN during that epoch.*

Definition 11. *x-A-DTN: A network is classified as an x-A-DTN in an epoch if it is neither an x-SPN nor an x-U-DTN.*

Similarly as in node pair classification, in order to capture the potential network character change over time, we classify the network in each epoch and the network classification over its lifetime is given by the percentage of time that it spends in each class[2].

x	x-SPN	x-U-DTN	x-A-DTN
100	0.5%	6.6%	92.9%
90	0.5%	7.7%	91.8%
50	3.3%	17.3%	79.4%

Table 2: Network Classification on the Haggle Trace

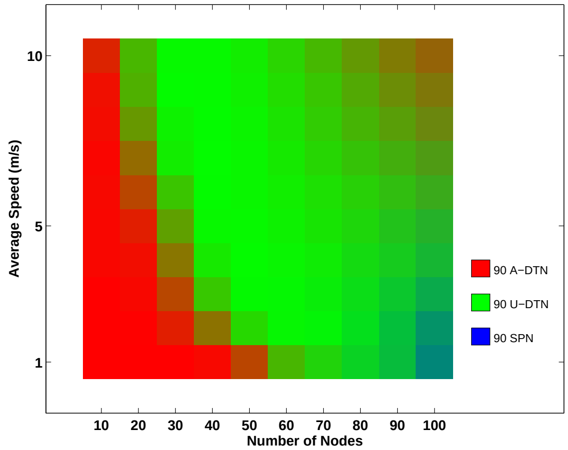
3.3.1 Examples of Network Classification

We first apply our classification method to the Haggle trace with $\delta = 2$ seconds and $\gamma = 3600$ seconds and results are presented in Table 2. When x=100, the network is mostly classified A-DTN due to the strictness of the 100% constraint. As x decreases, classification results show that a significant number of space and space-time paths actually exist for certain epochs, thus revealing an intrinsic property of the network.

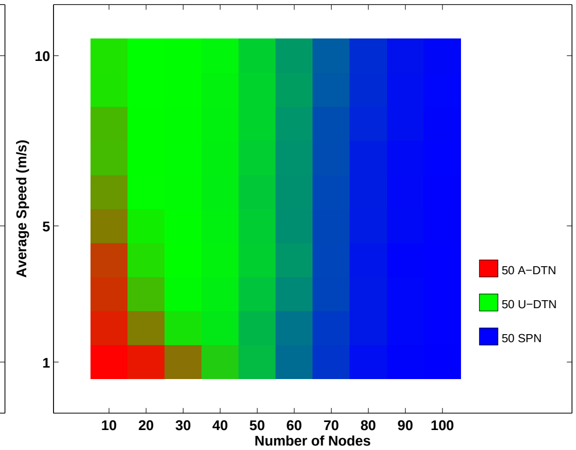
We next show classification results using synthetic traces derived from the RWP model. In our model a given number of nodes move in a 2km by 2km area for 3 hours. Their communication range is 250 m. The pausing time is uniformly distributed between 0 and 10 seconds. We adjust the number of nodes and the average node speeds in our experiments. The results are shown in Figure 9. Each square in the space represents a network with corresponding number of nodes (x-axis) and average speed (y-axis). Different colors represent network classes (A-DTN, U-DTN and A-DTN) now. Each square is filled in with a mixture of these colors that represent the percentage of time the network spends in each class. These figures should be compared to the informal sketch in Figure 4: the blue shades correspond to Class 1 networks and the red shades correspond to Class 2 networks.

These figures show that when node density (number of nodes) is low, increasing speed creates more space time paths. However, when node density is high, a high speed causes more unstable space paths and lower SPN classification accordingly. Similarly, when the node speed is high, although high node density means more connectivity, the space path is less stable. Note that classification with an $x = 50$ illustrates the trend better than the classification result from $x = 90$. The reason is that with $x = 90$, a few N-Pairs in an epoch

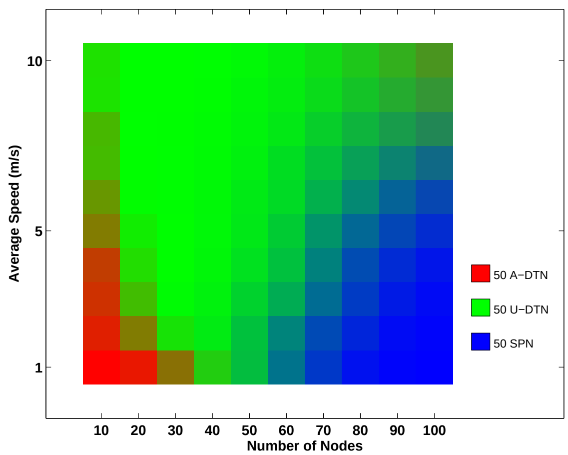
[2] Note that while the classification in [19] is closely related to the classification presented here when $x = 100\%$, it is not identical because of the manner in which we define whole network classification as an aggregation of node-pair classification.



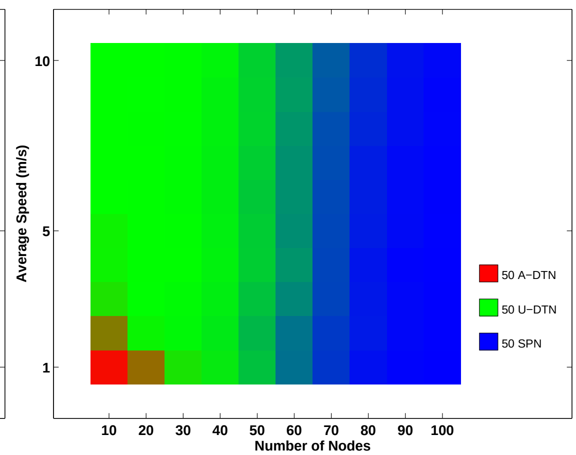
(a) x = 90; γ = 300; δ = 2



(b) x = 50; γ = 300; δ = 2



(c) x = 50; γ = 300; δ = 5



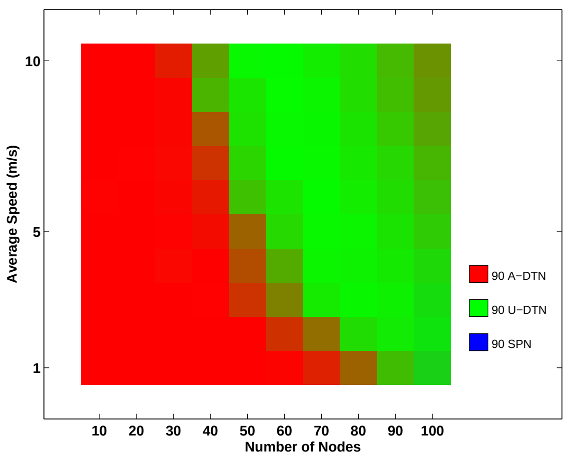
(d) x = 50; γ = 600; δ = 2

Figure 9: Joint Effect of Node Density and Speed on Network Classification: Traces from RWP Model

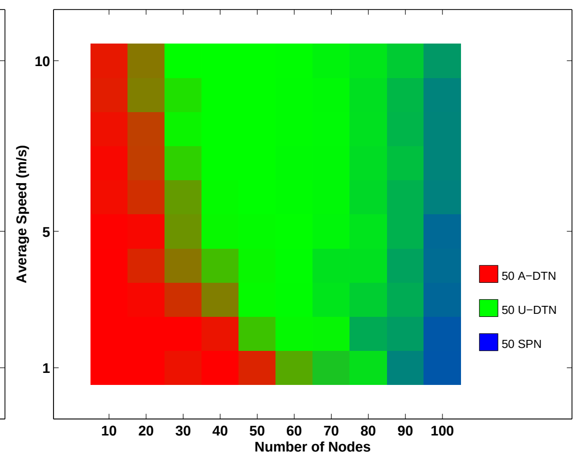
dominates other S-Pairs or ST-Pairs in the classification and the whole network is classified as an A-DTN. This is especially noticeable for results in Figure 9a when the number of nodes is large and the average node speed is high. Although over 50% nodes pairs are S-Pair most of the time as revealed in Figure 9b, the network is classified as A-DTN in significant portion of the 3 hours duration.

While these observations can possibly be made at least qualitatively without applying our framework, we contend that our approach provides a more precise language and context for discussing and evaluating network properties. One of the valuable aspects of our approach is its ability to detect network character changes in a manner that considers only network properties.

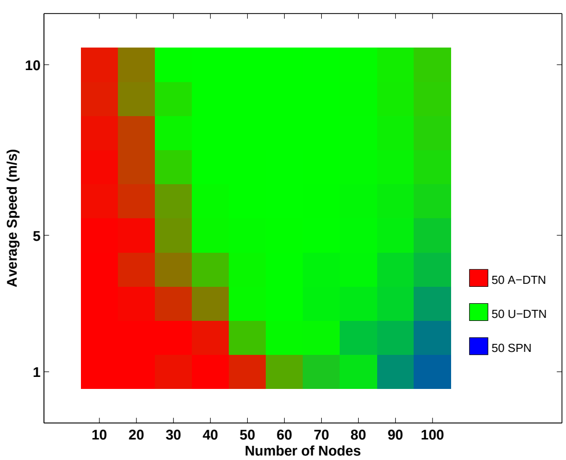
The effect of other parameters in the classification procedure is shown in Figure 9b, 9c and 9d. With a smaller γ value, it is more difficult to find a space time path with a satisfying duration. The time percentage that the network is classified as A-DTN increases accordingly. On the other hand, a larger δ value puts stricter constraint on space path persistence. Even with the same network features, i.e., number of nodes and average node speed, less "usable" space paths are found and the network is classified as SPN in less epochs.



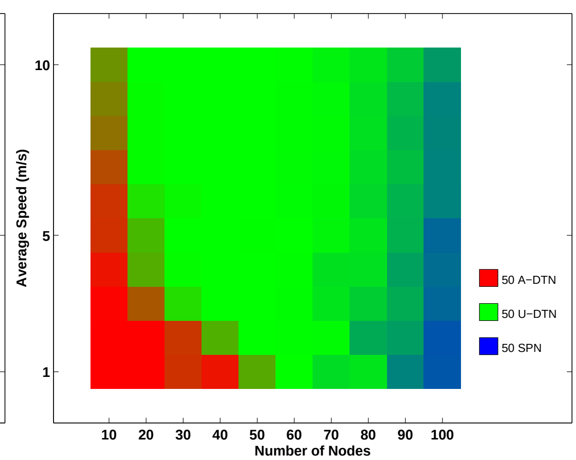
(a) x = 90; γ = 300; δ = 2



(b) x = 50; γ = 300; δ = 2



(c) x = 50; γ = 300; δ = 5



(d) x = 50; γ = 600; δ = 2

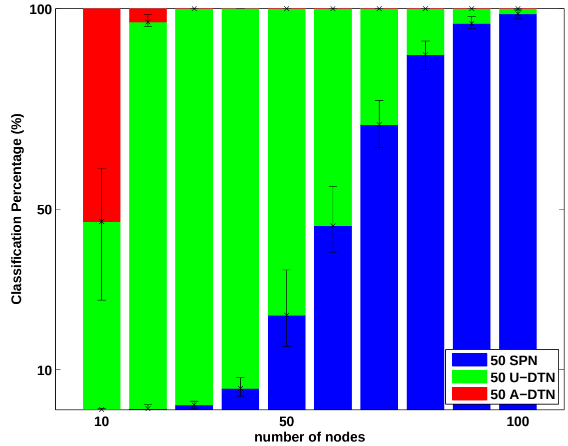
Figure 10: Joint Effect of Node Density and Speed on Network Classification: Traces from TLW Model

Beside the effect the parameters such as number of nodes and node speed, our network classification framework is applied to synthesized contact traces from a different mobility model to illustrate its capability in describing intrinsic connectivity characteristics of the WAM networks. We choose Levy Walk model from [83] as it is shown to fit human movement better than RWP model. In this mobility model, nodes travel by short distances locally at certain regions and occasionally make long “flight” to travel to a different region. Nodes in Levy Walk model are distributed more evenly in the simulation area whereas RWP model has a biased spatial node distribution near the center of the simulation area [10].

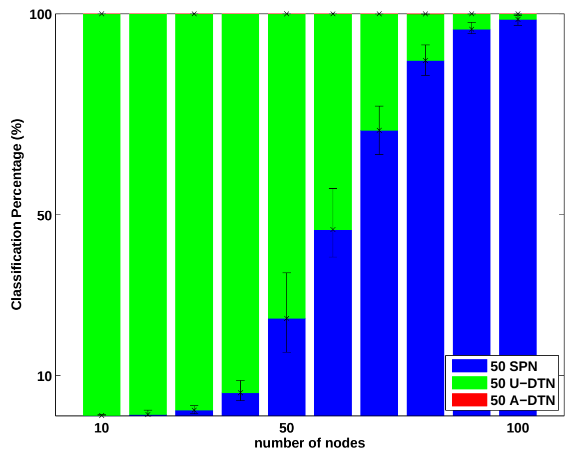
With the same parameters on simulation area and communication range as in contact traces generated from RWP model, we adjust the number of nodes and the average node speeds in generating contact traces for our classification framework. As nodes are distributed more evenly and their movements are limited to local regions most of the time, space path and space time path have less occurrence among most node pairs compared with traces from the RWP model. Therefore, SPN and U-DTN percentages in classification results are much lower than corresponding values in RWP traces' classification results shown in Figure 9. However, effects of different parameters such as γ value on network classification results are the same as those shown with RWP traces.

As a final illustration here we show how our scheme can also provide a methodology to assess the effect of network enhancement schemes such as those proposed with the use of message ferrying [93, 108]. In message ferrying, a special node called *the ferry* moves in the network space and provides data movement capability among nodes. We consider network classification using a trace generated from the RWP model described previously with average node speed of 1 m/s. We consider two scenarios: one with just the nodes and the other in which we introduce a message ferry moving along a square route with diagonal points (500, 500) and (1500, 1500) at 20 m/s.

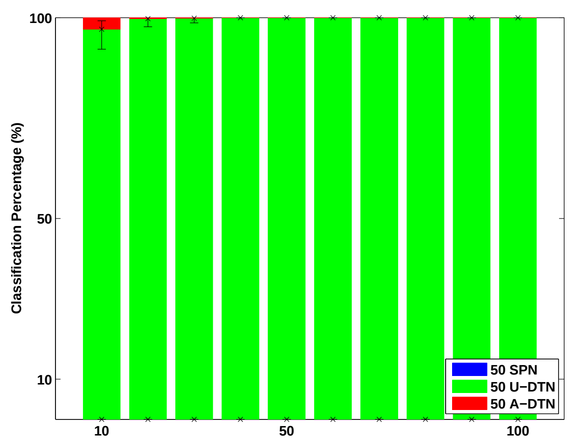
For each number of node and node speed combination, we generate 10 contact traces with different random seed. Average and the range of each classification's percentage for $\gamma = 600$ seconds and $\delta = 5$ seconds are shown in Figures 11a and 11b for cases without the ferry and with the ferry respectively. While the SPN percentage does not change after the ferry is introduced, a significant percentage of A-DTN classification is converted to U-DTN



(a) With no Ferry



(b) With 1 Ferry



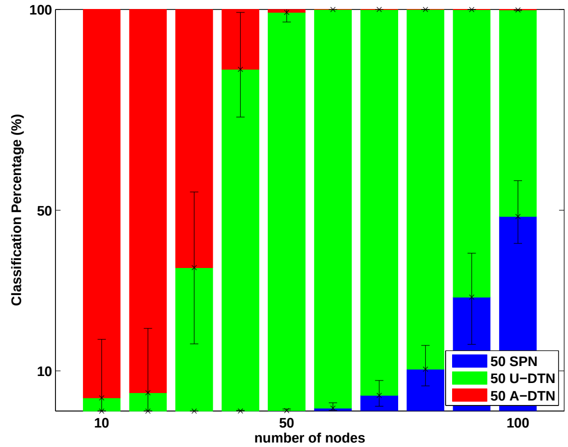
(c) Ferry/node Contacts only

Figure 11: Effect of Message Ferrying on Network Classification

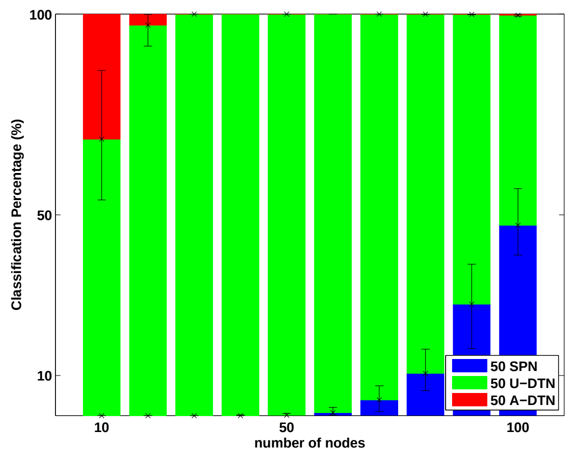
classification. This effect is well known and it's not our objective to demonstrate the effect. Rather, our framework, again allows us to formally evaluate the effect of a message ferrying enhancement from a connectivity viewpoint without needing to simulate the network.

We also show another classification result in Figure 11c when only contacts between node and the ferry is considered. This represents the special case that only message ferrying is used in this WAM network. While most of space paths no longer exist, the ferry is able to provide space-time path among node pairs. In some cases, this approach is favorable due to the tradeoff between data delivery latency and energy availability in the WAM [56].

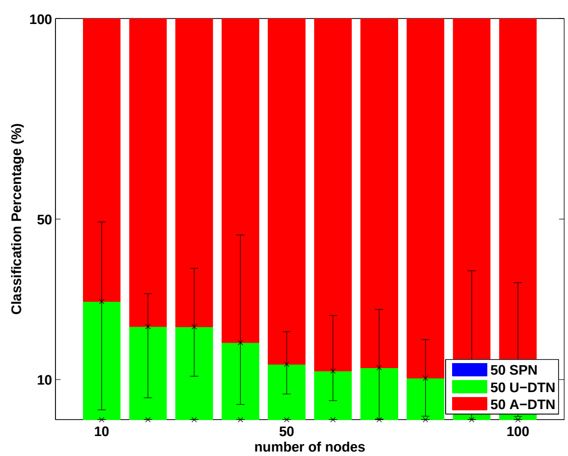
The effect of message ferrying is also evaluated in the WAM network instances generated from Levy Walk model. Figure 12b indicates that introducing message ferrying helps on establishing space time path among nodes possibly moving at different regions. However, the classification results in Figure 12c are significantly different from those in Figure 11c. The reason is that nodes' spatial distribution in RWP traces concentrates at the simulation area center which is covered by the ferry route. Therefore, the ferry has frequent contacts with most of the nodes. Plenty space time paths exist even with ferry/node contacts only. On the contrary, node's spatial occurrence in Levy Walk traces is distributed more evenly over the entire simulation area which is not completely covered by the ferry route. Less encounters between ferry and nodes lead to limited space time paths between node pairs.



(a) With no Ferry



(b) With 1 Ferry



(c) Ferry/node Contacts only

Figure 12: Effect of Message Ferrying on Network Classification

CHAPTER IV

NETWORK CLASSIFICATION FRAMEWORK EXTENSIONS

In this chapter, we first extend our instantiation of the WAM Continuum framework described above to further illustrate its power in formalizing and evaluating the effect of power management schemes deployed in WAMs. Needless to say energy provisioning and management are essential issues in WAM networks. Various power management schemes have been proposed for both MANET and DTN contexts. While most of them are designed to efficiently use available energy, an important question that is not always answered is whether a certain amount of energy is "sufficient" for the WAM network's operation?

We provide a framework for answering this question by providing the classification of a WAM's energy "sufficiency". We start with the understanding that a network's classification from energy perspective is jointly determined by many factors, including its network connectivity properties, available energy, and power management scheme. These last two factors are new elements that we bring to enhance our framework for the purpose of providing useful insight on WAM operation from energy management point of view.

Computational collaboration initiated from mobile nodes becomes a feasible approach to support resource intensive applications in WAM networks with the advances on both device hardware and code execution schemes. In WAM networks where space paths do not always exist between node pair, results from distributed tasks may not be returned to the task initiator in time. Therefore, various protocols have been developed on how to distribute and schedule those tasks based on contacts among nodes.

In this chapter, we extend the existing classification framework to answer another important question about whether initiating computational collaboration in a WAM network is "advantageous", i.e., being able to finish such tasks earlier. Due to the nature of computational collaboration, end-to-end round trips' availability is evaluated. This and the collaboration time requirement jointly define the WAM network's classification.

4.1 Energy Sufficiency Classification

We use a simple energy consumption model: when the radio is ON, it consumes energy at a fixed rate $\mathcal{R}$ and when the radio is OFF, it does not consume any energy. Typical power management strategies for WAMs turn off the radio [16, 55, 102] from time to time. These schemes typically focus on maintaining necessary communications among nodes while reducing the energy consumption rate as much as possible.

To describe network classes based on energy availability, we use the term *Energy Sufficient Node Pair* to describe those node pairs between which the data communication, in particular, the path type, is not affected by energy availability with the particular power management scheme. Similarly, the term *Energy Sufficient Network* denotes those WAMs in which the path properties among all nodes, is not affected. Energy limited node pairs and networks are those that are not energy sufficient. In the same spirit of our previous classification exercise, the level of "sufficiency" is flexible and is described by the extent path properties among nodes are affected compared to the case when energy availability is not a concern.

4.1.1 Energy Related Network Features

Available Energy

We assume that a WAM needs to operate for a period of $\mathcal{T}$ time units without running out of energy. This could be the network lifetime or the time between recharging events. We consider a network has run out of energy if any node's energy is depleted. For simplicity of exposition we assume that all nodes in a network start with the same energy supply of $\mathcal{E}$.

We define $\mathcal{P}$ as the normalized energy availability for a node which is defined as $\mathcal{P} = \mathcal{E}/\mathcal{R}\mathcal{T}$. When $\mathcal{P} \geq 1$ then we can say that the node has abundant energy and does not need to apply a power management scheme. Otherwise, we need to apply a power management scheme that only turns the node's radio on for at most $\mathcal{P}$ of the time.

Power Management Schemes

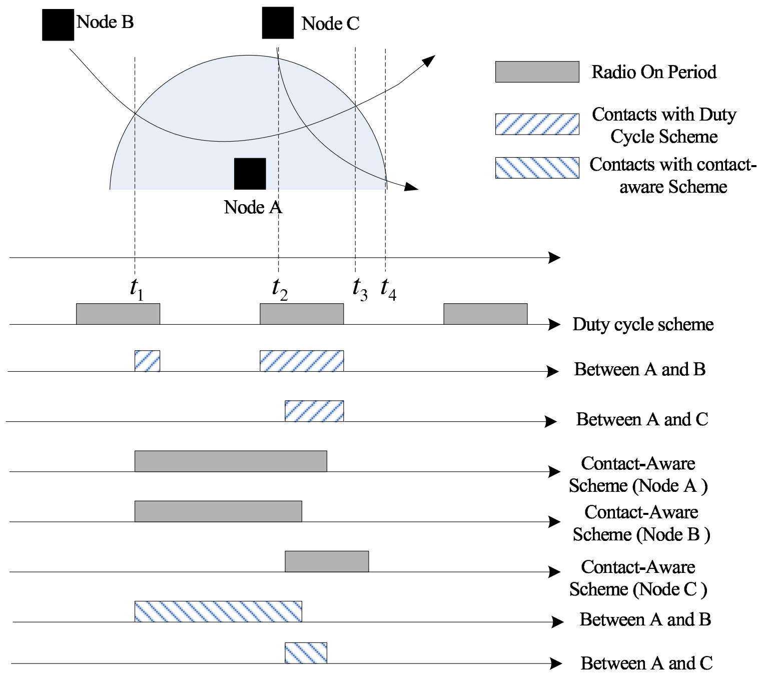


Figure 13: Power Management Scheme Examples

How a WAM is classified will depend on its power management scheme. We consider abstracted power management schemes. Figure 13 shows two schemes which we use in the demonstration of our classification and their effect on contacts.

The first one is *a fixed duty cycle scheme* in which the radio shifts between the ON and OFF states periodically. The proportion of the ON period in each cycle is equal to $max(\mathcal{P}, 1)$. Duty cycles on nodes can be *synchronized* or with *random offsets* from node to node.

The second scheme is an idealized *contact-aware scheme* where a node's radio will be turned off if no contact is possible. The radio is potentially ON only it is involved in a contact with another node. We denote the cumulative time that a node i is involved in some contacts during time period $\mathcal{T}$ as $\mathcal{C}_i$. If $\mathcal{C}_i/\mathcal{T}$ is less than or equal to $\mathcal{P}$ then the node can stay ON during all its contacts. Otherwise, we require the node's radio to be turned on for the initial $\mathcal{P}/(\mathcal{C}_i/\mathcal{T})$ portion of an aggregated contact period of this node. In the above example, the radio of node A only turns on some portion of the aggregated contact period from t_1 to t_4.

There are many other power management schemes. Each of them can be evaluated under our framework. We do not exhaust all choices but select the above two to highlight the potential of our classification scheme.

4.1.2 Routing Paradigm Based Classification

It is important to note that the combination of the specification of the normalized available energy and a power management scheme will effectively change the contact sequence experienced by nodes in a WAM. This in turn will affect (actually degrade) their connectivity specification within the framework we developed previously. Our energy-based classification is, therefore, a taxonomy for characterizing this degradation.

More formally, a WAM is now defined by two evolving graphs: $\mathcal{G}$ which is the evolving graph before applying any power management scheme and $\mathcal{G}'(\mathcal{E}, m)$ which is the evolving graph resulting from applying the power management scheme m with an initial available energy per node of $\mathcal{E}$.

We now formally define the node pair energy sufficiency classes based on the path type classification discussed in previous section.

Definition 12. *Energy Sufficient Node Pair: A node pair is said to be energy sufficient in an epoch if its classification under $\mathcal{G}$ is either S-Pair or ST-Pair in that epoch and its classification under $\mathcal{G}'$ does not* not *downgrade to N-Pair.*

Definition 13. *Energy Limited Node Pair: A node pair is said to be energy limited in an epoch if its classification under $\mathcal{G}$ is either S-Pair or ST-Pair in that epoch and its classification under $\mathcal{G}'$ downgrades to N-Pair.*

Note that if a node pair is N-Pair under $\mathcal{G}$, we cannot classify it from energy sufficiency point of view since whether we provide abundant energy or no energy at all, the path type will not change.

We can further classify whole networks according to their energy sufficiency as follows:

Definition 14. *y-Energy Sufficient Network (y-SN): A network is said to be energy sufficient in an epoch if more than y% of S- or ST-Pairs do not downgrade to N-Pairs between $\mathcal{G}$ and $\mathcal{G}'$ during that epoch.*

Definition 15. *y-Energy Limited Network (y-LN): A network is said to be energy limited in an epoch if more than* $(100 - y)\%$ *of S- or ST-Pairs downgrade to N-Pais between* $\mathcal{G}$ *to* $\mathcal{G}'$ *during that epoch.*

Note that if all node pairs are N-Pair under $\mathcal{G}$, there is no definition of network classification from energy sufficiency point of view since the network's character does not change given any possible energy availability.

4.1.3 Traffic Handling Capacity Based Classification

In previous section, we define the energy sufficient by comparing how much percentage of the time that path types between node pairs degrade. On the other hand, missing contact opportunities will possibly decrease the amount of traffic that can be delivered in the network. In this section, we define the energy sufficiency from traffic handling capacity point of view.

Definition 16. *Deliverable Traffic Portion* λ*: Suppose* b_{ij} *is the long term average traffic load between node i and j.* λ *is the maximum value that all* λb_{ij}*'s are satisfied by multi-path routing. We adopt the Linear Programming formulated in [111] for calculating* λ*.*

Definition 17. *z-Energy Sufficient Network (z-SN): Suppose* λ *is the deliverable traffic portion with the original contact trace.* λ*' is from* $\mathcal{G}'$*. A network is said to be z% energy sufficiency given* $z\% = \lambda'/\lambda \times 100\%$*.*

Under this new definition, we are able to evaluate different power management schemes' effect on handling long term traffic load. So depends on what type of application is running in the network: sporadic messaging whose concern is whether the delivery can be done within a deadline or applications with constant traffic demand, we can provide corresponding classification from energy sufficiency perspective.

4.1.4 Examples of Energy-based Classification

We now provide examples to illustrate the use of the classification framework in understanding the effect of power management schemes and the amount of available energy on network classification. As with our previous classification illustrations, our goal is not to discover new power management schemes or to argue for the use of one scheme over another. Rather, we are interested in showing the power of our framework as an approach to understanding and evaluating these effects on WAMs in a systematic and formal manner.

In these examples we apply power management schemes with varying levels of available energy to the same set of traces (describing an evolving graph $\mathcal{G}$) used in the previous classification study. This results in modified contact traces (describing a modified evolving graph $\mathcal{G}'$). During the path type classification for node pairs, we choose $\delta = 5$ seconds and $\gamma = 3600$ seconds for the Haggle trace and $\delta = 5$ seconds and $\gamma = 600$ seconds for traces from the RWP model. In all our experiments, we choose $y = 90$.

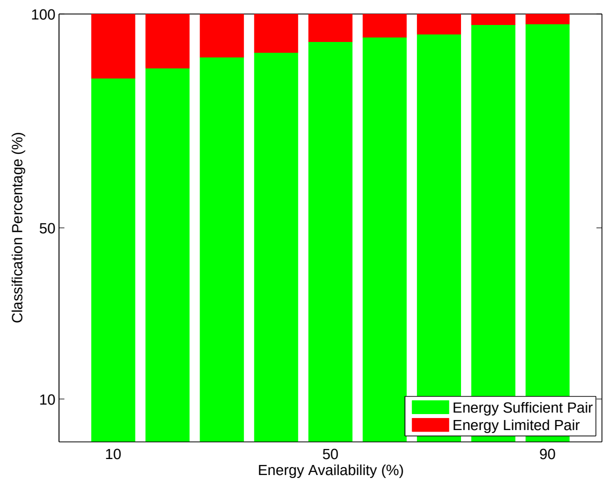
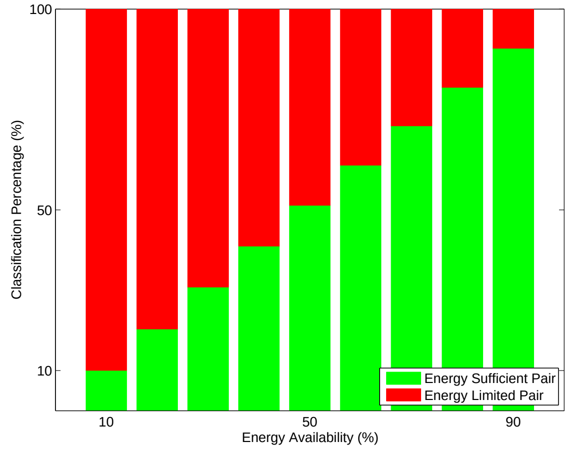
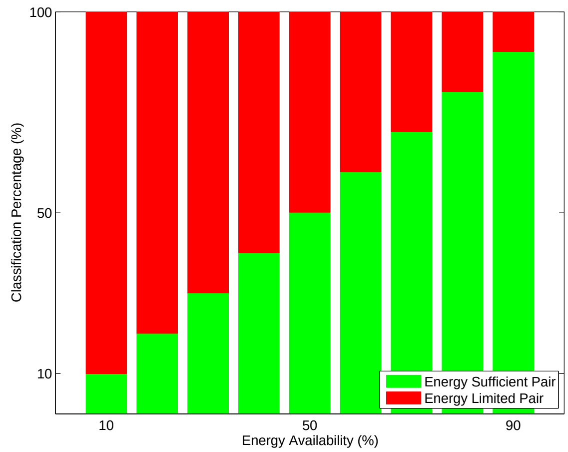


Figure 14: Energy Sufficiency Node Pair Classification: the Haggle Trace

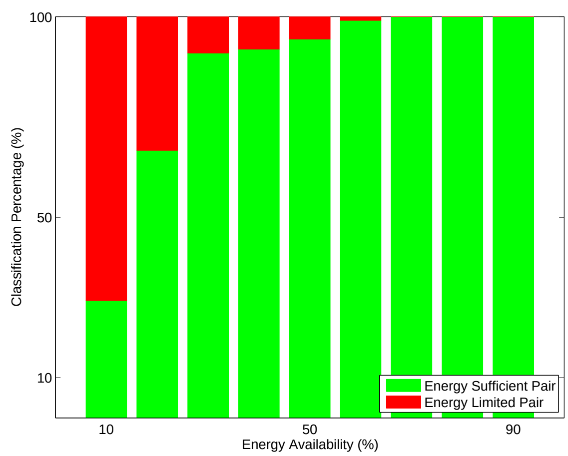
We first fix the power management scheme and show how the energy availability affects the outcome of energy-based node pair classification of the Haggle trace in Figure 14. The fixed duty cycle scheme with a synchronized 300 seconds cycle is used. When the energy availability level is as low as 10%, node pairs on average experience a 20% downgrading. When the energy availability increases, radios on nodes are ON for a longer time and less contact opportunities are missed. One interesting observation is that even with a straightforward fixed duty cycle scheme, node pairs in the Haggle trace are mostly energy "sufficient" even when energy availability is low. In Figure **??**, we show that for this trace, node pairs are classified as N-Pair in most epochs. Those epochs are not considered in the



(a) Fixed Duty Cycle: 300 seconds



(b) Fixed Duty Cycle: 60 seconds

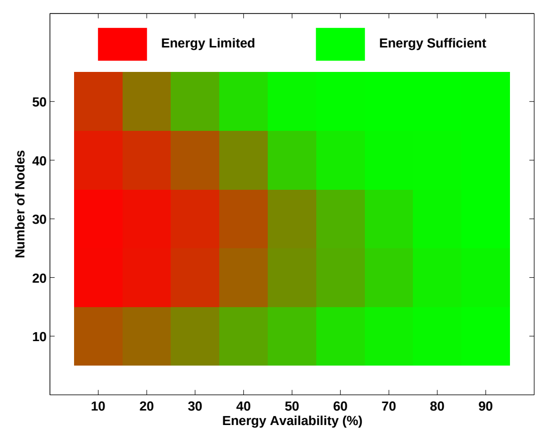


(c) Contact Aware

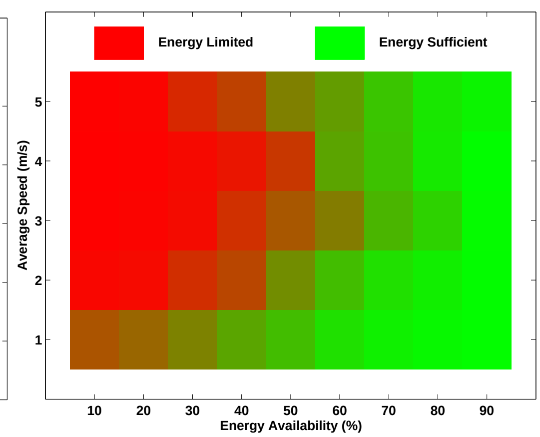
Figure 15: Energy Sufficiency Network Classification (from Capacity Perspective): the Haggle Trace

energy sufficiency classification because no downgrading can happen to N-Pairs in those epochs. During time periods when space paths and space-time paths exist between node pairs, there are plenty of connectivity opportunities among all nodes, i.e., high percentage of S-Pair or ST-Pair classifications in those epochs. Therefore, alternate space-path/space-time path can be found even when radios on some nodes are turned off.

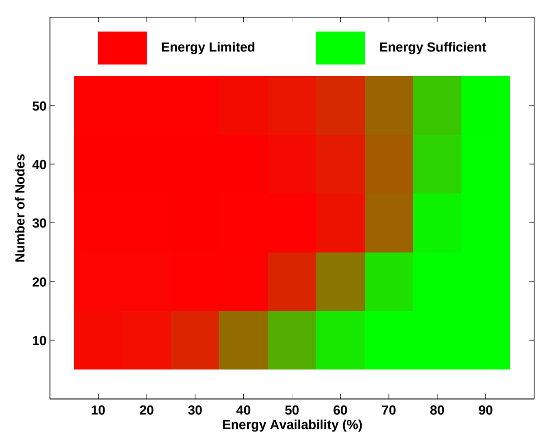
Note for the same contact trace, we show the energy sufficiency classification based on network capacity changes in Figure 15. In this case, the fixed duty cycle scheme is able to keep certain percentage of contact opportunities given the level of energy availability. Thus, the sufficiency level decreases linearly with the energy availability level. On the other hand, the contact aware scheme saves energy for the period when node encounters happen. therefore, it is able to handle as much traffic even when energy level is 30%.



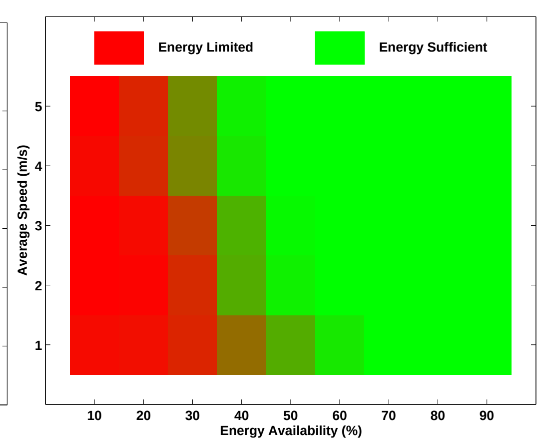
(a) Fixed Duty Cycle: Speed = 1m/s



(b) Fixed Duty Cycle: 10 Nodes



(c) Contact Aware: Speed = 1m/s



(d) Contact Aware: 10 Nodes

Figure 16: Energy Sufficiency Network Classification: Traces from RWP Model

We demonstrate the joint effect of energy availability and node density/node speed on energy sufficiency classification in Figure 16. We only consider RWP traces in this set of experiments. Synchronized duty cycle scheme with a fixed 300 seconds cycle and contact aware scheme are used. In this figure, each square in the space represents a network with a different energy availability level (x-axis) and number of nodes/node speed (y-axis). Two colors (white and black) are used to represent energy sufficiency classes (Sufficient and Limited). Each square is filled in with a mixture of these colors that represents the percentage of time network stays in each class.

For extreme cases, networks are classified as 100% energy limited with 0% available energy and classified as 100% energy sufficient with 100% available energy. Regardless of other network features and power management schemes, networks are classified more as energy sufficient with more available energy.

Note that when energy availability is high ($\mathcal{P} > 0.8$), all those networks are classified as energy sufficient most of the time, i.e., path types among nodes are not affected much. However, when energy availability is relatively low, different network features have interesting effects on the classification.

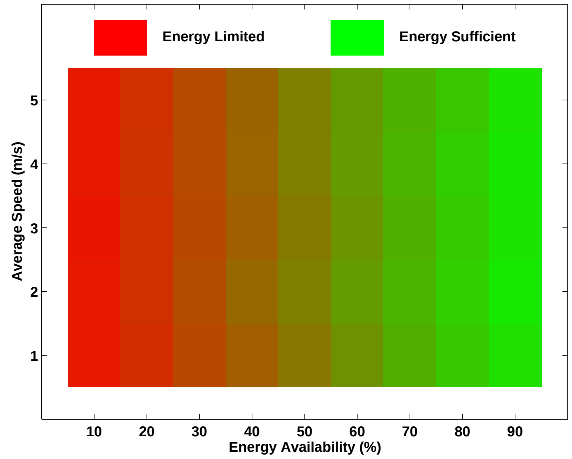
Figure 16a illustrates the joint effect of node density and energy availability when the average node speed is fixed at 1m/s. When the number of nodes is small, most of the existing space paths or space-time paths consist of a small number of hops. As the number of nodes increases, there are more space-time/space paths with more hops between node pairs. If the energy availability is low and nodes have to turn off their radios frequently, a path consisting of multiple links has a higher chance of being affected. The higher downgrading rate results in higher energy limited classification percentage. However, with a large number of nodes, there are many possible space-time/space paths between node pairs, the limited energy might affect some of them but not all of them. Therefore, less downgrading occurs and the percentage of energy sufficient classification increases again.

Similarly, with a fixed number of nodes, an increasing speed first creates forwarding paths consisting of multiple hops, which leads to higher path type downgrading when node radios have to be turned off frequently. As the speed increases, more paths appear between node pairs which provide alternatives when some of them no longer exist because an intermediate hop's radio is turned off. This joint effect is illustrated in Figure 16b.

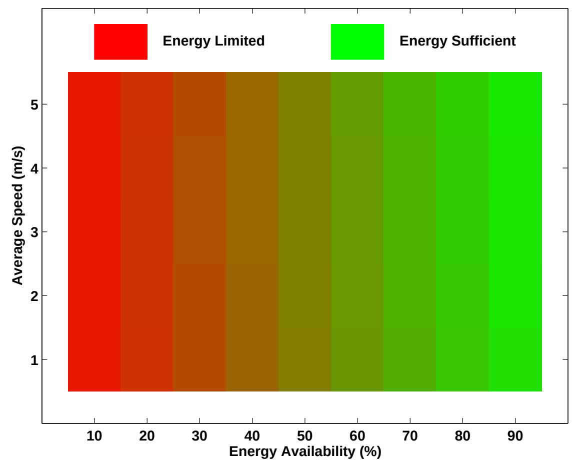
In terms of power management scheme selection, the classification result in Figure 16c shows that the contact-aware scheme performs worse than the duty cycle scheme when the energy availability is not high. The discrepancy is more obvious when the node density increases. The reason is that contacts between nodes overlap more and result in longer aggregated contact periods as illustrated in Figure 13. Since the contact aware scheme we use in the classification always keeps the front portion of an aggregated contact period, contacts that occur later in the aggregated contact period are removed in $\mathcal{G}'$. Therefore, increasing the number of nodes in this case leads to a sharp increase of energy limited classification percentage. But when nodes are sparsely distributed, classification result in Figure 16d illustrates that contact-aware scheme performs better than duty cycle scheme when the energy availability is high because there are not many overlapping contact in this set of experiment.

Similarly to the observation from Haggle Trace case, energy sufficiency classification from capacity perspective degrades linearly with decreasing energy level (Figure 17a and 17b). However, this degradation is much slower with contact-aware scheme (Figure 17c). This shows that the extra effort to keep radio ON during contact and OFF otherwise is worthwhile when the concern is to reduce the degradation on deliverable traffic load.

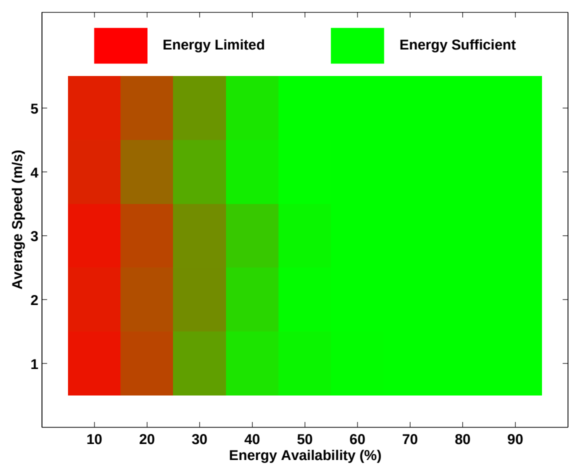
If we introduce a ferry, which normally has good energy provisioning and does not need a power management scheme, and only allows contacts between nodes and the ferry, we have a 100% energy sufficiency WAM with 10 to 50 nodes with an average speed of 1m/s even with a 10% energy availability. By removing node to node contacts, the space path between node pairs might downgrade to space time path or the space time path's span might be longer as illustrated in Figure 11c. However, the $\mathcal{C}_i/\mathcal{T}$ for node i drops significantly, which contributes to little downgrading from the energy sufficiency perspective.



(a) Fixed Duty Cycle: 300 seconds



(b) Fixed Duty Cycle: 60 seconds



(c) Contact Aware

Figure 17: Energy Sufficiency Network Classification (from Capacity Perspective): Traces from RWP Model

4.2 Collaboration Advantage Classification

The framework described thus far classifies networks based on the availability and type of end-to-end paths between node pairs. Note that a space time path is asymmetric and its temporal span is calculated over the journey from a source node to a destination node. However, in mobile computational collaboration, a computational task is assigned from a job initiator to worker nodes. After computation on each worker node finishes, the result must be sent back to the job initiator to complete the task.

In our current classification framework, the classification of node pair is based on one way communication. Due to the asymmetric nature of the space time path, existence of a space time path from source node s to destination node d and another one from d to s at the time t does not mean that a round trip from s to d and back to s cannot be found at t. To describe network classification based on whether the computation collaboration initiation can take the advantage of resource from peers, we first extend the framework to describe *Collaboration Advantageous Node* based on round trip's availability from such a node to its peers. The network's classification is then generalized from results of node classification.

4.2.1 Computational Collaboration Model

Round Trip Time

Round-trip time of the two way communication in a computational collaboration consists of three parts as shown in Figure 18:

- Sending time: The time interval from the task leaves the source to the task arrives the destination.
- Processing time: The time it takes to finish processing the data at the destination node and generate a result/acknowledgement.
- Returning time: The duration of the result's travel time from destination back to the source.

We assume that the time of assembling all tasks' results is negligible compared with the three time components mentioned above.

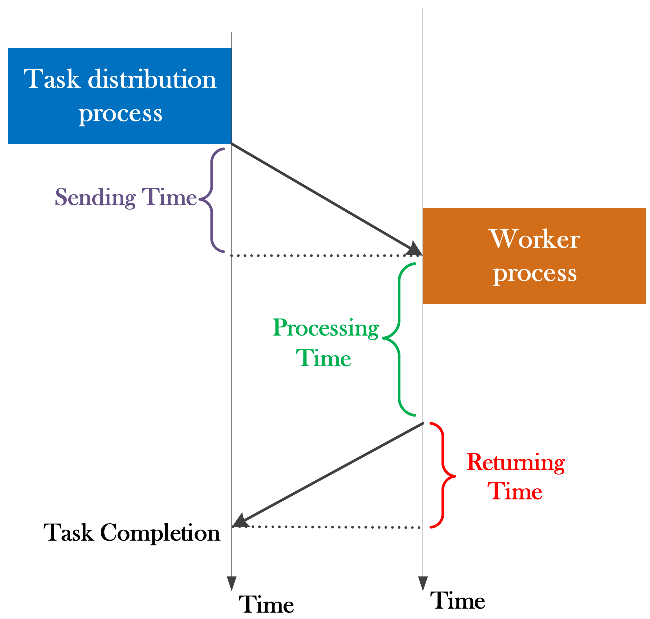
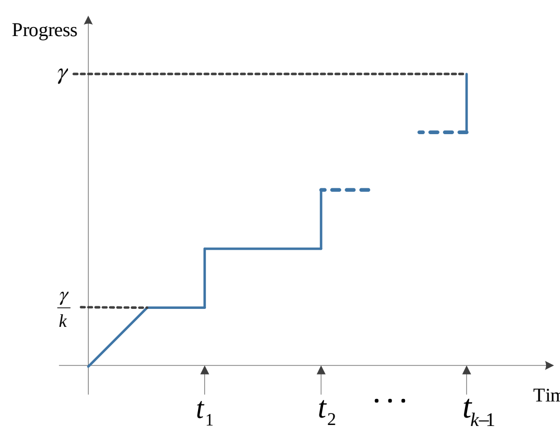
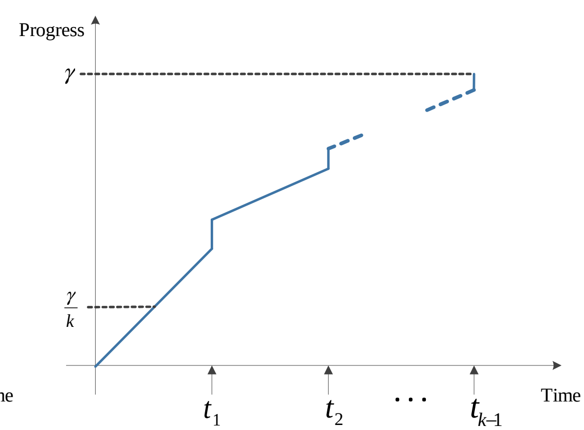


Figure 18: Round Trip Time Breakdown

Task Distribution and Result Collection



(a) Collaboration All



(b) Collaboration Single

Figure 19: Collaboration Scheme Examples

Implementations of task distribution and result collection determine how round trips in the network can be utilized in the computational collaboration. In this thesis, we consider two abstracted schemes shown in Figure 19.

We assume a computational-intensive application needs γ time to finish with a single node's resource. It is divided into k tasks each of which takes γ/k time to finish and these tasks are distributed among nodes. All nodes have same amount of resource and one node (including the task distributor) only accepts one task.

In the *Collaboration All scheme* illustrated in Figure 19a, the task distributor waits for results from other nodes while it finishes its own task. When one result is returned at t_i, the application completion progress advances by γ/k. When $k-1$ results from other nodes are collected, the computational application finishes.

Figure 19b shows the *Collaboration Single scheme*. In this scheme, the task distributor continues with tasks for other nodes in a round robin fashion after it finishes its own task. Therefore, the application completion progress advances all the time. When one result is returned at t_i, the remaining part of corresponding task is no longer processed on the task distributor node.

There are many possible task distribution and result collection approaches. We do not exhaust all schemes but select the above two to highlight the capability of our classification framework.

4.2.2 Node Classification

To extend our classification framework to accommodate the nature of these applications requesting round trip communication, we have following definitions from an evolving graph $\mathcal{G}$ which describes the wireless and mobile network as in Chapter 3.

Definition 18. *Space Round-trip (SR) from i to j: The concatenation of a space path from node i to node j and another space path from node j to node i in $\mathcal{G}$.*

Definition 19. *Space Round-trip Pair (SR-Pair): A pair of nodes i and j is called an SR-Pair if a space round-trip can always be found from i to j to i in $\mathcal{G}$.*

Note that the definition of SR-Pair is the same as S-Pair discussed in Chapter 3. The reason is that a space path is always symmetric. If there is path consists of contemporaneously available links from node i to j, there is a space path from j to i. However, if a space round-trip does not exist from node i to j to i, we have following definition.

Definition 20. *Space-Time Round-trip Pair (STR-Pair): A pair of nodes i and j is an STR-Pair if:*

- *this pair is an SR-Pair or*

- *$\forall t$, a round trip consists of space or space-time path from i to j to i exists in $\mathcal{G}$ starting at time t;*

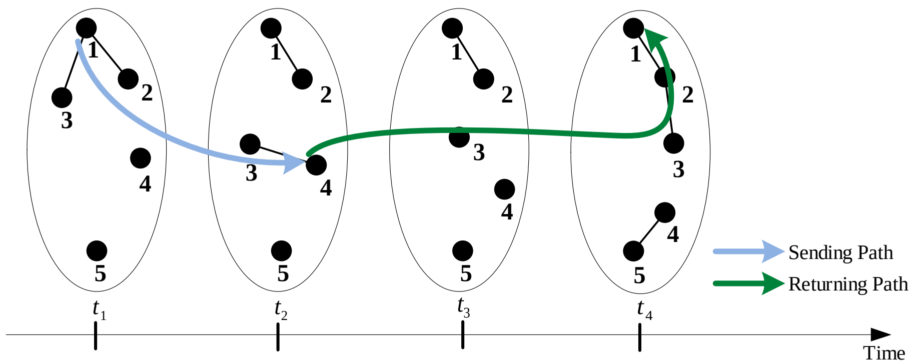


Figure 20: Round Trip Time Breakdown

Node 1 and 4 is a STR-Pair in Figure 20's example. There is a space time path from node 1 to 4 starting at t_1 and ending at t_2. In the meanwhile, there is a space time path from node 4 to 1 starting at t_2 and ending at t_4.

Definition 21. *No Round-trip Pair (NR-Pair): A pair of nodes i and j is an NR-Pair if it is not STR-Pair.*

According to the definition, if node i and j are considered as a STR-Pair, they should be classified as a space time path pair. On the contrary, a space time path pair is not necessarily STR-Pair. For example, node 1 and 5 are a space time path pair but NR-Pair in Figure 20.

Similar to the practical definitions of space time path, a space time round-trip should be time-bounded for any meaningful WAM applications. Therefore, we have following definition.

Definition 22. (γ) *Space Time Round-trip Pair: A (γ) STR-Pair is an STR-pair where the round-trips from i to j to i are always less than or equal to γ in duration.*

Node 1 and 4 in Figure 20 is a (γ) Space Time Round-trip Pair if the value of (γ) is less than or equal to $t_4 - t_1$. Note that beside the practical requirement on the duration of entire round-trip, the processing latency, i.e., the time needed to finish the collaboration task, can be comparable to the duration of space time path among nodes as shown in Figure 18. If the data processing does not finish when the space time path from destination node to source node starts, this round-trip is not *usable* since no result can be returned via this path. In the same example, if the processing on node 4 takes longer than $t_3 - t_2$, no results can be returned on the space time path back to node 1. Therefore, we include the consideration of this processing latency τ in following definition.

Definition 23. (γ, τ) *Space Time Round-trip Pair: A pair of node i and j is a (γ, τ) STR Pair if:*

- *this pair is an (γ) SR-Pair and*
- *$\forall t$, $\exists t' \leq (t + \gamma)$ such that a space time path from node i to j with duration less than or equal to $(t' - t)$ exists and*
- *$\forall t$, $\exists t'' \leq (t + \gamma)$ such that a space time path from node j to i with duration less than or equal to $(t + \gamma - t'')$ exists and*
- *$(t'' - t') \geq \tau$;*

Note that (γ) Space Time Round-trip Pair is a special cases of this definitions with τ equals to 0.

Note that in applications such as mobile computation, the source node may assign data processing tasks to more than one node. If all nodes are equipped with similar storage/computation capacity, it is more important to know whether the source node and a certain number of work nodes are (γ, τ) STR-Pair than evaluating if the source node and a particular destination node is (γ, τ) STR-Pair. Therefore, we have following definitions:

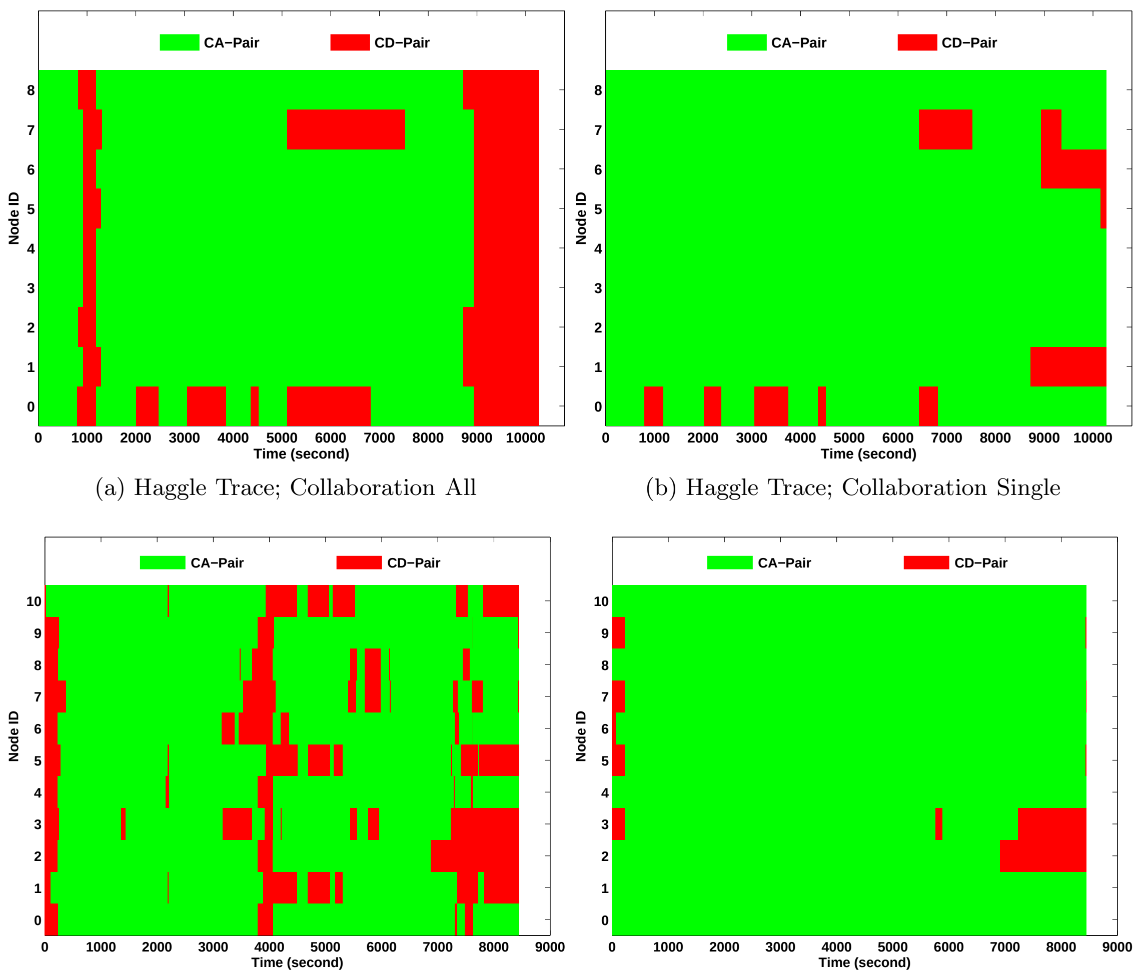
Definition 24. (γ, τ, k) *Space Time Round-trip Node: a node forms a (γ, τ) Space Time Round-trip Pair with at least k peers in the network.*

We now formally define the node collaboration advantageous classes.

Definition 25. *Collaboration Advantage (CA) Node: Collaboration initiated from this node in an epoch can finish the computation faster than completing all tasks at this node.*

Definition 26. *Collaboration Disadvantage (CD) Node: Collaboration initiated from this node in an epoch finishes the computation using longer time than completing all tasks at this node.*

If the computation takes γ time with the resource from a single node and it is partitioned in k tasks, a CA node is a $(\gamma, \gamma/k, k-1)$ Space Time Round-trip Node if Collaboration All scheme is used. When Collaboration Single scheme is used, a CA node is a $(\gamma, \gamma/k, 1)$ Space Time Round-trip Node.



(a) Haggle Trace; Collaboration All

(b) Haggle Trace; Collaboration Single

(c) RollerNet Trace; Collaboration All

(d) RollerNet Trace; Collaboration Single

Figure 21: Epoch by Epoch Node Classification

We apply the node classification methodology to the 3 hour portion of Haggle Trace and the RollerNet trace which are used in earlier discussion in Section 3.2.4. We choose γ= 600 seconds and $k = 6$. Classification results are presented in Figure 21.

Note that although the Haggle Trace has much more space path presence than RollerNet trace as illustrated in Figure 5, classification results of these two traces are similar from Collaboration Advantageous perspective. The reason is that the computational collaboration is able to tolerate certain latency. Round trips consists of space paths or space time paths are considered the same in this classification as long as the latter return results within γ.

However, when space time paths are not available due to lack of node contacts, for example, near the end of both Haggle and RollerNet traces, results from distributed tasks have difficulty to be returned to the task initiator. Therefore, it is *disadvantageous* to initiate the computational collaboration. In other words, the application can be finished earlier by execution at the single node instead of distributing tasks to peers.

If the Collaboration Single scheme is used, the probability of a node being classified as CA node increases noticeably due to the fact that the computation can be finished earlier even only one result is returned earlier than γ from the time the computation starts.

4.2.3 Network Classification

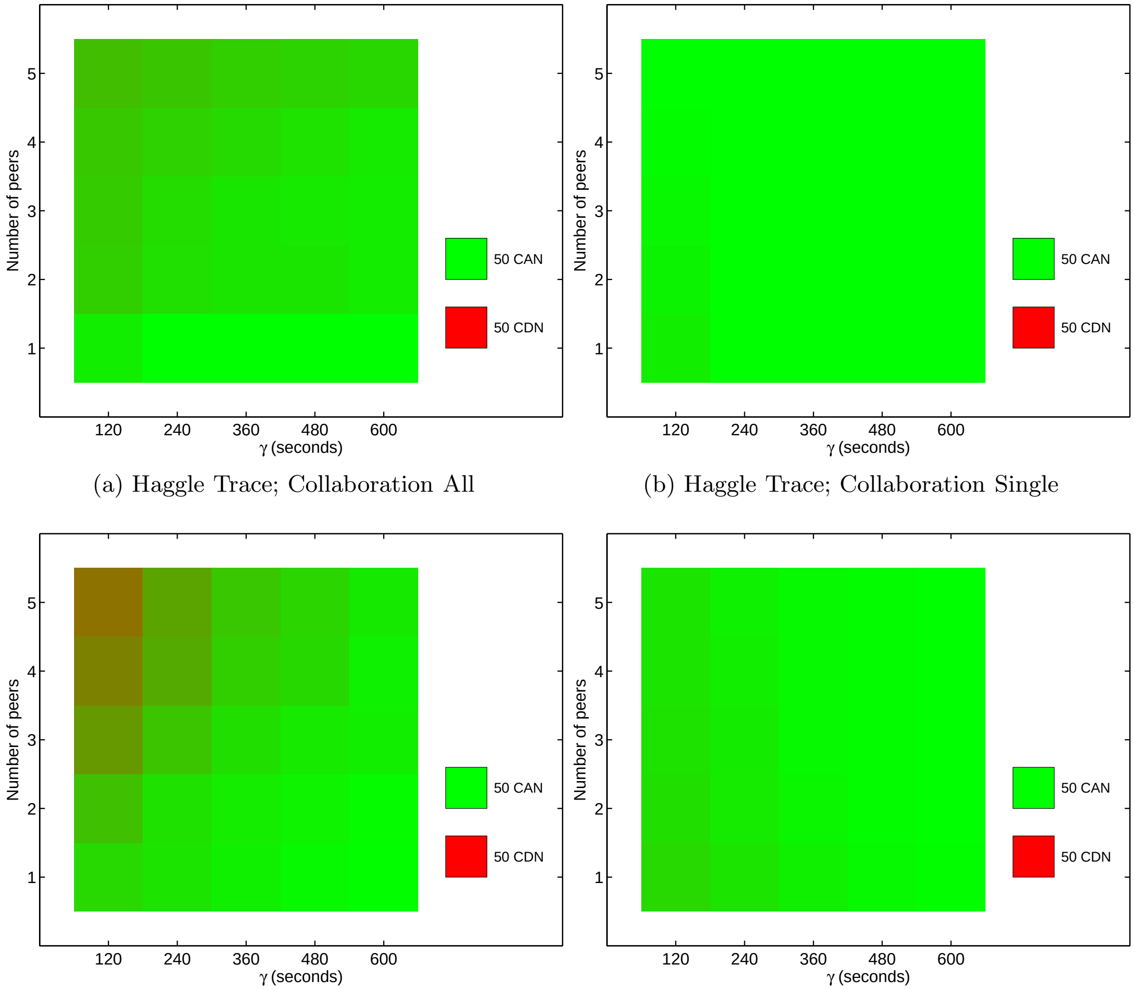
Similarly to the previous work, network classification can be achieved by generalization over node classification. There are two categories of network: Collaboration Advantageous Network (CAN) in which the computational collaboration should be used and Collaboration Disadvantageous Network (CDN) where it is not worthwhile to insatiate the collaboration.

In addition, we allow certain flexility in the definition so that a network can be classified as CAN even some nodes are CD nodes.

Definition 27. *x-CAN: A network is classified as an x-CAN in an epoch if at least x% nodes are classified as CA nodes in that epoch.*

Definition 28. *x-CDN: A network is classified as an x-CDN in an epoch if it is not x-CAN in that epoch.*

With an x value of 50, we show the effect of γ and number of computation partitioning on the network classification in Figure 22. Each square in the figure represent a network



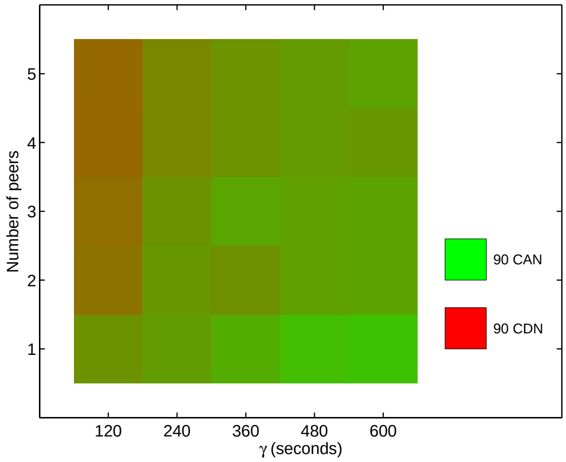
(a) Haggle Trace; Collaboration All (b) Haggle Trace; Collaboration Single

(c) RollerNet Trace; Collaboration All (d) RollerNet Trace; Collaboration Single

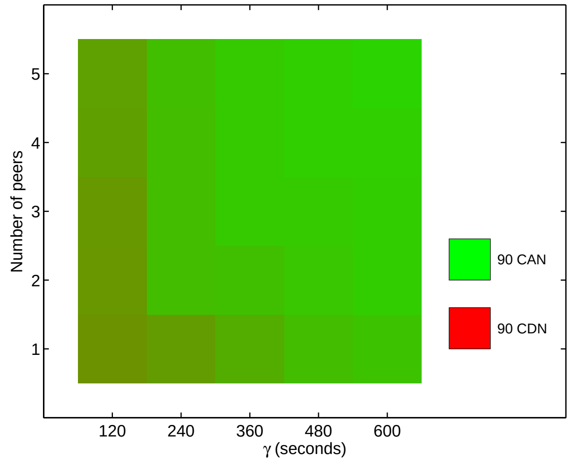
Figure 22: Joint Effect of γ and Number of Peers on Network Classification with $x = 50$

running the application requires γ (x-axis) time to finish and the number of peers (y-axis) in the collaboration. A square is filled in with a mixture of colors that represent the percentage of time this network is classified in such class.

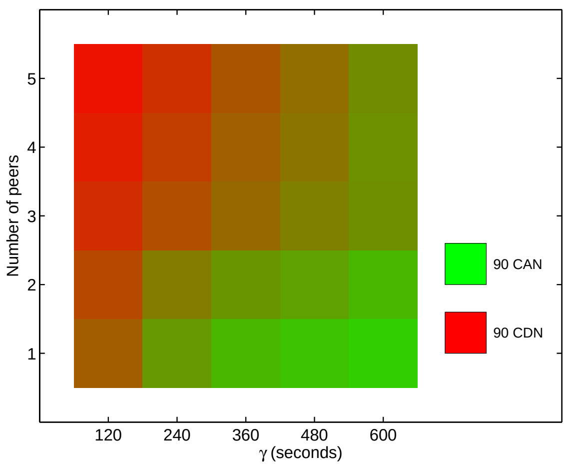
Except the observations that Collaboration Single scheme can always take more advantage than Collaboration all scheme and computational collaboration makes more sense as the task initiator can wait longer for results to be returned, we can see how does the number of tasks affect the classification result. As the number of tasks increases, the value τ decreases so that a round trip is easier to be found as one of the constraints in Definition 23 is relaxed. Therefore, it is more likely to find one required round trip and the CA classification with Collaboration Single scheme improves. However, for networks with Collaboration All scheme, the factor that more round trips have to be found out weight such constraint relaxation. As a result, the CA classification degrades as this number increases.



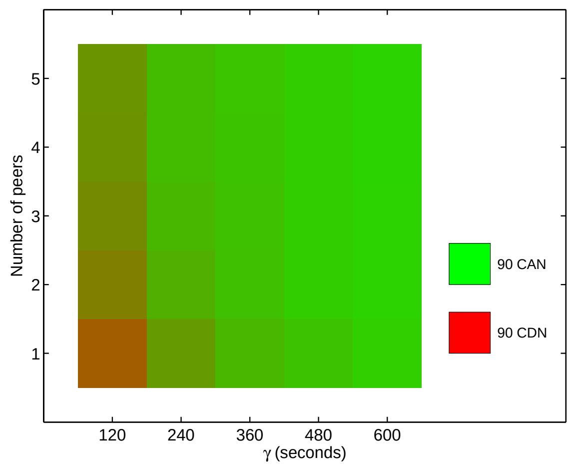
(a) Haggle Trace; Collaboration All



(b) Haggle Trace; Collaboration Single



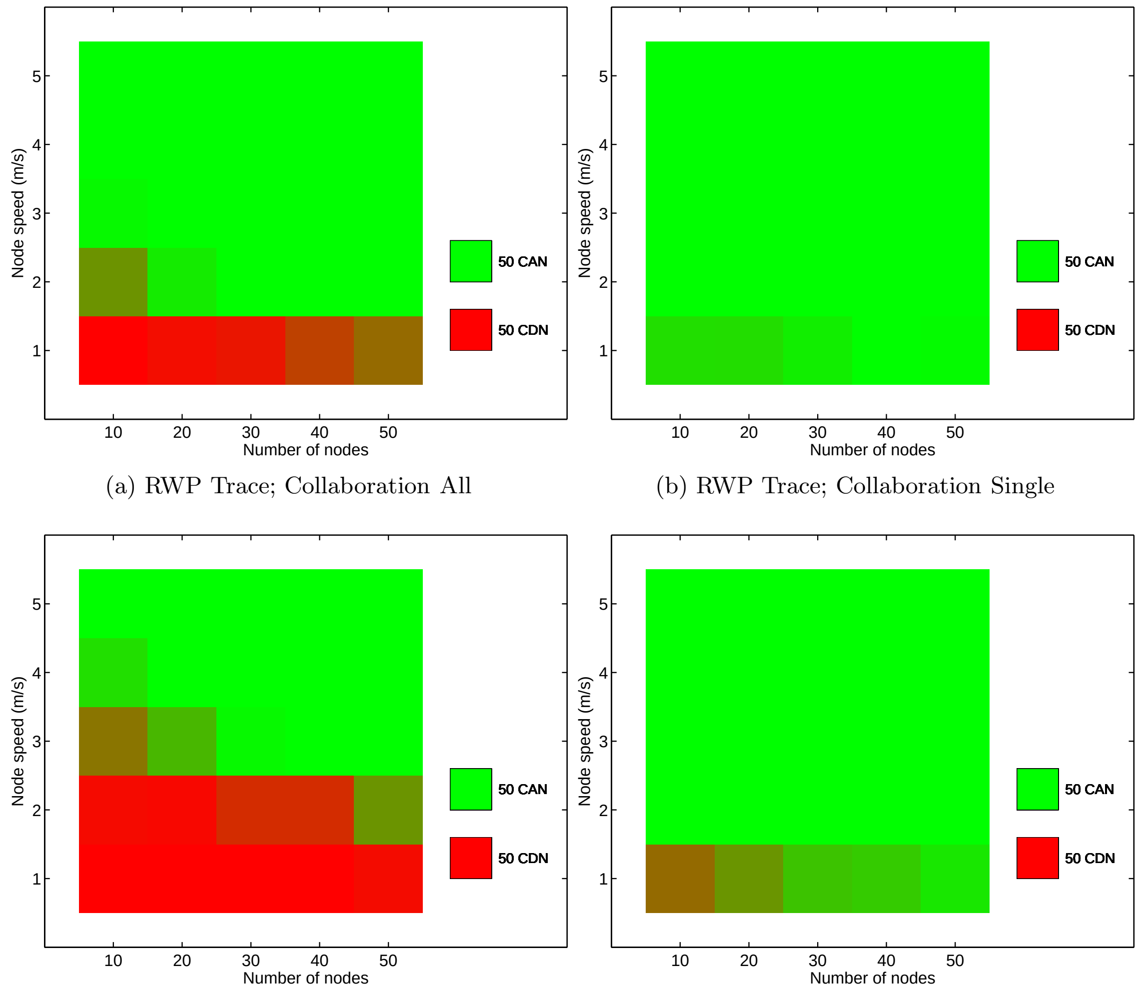
(c) RollerNet Trace; Collaboration All



(d) RollerNet Trace; Collaboration Single

Figure 23: Joint Effect of γ and Number of Peers on Network Classification with $x = 90$

Such difference becomes more obvious when we set x's value to be 90. When the number of peer is increased, there is a high probability that a network is classified as CDN in an epoch. When the per-epoch classification is averaged over all epochs, the trend of whole network's classification is noticeable in results from both Haggle trace and RollerNet trace as shown in Figure 23.



(a) RWP Trace; Collaboration All

(b) RWP Trace; Collaboration Single

(c) TLW Trace; Collaboration All

(d) TLW Trace; Collaboration Single

Figure 24: Joint Effect of Node Density and Speed on Network Classification

We also apply our classification framework to synthesized traces from RWP and Levy Walk model since we are able to adjust the number of nodes and average node speed in this case. Figure 24 present the results when $gamma = 600$ seconds and number of tasks from application partitioning is 5.

As number of nodes increases and average node speed increases, the connectivity in traces from both model improves. Therefore, the percentage of CAN classification increases as more round trips can be found. This trend is similar to what can be observed from end-to-end path based classification results in Figure 9 and Figure 10.

CHAPTER V

HYBRID ROUTING WITH MESSAGE FERRYING IN CLUSTERED WIRELESS NETWORK

Numerous routing protocols have been developed for data delivery in wireless networks. Most of these routing protocols are designed for mobile ad hoc networks (MANETs) [20] or delay tolerant networks (DTNs) [39]. In MANETs, an end-to-end multi-hop path is generally assumed between any node pairs. MANET routing primarily addresses the issues of node mobility and limited resources, such as limited bandwidth and energy supplies, that are common in MANETs. In DTNs, network partitions occur frequently and can last for a long period of time. DTN routing, which forwards data in a store-carry-and-forward manner, is concerned with how to utilize intermittent contact opportunities to deliver data and focus on networks with completely isolated nodes.

In this chapter, we study routing in *clustered DTNs* where nodes are partitioned into clusters. That is, nodes are neither connected as in MANETs nor completely isolated as considered in previous DTN routing studies. Clustered DTNs may arise in a variety of situations. For example, consider a sensor network that is deployed around "hot spots". Although sensors at the same "spot" are connected and collaborate in sensing and data collection, there is a lack for direct communication among sensors in different "spots". For these scenarios, MANET routing alone would fail to deliver data between different clusters. On the other hand, existing DTN routing, which focuses on utilizing node mobility to transport data, considers completely isolated nodes and is not able to exploit connectivity within each cluster. Therefore, to best utilize available network connectivity, new routing algorithms are needed that combine components from both MANET and DTN routing.

We focus on clustered DTNs with stationary nodes using message ferrying, a DTN scheme that utilizes controlled node mobility to deliver data [108, 109]. Message ferrying uses a special type of node called *message ferry*, which moves along pre-determined routes

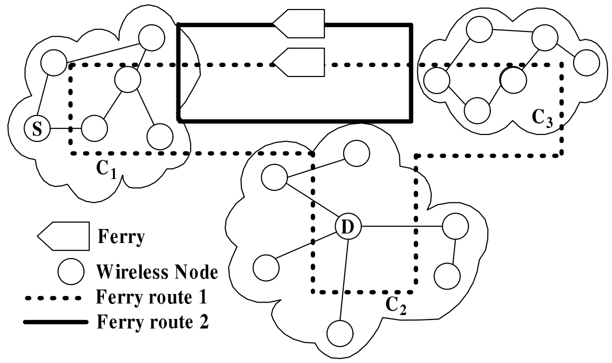


Figure 25: Clustered DTNs with Message Ferrying

to visit nodes. An example is shown in Figure 25. Ferries take messages from sources and deliver the messages to the destinations during direct contacts with nodes. This store-carry-and-forward scheme provides intermittent yet regular communication opportunities. Message ferrying is particularly suitable for clustered DTNs with ferries transporting data between different clusters. For example, in the above disaster relief and sensor network scenarios, vehicles or airplanes can be used as ferries to deliver data among rescuers in different areas and sensors in different "spots". In the meanwhile, MANET routing is used within each cluster to exploit rich connectivity in clusters. In this hybrid routing approach, traffic may be carried via multiple routing paradigms. This raises a question of how message ferrying and MANET routing interact with each other.

5.1 Hybrid Routing Framework

Multiple routing paradigms, namely MANET and DTN routing, must be jointly used to forward data in clustered DTNs. The interaction between these two paradigms thus can significantly affect data delivery performance.

5.1.1 Network Model

In this study, we consider networks with stationary nodes. All nodes are equipped with a wireless radio capable of transmitting to other nodes within a distance r. The data rate of the radio is B bits per second. The network is assumed to be partitioned into clusters [1].

[1] In later discussions, we will use the terms "cluster" and "partition" interchangeably.

That is, nodes in the same partition are connected and can communicate with each other using MANET routing protocols, while nodes in different clusters can not communicate directly. Nodes are sources and destinations of communication. Data transmission between nodes is in application layer data units called *messages*.

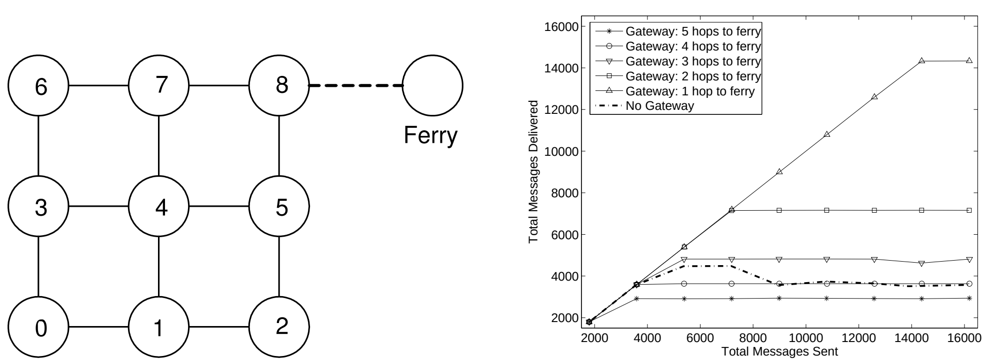
To support communication among different clusters which are disconnected, message ferrying is used. Specifically, a special type of nodes called *message ferries* are used. We assume that ferries are equipped with the same radios as nodes. They move around the deployment area to visit nodes and communicate with nodes via a shared wireless channel. Using physical movement, ferries gather messages from sources and deliver the messages to the destinations during direct contacts with nodes. In this paper, we consider networks with a *single* ferry, which has sufficient storage. That is, messages are not dropped at the ferry due to buffer overflows. And the ferry moves at a constant speed repeatedly on a fixed route. Ferry routes may be fixed due to application requirements. For example, the ferry can be a public bus [98] whose movement is determined by passenger transportation considerations. Alternatively, ferry movement can be controlled for communication purposes, e.g., unmanned aerial vehicles (UAV) [17] or mobile robots [97] can be deployed to act as ferries for data delivery. In the following, we assume that ferry routes are fixed. We will address the issue of controllable routes in Section 5.4.

5.1.2 Interfacing between MANET and MF Paradigms

In the following, we consider two methods for the interaction of message ferrying (MF) and MANET routing. In the first approach, the ferry would participate in the intra-partition MANET routing when it has the connectivity to those partitions. During the period when the ferry is not available, nodes buffer messages sent to other partitions in local storage. Once a route to the ferry is available, nodes send stored messages to the ferry via the MANET routing protocol used and the ferry will be responsible for delivering them to other clusters.

In MF, due to ferry mobility, contact opportunities between the ferry and nodes might be short with dynamic link status. During such a short period, routing information may not have a chance to reach nodes that are multiple hops away from the ferry, especially for proactive routing protocols such as DSDV. Furthermore, even if the correct routing information is propagated throughout the network, multiple nodes will transfer data to and receive data from the ferry simultaneously, causing network congestion and data losses.

In the second approach, the ferry does not participate in the MANET routing in clusters. Instead, the ferry interacts with only some designated nodes called *gateway nodes* (or *gateways* for short) in each cluster. Gateway nodes operate in both the MF and MANET routing paradigm. Specifically, inter-cluster traffic is first gathered at gateways in each cluster. When the ferry visits a cluster, gateway nodes will exchange messages with the ferry directly. After receiving messages from the ferry, gateway nodes relay these messages to destinations within their clusters. This approach has several advantages. First, although multiple nodes can send their messages to the same gateway node, these transmissions can be scheduled over time to reduce interference. Without node mobility, routing paths to gateways are stable. In addition, data exchange occurs between the ferry and gateway nodes directly, which reduces the effect of dynamic link changes. Second, minimal modification is required for MANET routing protocols used in clusters. Nodes in clusters send inter-cluster traffic to gateways using unmodified MANET protocols. Gateways are required to interact with the ferry for message exchange. Since gateways communicate with the ferry directly, modification to routing protocols at gateways is not significant.



(a) Network topology used in simulation (b) Effect of wireless interference

Figure 26: An illustrative example

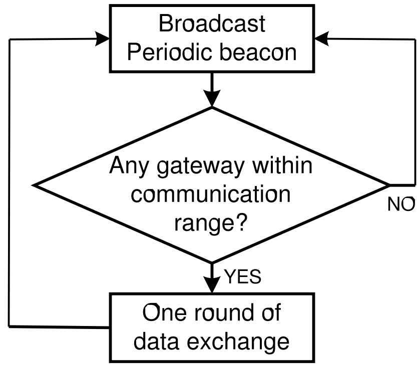
To illustrate the performance of the above approaches, we conduct simple *ns* simulations [73]. Figure 26a depicts the simple network in which a 9-node cluster has a 50 second contact with the ferry. Suppose all nodes have an equal number of messages to send to the ferry. In the first approach, i.e., the ferry participates in MANET routing protocol, DSR is used in our simulations for its fast adaptation to link dynamics caused by ferry movement. Once the routes to the ferry become available, i.e., the ferry has contacts with a cluster, nodes begin transferring buffered messages to the ferry along the shortest paths. In the second approach, one node is selected as the gateway node and all other nodes send their data to the gateway before ferry arrival. When the ferry visits a cluster, only the gateway node sends messages to the ferry. In our simulations, we set the gateway at different locations to evaluate the effects of the length of forwarding paths between the gateway and the ferry.

The simulation results are shown in Figure 26b. We can see that there is significant performance difference between these two interfacing approaches. When the gateway node is used, the effective bandwidth between the partition and the ferry is bounded by the transmission capacity between the ferry and the gateway. If the transmission is over an n-hop path for small n, the effective bandwidth is approximately $1/n$ of link capacity due to the self-interference from the same transmission over different hops. This suggests that it is preferable to select nodes with direct contacts with the ferry as gateways. We also observe that in the first approach, i.e., all nodes send data concurrently to the ferry, the multiple concurrent flows cause severe interference and the effective bandwidth is much less than the cases when the gateway is near the ferry. Therefore, in the rest of this paper, we focus on the approach that uses gateways to interact with the ferry.

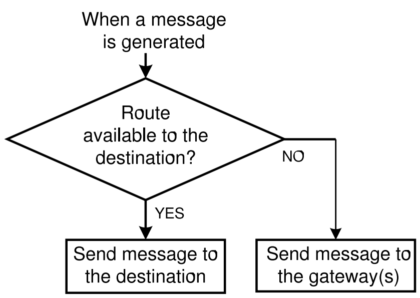
5.1.3 Gateway Based Approach

To utilize gateways for interaction between clusters and the ferry, we extend previous MF and MANET protocols as follows:

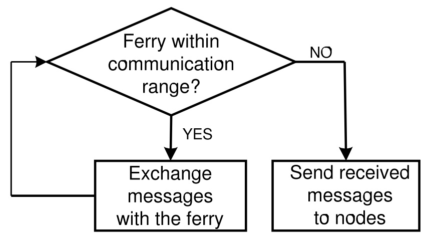
- MF Extension with GateWay (MFGW): Figure 27a depicts the operations of message ferrying. To discover nodes, the ferry sends out periodic beacons. When receiving a beacon message, a gateway node will respond with an acknowledgement message that



(a) Ferry operations in MFGW protocol



(b) Node operations in DSDVGW



(c) Gateway operations in DSDVGW

Figure 27: MF and DSDV protocol extensions

includes reachable nodes within its cluster. Once these acknowledgement messages are received, the ferry selects one of the gateways randomly to exchange data, i.e., the ferry receiver inter-cluster traffic from the gateway and transmits buffered messages with destinations in the cluster to the gateway. The scheduling of message exchange is determined by transmission scheduling algorithms described in the next section. The ferry and gateways will stop data transmissions when a new beacon message is broadcast. The same procedure is repeated, which allows different gateways in the same clusters to interact with the ferry when the ferry moves around.

- DSDV Extension with GateWay (DSDVGW): Figure 27b shows the operations of nodes in MANET routing protocols. Specifically, within each cluster, DSDV protocol is used for intra-cluster traffic. We choose this protocol because nodes are stationary and we do not consider energy constraints. DSDV maintains routes to all nodes with a cluster. When a node generates a message to a destination which is not found in its routing table, this message is forwarded to the gateway node. If there are multiple gateway nodes available, one of them is selected based on the data aggregation approaches to be described in the next section. The operations of gateways are shown in Figure 27c. A gateway can receive messages from other nodes in the cluster at any time. When receiving beacon messages from the ferry, gateways exchange messages with the ferry. Then gateways send received messages to destination using DSDV.

5.2 Interaction between Gateways and Ferry

In the previous section, we describe a hybrid routing framework that uses gateway nodes to interface between MF and MANET routing. In this approach, inter-cluster traffic will be forwarded to gateway nodes with a cluster. Since multiple nodes may have direct contacts with the ferry and are suitable to act as gateway nodes, there is a question of how sources select gateways to relay inter-cluster traffic. In fact, this is an issue of data aggregation at gateways which are representatives of nodes within their clusters for communication with the ferry. In addition, the ferry communicates with gateways over a shared wireless channel. That is, data transmission in both directions will compete for the use of the wireless channel. Given that the contact time between the ferry and gateways may be limited due to ferry movement, this raises a question of how to schedule transmissions between the ferry and gateways to best utilize available contact opportunities. As will be shown in our simulations, both data aggregation and transmission scheduling have significant impact on data delivery performance. In this section, we will describe different algorithms for data aggregation and transmission scheduling.

5.2.1 Data Aggregation (Gateway Selection)

We first consider the issue of data aggregation. Note that nodes send inter-cluster traffic to gateway nodes for delivery to destinations via the ferry. To select one of gateways to forward an inter-cluster messages, one needs to consider two factors. First, to reduce generated traffic in the network and consequently transmission interference, a node should transmit data to a gateway that is as close as possible. Second, since gateways have limited contact time with the ferry, nodes should transmit data to gateways in such a way that gateways are not overloaded. Depending on the network topology, ferry movement, and traffic conditions, these two objectives may conflict with each other.

In this paper, we consider several data aggregation heuristics. As described in Section 5.1.1, we assume that a fixed ferry route is used. Nodes with direct contacts with the ferry are potential gateways. A node has a list of all potential gateways in its cluster. This list can be hard-coded in each node or implemented by advertisement messages from the potential gateways. We consider the following data aggregation schemes.

- *Random selection*: In this scheme, a source randomly selects one of the potential gateways for each message. That is, if there is m gateway nodes, a message has a probability of $1/m$ to be delivered to any of them. By distributing traffic load among all potential gateways, this scheme tries to avoid overloading any gateway. However, messages may be forwarded to gateways along a long path.

- *Proportional selection*: In this scheme, nodes distribute traffic load among gateways according to their contact opportunities with the ferry. As in random selection, the objective here is to avoid overloading gateways. This approach requires information about contact opportunities between each gateway and the ferry. Specifically, for each message generated, the source node selects gateway j with probability $p_j = C_i^j / \sum_k C_i^k$, where C_i^j(or C_i^k) is the amount of traffic that gateway node j(or k) in cluster i can exchange with the ferry during each ferry visit.

- *Nearest selection*: In the two approaches mentioned above, messages are forwarded to different gateways to balance the traffic load on each gateway. In this scheme, we focus on the effects on intra-cluster forwarding. Specifically, each node sends its data to the nearest gateway in terms of the number of hops in the forwarding path. In DSDV, this information is available in the routing table. By reducing the number of forwarding hops, this scheme tries to reduce the total traffic generated in the cluster and minimize interference.

5.2.2 Transmission Scheduling

When the ferry is in contact with gateways, data transmission occurs in both directions. That is, gateways try to forward data gathered from nodes within the cluster to the ferry, while the ferry tries to relay buffered data to the gateways for delivery to destinations in the cluster. Scheduling transmissions in both directions thus have significant impact on the data delivery performance. If gateways are given priority to forward data to the ferry, the ferry may be starved for transmission opportunities and not be able to relay messages received. This is especially true when inter-cluster traffic load is high. In the extreme case, the ferry would accumulate a large number of messages but none would be delivered. On the other hand, if the ferry is given priority in transmission, gateways may not have enough opportunities to forward data to the ferry. This may result in empty buffers at the ferry, wasting the transporting capability of the ferry. Therefore, transmission scheduling needs to achieve a proper balance between traffic in both directions.

We consider the following transmission scheduling algorithms in this paper. All these algorithms are work-conserving in the sense that whenever contact opportunities are available, they are used for message forwarding unless all messages have already been forwarded.

- *Outgoing traffic First (OF):* In this approach, a gateway is given priority to send the messages accumulated in its storage to the ferry first. The ferry is allowed to send traffic to gateways only when there is no traffic from the gateway. From the perspective of gateways, this approach transmits outgoing traffic first.

- *Incoming traffic first (IF):* In this scheduling algorithm, the ferry sends all the messages with destinations in a cluster to gateways before it receives traffic from them. This is the opposite of the outgoing traffic first scheme.

- *Round Robin (RR):* In this scheme, the contact time between a gateway and the ferry is divided into slots of equal size. These slots are assigned equally to traffic in both directions.

In the above scheduling algorithms, data transmission assumes no knowledge about the incoming and outgoing traffic load. If such information is available, however, one can schedule transmission to achieve fairness among traffic to different destined clusters. Specifically, we consider a scheduling algorithm to achieve the following objective:

$$\begin{aligned} \text{maximize} \quad & \lambda \\ \text{subject to} \quad & \sum_{j=1}^{n}(a'_{ij} + a'_{ji}) \leq C_i \\ & a'_{ij} = \lambda a_{ij} \\ & 0 \leq \lambda \leq 1 \end{aligned} \tag{1}$$

where C_i represent the summation of data transmission capacity between cluster i and the ferry, a_{ij} is the inter-cluster traffic load between cluster i and j, and a'_{ij} is the achieved rate. Suppose the objective is achieved, the following equation holds: $a'_{ij}/a'_{mn} = a_{ij}/a_{mn}$. That is, the transmission capacity is allocated to traffic according to the corresponding data rates. Based on this result, we have the following scheduling scheme.

- *Proportional Allocation (PA):* In this scheme, the contact time between gateways and the ferry is assigned to traffic proportionally to the data rates. This can be done by solving the linear programming formulation in (1) and schedule traffic accordingly.

5.3 Evaluation of data aggregation and scheduling algorithms

In this section, we compare the performance of data delivery with various combination of data aggregation approaches and transmission scheduling algorithms via *ns* simulations.

5.3.1 Simulation Settings

We implemented the MFGW and DSDVGW Protocols in ns2 simulator [73]. In our simulations, 80 wireless nodes form four stationary clusters in a 6000m ×6000m area. These stationary clusters are centered at (1000, 1000), (1000, 5000), (5000, 5000) and (5000, 1000) respectively. Each cluster has a dimension of 1000m×1000m and 20 randomly located nodes. Nodes in the same cluster communicate with each other via wireless links. Our simulations use the IEEE 802.11 MAC layer. The radio range is 200m and the data rate is 1Mbps.

A single ferry is used which moves along a fixed route with a constant speed of 10m/s. In our simulations, we consider five ferry routes, which differ in the amount of contact opportunities between gateways and the ferry. Figure 28 shows the five ferry routes in a randomly generated network topology.

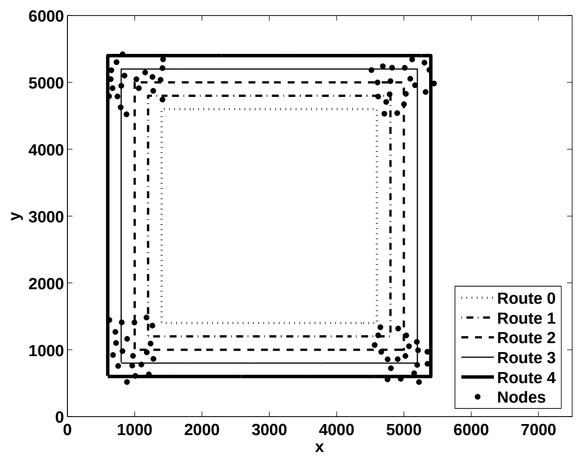


Figure 28: Network Topology

Among the 20 nodes in each cluster, 10 nodes are randomly selected as sources which generate CBR traffic with a message size of 1000 bytes and a data rate of 2 kbps. The destinations are randomly chosen among nodes in other clusters by default unless we specify differently. In this paper, we focus on routing performance. So we choose UDP as our transport layer protocol.

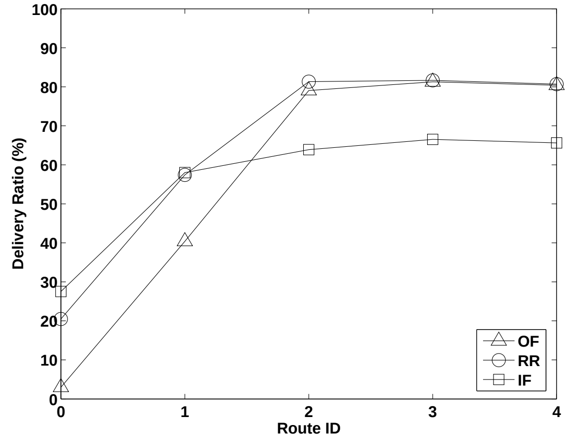
The main objective of the hybrid routing protocols is to maximize the message delivery ratio. In addition, although applications in DTNs should be able to tolerate large delay, lower delivery latency is still preferable. Therefore, we use the delivery ratio and average delivery latency in our evaluation. We average the results over 10 rounds, each of which lasts for 20,000 simulation seconds.

5.3.2 Effect of Transmission Scheduling

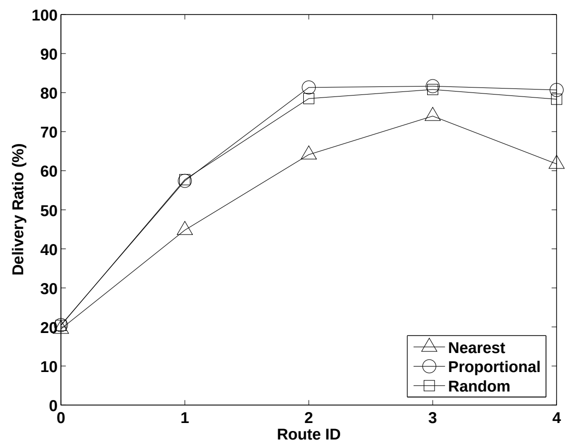
We first study the effects of transmission scheduling on data delivery performance. In proportional gateway selection, we calculate each node's average contact time with the ferry. When multiple nodes are within the ferry's communication range, we divide this time period into equal shares for each node. Figure 29a depicts the delivery ratio under different gateway selection heuristics. The X axis denotes the different ferry routes used. In these simulations, proportional scheduling is the same as round robin algorithm because incoming and outgoing traffic load at each cluster are the same. So we omit the results of proportional scheduling in Figure 29a.

We make the following observations. First, when the ferry moves along the route 0 and 1, it encounters only a small number of gateways. All three algorithms yield a delivery ratio less than 60% due to the limited contact opportunities. In particular, Outgoing traffic First (OF) algorithm becomes unstable, i.e., the ferry is starved in transmission opportunities to forward messages to gateways, and almost no data can be delivered. Second, OF and Incoming traffic First (IF) algorithms perform differently under different ferry routes. IF scheduling performs better when route 1 or route 2 is used. This is because OF scheduling has stability problem when the traffic load is high as compared to the delivery capacity provided by ferry/gateway contacts. In such cases, the ferry can only receive data from gateways and no data can be actually delivered. As the contact opportunities increase, however, OF scheduling has a better delivery ratio. This is due to the difference of data forwarding at gateways and the ferry. Note that while a gateway can only send outgoing traffic during its contact with the ferry, incoming traffic from the ferry can be given to any gateways. So in IF scheduling, if the ferry carries plenty of traffic to one cluster, the first few gateways the ferry encounters might not be able to send their outgoing traffic, leading to lower delivery ratios. Third, the Round Robin (RR) scheduling intentionally balances the incoming and outgoing traffic. Therefore, it avoids the problems with the other two algorithms and exhibits consistently best performance on different ferry routes. We obtain results for the average latencies of these three algorithms, which show similar trends. Due to space constraints, we omit these results in this paper.

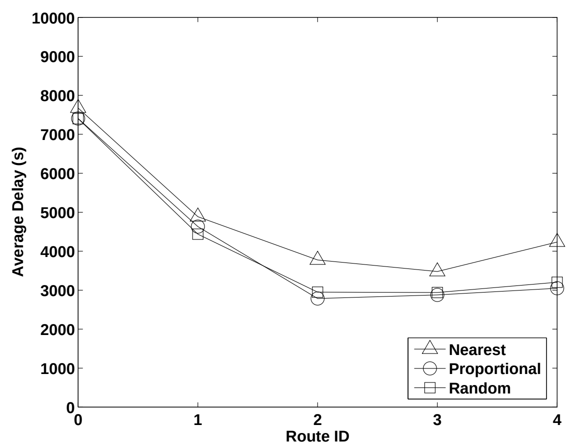
In the above simulations, we assume a symmetric incoming/outgoing traffic load. Therefore, Proportional Allocation (PA) scheduling functions the same way as the RR scheduling. When the traffic load is not symmetric, their operations become different. We consider scenarios where the incoming traffic of a "hot-spot" cluster is four times of the outgoing traffic load (16 destination nodes and 4 source nodes). Each of the other three clusters has 6



(a) Delivery ratio under different transmission scheduling



(b) Delivery ratio under different gateway selection



(c) Delay under different gateway selection

Figure 29: Ferry/Gateway Interaction: Source Rate 2 kbps

destination nodes and 10 source nodes. With the proportional gateway selection, we show in Table 3 the delivery ratios of these two scheduling algorithms when the ferry moves along route 3. While both RR and PA scheduling have similar overall delivery ratios, PA scheduling allocates contact opportunities between incoming and outgoing traffic more evenly. The delivery ratios for traffic to and from the hot-spot cluster are 83.6% and 89.0% respectively, as compared to 80.1% and 93.1% in the RR scheduling. This is because PA scheduling takes into account of traffic load information, while RR scheduling gives equal opportunity to incoming and outgoing traffic. These two schemes perform differently in clusters with asymmetric incoming/outgoing traffic load.

	RR	PA
Traffic to the "hot-spot" cluster	80.1%	83.6%
Traffic from the "hot-spot" cluster	93.1%	89.0%
Total Traffic	86.1%	87.2%

Table 3: Delivery ratio with different scheduling algorithms

5.3.3 Effect of Gateway Selection

We now consider the effects of gateway selection schemes on data delivery performance. We focus on the RR scheduling since it achieves the best performance. Figure 29b shows the delivery ratios of different gateway selection approaches. We can see that the nearest selection approach has the worst performance among the three. In this approach, gateway selection is determined by factors other than the contact opportunities between gateways and the ferry. Data may be forwarded to a gateway with very limited contact with the ferry. Proportional gateway selection, on the other hand, has the highest delivery ratio because it avoids overloading gateways which have limited contact opportunities with the ferry. And by distributing outgoing traffic to multiple gateways, random gateway selection has a similar delivery ratio as proportional selection. We note that the difference between random selection and proportional selection is insignificant under all ferry routes. This can be explained as follows. When there are plenty of contact opportunities, e.g., the ferry moves along route 3, the traffic load on each gateway is always less than the effective capacity and both gateway selection approaches have high delivery ratios. When the amount of contact opportunities is small, e.g., the ferry moves along route 1, the traffic load on each gateway with both gateway selection approach can be higher than the effective capacity. The achievable data delivery rate is half of the effective capacity since the round robin scheduling algorithm is used.

The average latencies of these three approaches with round robin are illustrated in Figure 29c. We can see that the proportional and random selection schemes have lower delays. Simulations with other scheduling algorithms have similar results and thus are omitted.

5.3.4 Effect of Intra-cluster Traffic

We consider only inter-cluster traffic in previous simulations. In a cluster, there are possible data exchanges between nodes in the cluster. Furthermore, the data rate of such traffic can be much higher than the inter-cluster traffic because it is sent over multi-hop paths. We now evaluate the effect of background MANET traffic over the inter-cluster traffic. We use route 0 and route 3 as the two extreme cases for contact availability. And 30% of the sources now generate intra-cluster traffic; Figure 30 shows the delivery ratios under different date rates and different ratios between inter/intra-cluster traffic. The label "Ratio 10" means the intra-cluster traffic source generates message 10 times faster than an inter-cluster traffic source; We can see that intra-cluster traffic has significant effect over the performance of inter-cluster traffic. For example, when the source rate is 4kbps, the delivery ratio drops from 62% to 32% under route 0 and high intra-cluster traffic load. This is because of two reasons. First, with higher intra-cluster traffic load, wireless interference is more severe, reducing the effective capacity between gateways and the ferry. So fewer messages can be exchanged during the gateway/ferry contacts. Second, the large numbers of MANET packets cause more collisions and more drops of any type of traffic, including inter-cluster traffic.

5.4 Ferry Route Design

The discussion above is based on the assumption that the ferry follows a given route, which is not specifically designed for optimal message delivery performance. As we have shown in

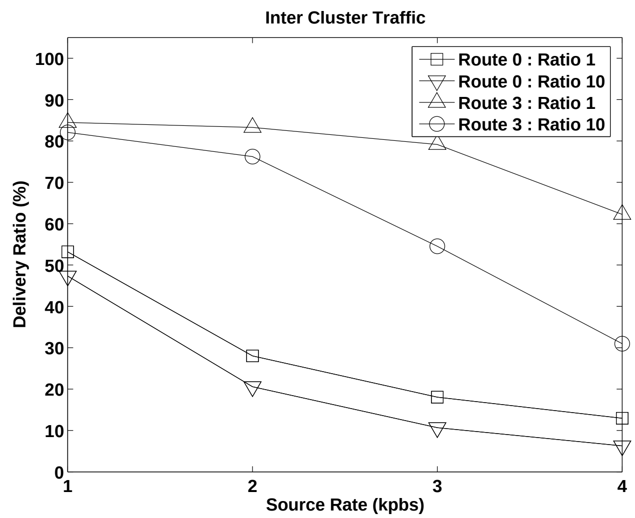


Figure 30: Effect of intra-cluster MANET traffic.

the simulations, both the data delivery ratio and average delay change significantly as the ferry moves along different routes. In cases where we are able to control ferry movement or design a ferry route, we can customize the ferry route according to traffic condition to improve performance.

Ferry route design has the potential for reducing message delay and supporting higher throughput. In our prior work [109], we consider ferry route design in networks with stationary nodes that are separated from each other. In this paper, we study clustered DTNs where connectivity within clusters provides opportunities to refine the ferry route. In the following, we first review ferry route design in networks without clusters. Then we develop algorithms for designing ferry routes in clustered DTNs.

5.4.1 Ferry Route Design without Clusters

In our prior work [109], we define the ferry route design problem. Specifically, let b_{ij} be the data rate from node i to node j. For a ferry route T, the average delay is defined as $D^T = \frac{\sum_{i,j} b_{ij} d_{ij}}{\sum_{i,j} b_{ij}}$ where d_{ij} is the average delay for data from node i to node j under ferry route T. Given a set of nodes and a traffic matrix between nodes, the ferry route design problem is to determine a ferry route T such that the traffic requirement is met and the average delay D^T is minimized. It can be shown that solving the ferry route design problem optimally is NP-hard. Thus we develop heuristic algorithms to compute ferry routes.

To compute a ferry route, we divide the overall problem into two sub-problems, which consider minimizing delay and meeting traffic requirement respectively. For the first sub-problem, which determines the order of visiting nodes to minimize the average delay, we adapt solutions for the well-studied traveling salesman problem (TSP) which computes a shortest route to visit all nodes. But instead of optimizing the length of the route as in TSP, we minimize the average delay. Specifically, we first generate an initial route using some TSP heuristic algorithm, e.g., the nearest neighbor heuristic, and then refine the initial route using local optimization techniques.

In the first sub-problem, we consider only the average delay. In the second sub-problem, we consider how to extend the ferry route, if necessary, to meet the traffic requirement. For a given route, the transmission capacity between the ferry and a node is determined by the fraction of time that the node communicates with the ferry. If the capacity is not enough to support the traffic load, we need to extend the amount of time the ferry spends in the vicinity of this node. Let x_i be the length of route extension around node i, the total length of ferry route segment within the communication range of node i is $x_i + 2r$. Let s_i be the summation of incoming and outgoing traffic load of node i. We have

$$\frac{(x_i + 2r)W}{L + \sum_j x_j} \geq s_i$$

where L is the route length before extension. We formulate the route extension problem as the following linear programming (LP) problem which can be solved efficiently using LP methods.

$$\begin{aligned} \text{minimize} \quad & \sum_i x_i \\ \text{subject to} \quad & W x_i - s_i \sum_j x_j \geq s_i L - 2rW \\ & x_i \geq 0 \end{aligned} \tag{2}$$

5.4.2 Ferry Route Design in Clustered DTNs

We now consider the design of ferry routes in clustered DTNs. In a clustered DTN, nodes within a cluster can communicate with each other. As illustrated in the previous sections, gateway nodes can be used to relay messages between other nodes in the cluster and the ferry. In this case, the ferry does not need to visit every node in the clusters. Thus in clustered DTNs, route design has the flexibility to visit a subset of nodes, i.e., gateways, in the network. This raises a question of how to select gateways in clusters.

In this paper, we design ferry routes in the following three steps.

1. *Determining cluster visit order.* The algorithm first creates a "virtual" node at the center of each cluster which has the aggregate traffic load of the cluster. Then we apply the route design algorithms in [109] to compute a ferry route for the "virtual" nodes. That is, the algorithm determines the order in which the ferry visits each cluster.

2. *Gateway selection.* In this step, the algorithm selects gateway nodes in each cluster. Then the algorithm refines the ferry route to visit gateways instead of "virtual" nodes.

3. *Bandwidth extension.* The algorithms compute transmission capacity provided by the ferry route generated in step (2). If the capacity is not enough to support the traffic load, the ferry route is extended to meet the traffic requirement. This is done by solving the linear programming problem in (2).

We consider several schemes to select gateways in each cluster. With connectivity in clusters, the ferry is allowed to visit only a subset of nodes in the network. Depending on which performance objective to optimize, one can select gateway nodes in different ways. Specifically, we study the following three gateway selection schemes.

- *MF with center node (MF-CN).* In this scheme, we choose the center node of each cluster as the gateway. This gateway will relay all inter-cluster traffic between the cluster and the ferry. And the ferry visits these gateways in the same order as visiting "virtual" nodes which is determined by step (1).

- *MF with minimum length (MF-ML).* In this scheme, we design the ferry route to have the minimum length. Specifically, we choose one node from each cluster as the gateway such that the total length of the ferry route is minimized. This can be determined by solving the following 0-1 integer linear programming problem.

$$
\begin{aligned}
\text{minimize} \quad & \sum_i \sum_j d_{ij} x_{ij} \\
\text{subject to} \quad & \sum_j x_{ij} - \sum_j x_{ji} = 0 \\
& \sum_{i_k} \sum_j x_{i_k j} = 1 \quad \text{node } i_k \text{ is in cluster } k \\
& \sum_{i_k} \sum_j x_{j i_k} = 1 \quad \text{node } i_k \text{ is in cluster } k \\
& x_{ij} = 0 \text{ or } 1;
\end{aligned}
$$

where d_{ij} is the distance from node i to node j and x_{ij} is an indicator of whether the ferry will visit node i and j in that order on the designed route.

- *MF with sources/destinations (MF-SD).* In this scheme, the ferry will visit all sources and destinations. That is, each source and destination will act as a gateway for its own traffic. So there is no need to transfer inter-cluster traffic over multi-hop paths within clusters.

The above gateway selection schemes focus on optimizing different aspects of data delivery. The MF with center node scheme, which selects the center nodes as gateways, tries to position gateways at the center of each cluster. This way, it minimizes the longest paths from all sources and destinations to the gateway. In MF with minimum length, the length of the ferry route is minimized. This scheme tries to minimize the message delay and increase the contact capacity between gateways and the ferry. In the MF with sources/destinations scheme, all sources and destinations communicate with the ferry directly. So it avoids the data losses that otherwise would occur when transferring data over multi-hop paths within clusters. In addition, by visiting all sources and destinations instead of single gateways in other schemes, the ferry is able to utilize more contact opportunities.

5.5 Evaluation of ferry route design heuristics

In this section, we evaluate different ferry route design schemes. As discussed in the previous section, ferry route design aims to improve message delivery ratios and reduce delay.

5.5.1 Simulation Settings

In our simulations, we use the same simulation settings as in Section 5.3 except for the following changes. Specifically, four stationary clusters are randomly deployed in a square area of size 6000m×6000m and 3000m×3000m. The distance between cluster centers is required to be larger than 2000m or 1000m respectively. Each cluster consists of a random number of nodes. Either 20% or 50% nodes are chosen to be the source which generates the traffic with a rate from 1 kbps to 4 kbps. And 30% of the sources choose a destination within the same cluster. That is, 70% of total traffic load is between clusters. The ratio between intra-cluster and inter-cluster traffic is 1 or 10. Although the wireless link capacity is 1 Mbps, the effective bandwidth W never exceeds $800kbps$ in our measurement. To reflect the impact of wireless interference, we also consider $W = 300kbps$ in our simulations. We run simulations for 20,000 simulation seconds, and each result is averaged over 5 rounds using different random seeds.

To evaluate the utility of ferry route design, we also consider the case with fixed routes. Specifically, we compute a fixed ferry route that visits the "virtual" nodes in the order determined by step (1) in the ferry route design algorithm in Section 5.4.2. And all nodes having contact opportunity with the ferry are considered as gateway nodes.

5.5.2 Delivery Ratio

We first evaluate how ferry route design affects the delivery ratio. Figure 31 shows the delivery ratios under different route design approaches when 50% nodes generates traffic in the 6000m×6000m area. We can see that as traffic generation rate increases, MF with fixed routes becomes inferior because of limitations in contact opportunities between gateways and the ferry. Without detours that allow the ferry to communicate with gateways for a longer time, gateways are not able to forward gathered messages to the ferry. We also note that all three MF schemes, which extend the ferry route based on traffic load, have better delivery ratios than the MF scheme with fixed routes. This suggests that route extension is necessary in situations where inter-cluster traffic load is high or contact opportunities between gateways and the ferry is limited. Among the three MF schemes that extend the ferry route based on traffic load, MF with sources/destinations achieves the best delivery ratio especially when the traffic load is high. The reason is that if we choose only one node as the gateway for each cluster, all source nodes must send their inter-cluster traffic to the gateway via multi-hop routing. Similarly, data received from the ferry must be distributed to destinations via possibly multi-hop paths. Due to the interference and message losses, the overall delivery ratio is reduced. However, if the ferry visits all sources and destinations directly, the ferry would communicate with them directly, reducing the possibility of message losses that otherwise would occur in multi-hop forwarding. In addition, in the case with $W = 800kbps$, which ignores the effects of wireless interference on contact opportunity, the delivery ratio is lower. This is because we underestimate the detour needed and the delivery ratio suffers accordingly.

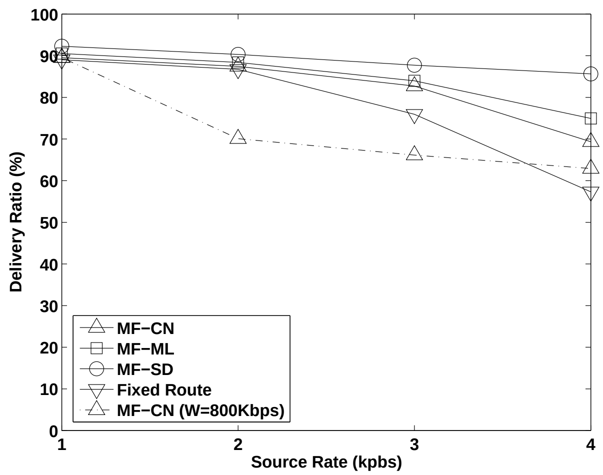
Figure 31b shows the delivery ratios with higher intra-cluster traffic load, i.e., the ratio between intra- and inter-cluster traffic is 10. We can see that the delivery ratios for all route design schemes decrease significantly. This is because with higher intra-cluster traffic, the intensified interference not only reduces the effective capacity of gateway/ferry contacts, but also cause more message losses when data are forwarded within clusters. We have conducted simulations with 20% nodes as sources or under a 3km $\times$ 3km area. Due to the low traffic load or the more frequent contacts between gateways and the ferry, most messages are delivered successfully.

5.5.3 Message Delay

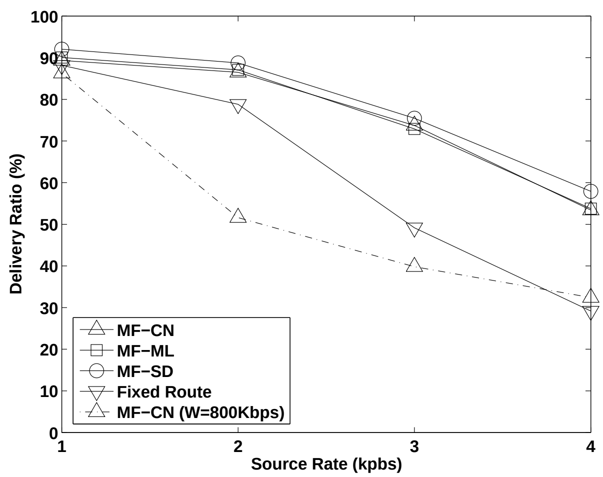
Delay (sec)	Small Area		Large Area	
	Low load	High load	Low load	high load
MF-CN	936	1954	2190	4268
MF-ML	655	1177	1865	3643
MF-SD	957	1451	1531	2719
Fixed Route	904	1710	2072	4377
*The ratio is 10 and $W = 300kbps$ for all the results				

Table 4: Different Route Design

We now show the simulation results for the average delay in Table 4. We depict the message delay under both low traffic load where the source rate is $1kbps$ and high traffic



(a) Large Area: Src Percent (50%): W (300 kbps): Ratio (1)



(b) Large Area: Src Percent (50%): W (300 kbps): Ratio (10)

Figure 31: Different Route Designs

load where the rate is $3kbps$. With a smaller area, MF with minimum length is able to achieve a 30% decrement in message delay as compared to other three approaches. This is because the ferry route is designed to choose gateways such that the total length of the ferry route is minimized.

In the large area simulations, the distance between clusters becomes the dominant factor in determining the length of the ferry route. So in MF with minimum length, the reduction in message delay due to the shortened ferry route is less significant. In fact, MF with sources/destinations has the lowest delay under both low and high traffic load. This is because as the total ferry route length increases for a larger deployment area, detour becomes necessary to satisfy the traffic load. When the ferry visits each source and destination, the ferry is able to use more contacts for transmission. Thus less amount of detour is required. We also see that MF with minimum length has the second lowest delay because of the shorter route length.

CHAPTER VI

A WIRELESS AND MOBILE NETWORK SYSTEM IN OILFIELD OPERATIONS

In today's oilfield operations, data communication at field location is essential for operation control, equipment monitoring and crew coordination. Data communication is also desirable between oil field locations and services running on Internet or inside Enterprise network infrastructure. For example, important job parameters during a field job can be sent to a central data server where clients are able to view the job progress and provide feedback/comments. In the meanwhile, orders and notifications to the crew can be issued by messaging or emails.

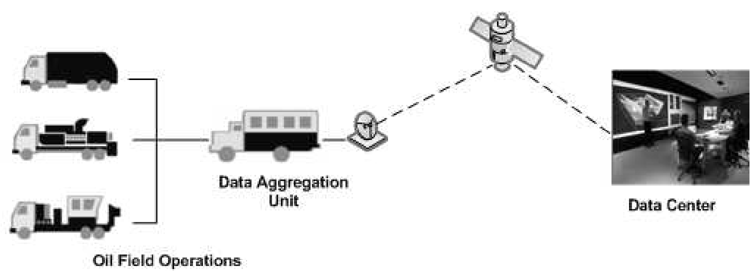


Figure 32: An Oilfield Network Example

Since most of field operations are conducted in remote areas, satellite links have been considered as the only option for a long time. Figure 32 shows such an example. On the one hand, a wireless or wired Local Area Network (LAN) provides good connectivity at the site. On the other hand, a VSAT satellite link from iDirect [5] connects the operation crew to the Internet and it is shared by various applications which need data links to central servers.

After the BP Macnodo incidence [1], stricter governmental regulations introduce new data communication requirements to field operations. For example, status of oilfield equipments should be reported to data center regularly. In this chapter, we first present our observation that the existing network in Figure 32 became a challenged one for such a new application. Then we report our effort of challenged network transforming which includes a comprehensive outdoor wireless links measurement and evaluation.

6.1 Network Classification and Transformation

In infrastructure-less network, one major approach to transform a challenged network is introducing node mobility. In transforming an infrastructure-based wireless and mobile network to support specific applications, we focus on the wireless links' characteristics and how applications perform over those links.

6.1.1 Bandwidth Constraint

As a recent effort of improving reliability in job execution upon policy changes, a data collecting and reporting application is developed to monitor numerous sensors on pumps used in the oilfields. The data would be valuable for trouble diagnosis, maintenance scheduling and loss prevention by early parts repair/replacement. Therefore, this set of data needs to be sent back to data center for expert evaluation. However, the complete data set is generated at a rate of hundreds of kbps even after compression. Although satellite link is able to provides coverage at remote areas, the bandwidth is always limited. In order to ensure quality of service to existing applications, there is an upper bound on bandwidth consumption, especially on the upload link, for this new application.

In this case, the space path always exists between the job site and the data center. However, the bandwidth constraint on the space path make the space path not usable. In our connectivity based classification framework, this path is classified as assistant-needed, in other words, unless further assistant would be able to create more contact opportunities, the network is completely partitioned.

However, if we look at the data set further, we'd notice that the different types of information can be extracted and separated in the whole data set. There are important alarms which needs immediate attention of experts in the data center or operators at job sites. For example, the engine oil temperature exceeds a limitation. The rest of the data set is important but does not require real-time transmission. We name such data type as bulk data in our study. Therefore, we start from the application's data set and split the information. Only alarms will be sent in real-time with the bandwidth consumption around 15 kbps while the rest of the data set can be stored in local storage. Therefore, this satellite link becomes a space path for the real-time data.

6.1.2 Latency Constraint

At the job site, those real-time alarms are sent out strictly with an one-second interval. On the other side of the application, real-time monitoring of those alarms at data center requires an average latency of data delivery less than 2 seconds.

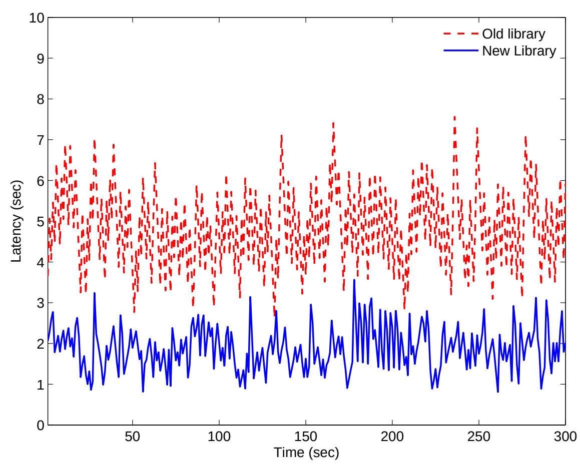


Figure 33: Latency Performance Comparison

With the existing transport layer library for data delivery from the job site to data center, the average latency is around 4 seconds as shown in Figure 33. Therefore, although a space path exists between job site and data center theoretically, it is not usable to the application due to latency violation. Similar to bandwidth constraint handling mentioned before, we focus on wireless link characteristic and the application using that link in the challenged network transformation.

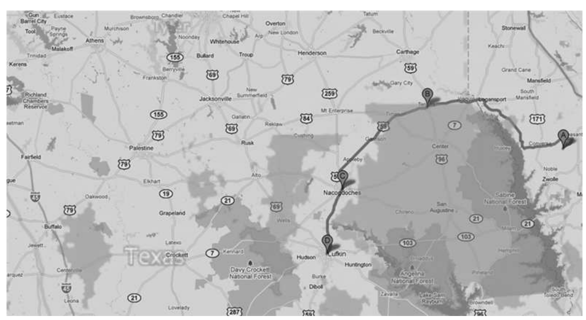
As we will show in later section, the end-to-end latency on satellite link is less than 2 seconds. The excessive latency is from inefficient real-time data transfer handling in the application. We replace the existing transport layer library with a new Java Message Service middleware which is designed for real-time data delivery. The improvement over latency is significant and we make a successful transformation of the network from assistant-needed to the one with a usable space path.

6.1.3 Alternate Wireless Links Provisioning

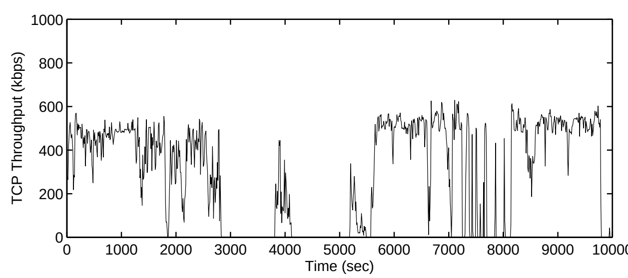
By separating alarm data and replacing transport layer library, portion of the data set is able to use the satellite link in real-time. The rest of the data set is stored locally first but it is required to be transferred to and managed by a central archiving system. With the single satellite link between the job site to the Internet, other assistance is needed from the connectivity-based classification.

Company IT policy rules out the possibility of using a ferry based approach like the one we discussed earlier in Chapter 5 since it may relies a 3rd party, e.g., human or vehicle, which may not always under the company's regulation. Therefore, we add other direct links between job sites and the Internet and explore the possibilities of making the network transformation.

6.1.3.1 Feasibility Study



(a) Coverage over field tests area



(b) Upload rate on the route

Figure 34: Area of field test locations

Recent research works evaluate outdoor Internet access from vehicles using cellular service [12,35,105]. High bandwidth and stable connectivity from cellular data link exist at all those areas even under fast movements. However, all these studies were conducted in urban regions where cellular tower deployment density is high. Performance of cellular data links at remote areas far from cellular towers has not been evaluated in-depth.

From 03/31/2010 to 04/09/2010, we visited 12 field locations spread out in an area of nearly 35,000 km^2 in northern Texas/Lousiana shown in Figure 34a[1]. At each location, we connect AT&T or Verizon modem to a Dell Latitude laptop with Windows XP. Commercial Internet speed test server [3] and an internal link speed test server inside our data center are used to measure the upload/download link speed for a few times. If data service is available, average link speed is recorded. Data service coverage and link speed of both service providers are evaluated.

During our tests, we found out that the coverage map from service providers can be a good reference but disagreements from actual measurement do occur. We overlaid Verizon's coverage map from [4] on the map of our field tests. Those shadows on Figure 34a represent areas without coverage. Among the three field locations where we did not get Verizon data service, two are actually inside those shadows. The one location "should" have service but actually doesn't is outside shadows. But its terrestrial condition is not favorable: surrounding grounds are higher than the actual field location. We also monitor the TCP throughput in a 3 hours driving from point A on the map (not among those field locations) to a nearby city, i.e., point D. 600MB data is being continuously uploaded during the trip. The TCP throughput variations over time illustrated in Figure 34b generally agree with coverage along the route with occasional odds.

Coverage (%)	ATT	VZN	Bandwidth	ATT	VZN
3G	0	75	Upload	94	323
non-3G	100	0	Download	106	645

Table 5: Field test summary of cellular links

[1]Due to business concerns, we cannot disclose those fields' exact locations on this map.

Field test results are summarized in Table 5. AT&T has EDGE service at all those location but no high speed 3G coverage at any of them. On the other hand, Verizon provides 3G EVDO service at 9 locations and no service in the rest 3. Therefore, significant difference on the average uploand/download speeds between these two service providers are observed during our tests.

6.1.3.2 *Hardware Configuration*

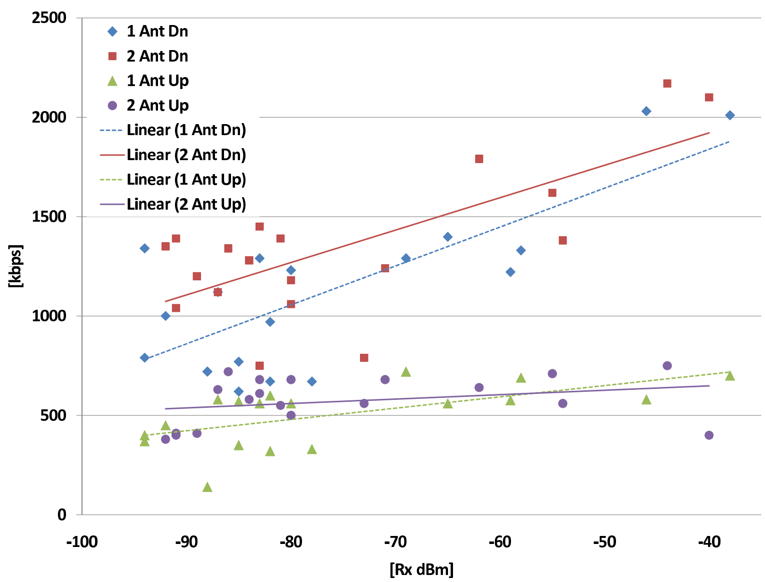


Figure 35: Antenna setup and Verzion's 3G link speed

We plot download/upload speeds over Verizon's 3G links against signal strength readings from data modems in Figure 35. Assuming those readings represent strength of received signal, linear fittings indicate that 1dB increment on signal strength can lead to an increment of 28.4 kbps in download speed and 7 kbps in upload speed with the one antenna case. Using two antennas generally increases average signal strength by 1 dB. However, the effect is a 15% download speed increment. We believe this is a result from spatial diversity provided by two antennas. On the other hand, uploading speed is not affected much. Unlike the signal spatial diversity study in [96] where geographic distance between antennas can be up to 500 meters, the distance between antennas in our setting is a few meters. Using two antennas helps on link speed in our field tests but cannot reach 3G data service either at locations where a single antenna setup fails.

Test results shown in Figure 35 are used to finalize the communication hardware configuration. We use two dual band flexible omnidirectional antennas. The choice of this type of antenna is from specific oilfield operational restriction: the cellular antenna must be placed on the roof top of trailers and should be flexible to prevent damage caused by potential strong vibrations or impacts from vegetation as field operation are carried out at places with harsh road conditions from time to time. This rules out many other choices such as electronically steerable antenna [72]. The gain of this flexible antenna is 5 dB since higher gain antennas are usually longer and associated with higher probability to break during field operations. The AT&T and Verizon 3G modems we used are from DIGI and come with one or two (Verizon model) external antenna connectors. Both antenna and cellular data modems installation pass our internal environmental qualification procedure which involves tests such as strong vibration and extreme temperature condition.

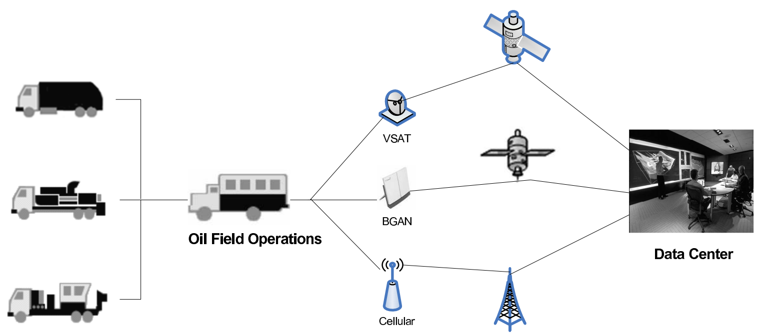
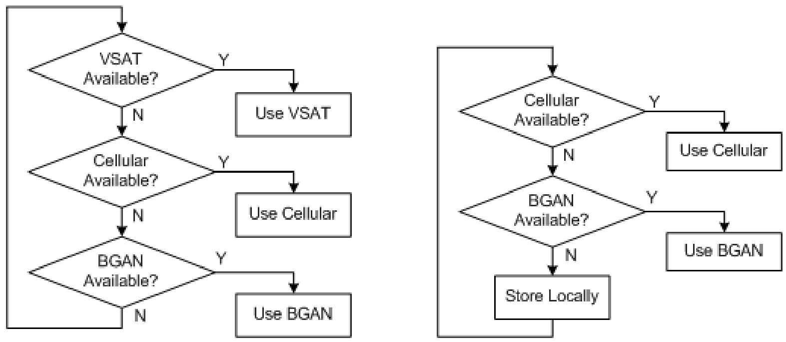


Figure 36: New Oilfield Network under Evaluation

In addition to evaluating cellular data link, we test the satellite link provided by BGAN modem from Inmarsat [2] at those 12 field locations as well. Unlike cellular link, BGAN link is available at all locations. Therefore, we include this type of link in our further evaluation. The final network setup is shown in Figure 36.

All three modems are connected to the same laptop via the Ethernet port and two USB/Ethernet convertors. Different IP addresses are assigned with DHCP protocols on each of these three interfaces and we manipulate Windows's local routing table to direct the traffic according to the selection procedure illustrated in Figure 37.

During field crew's operations, e.g., fracturing, real-time data is generated continuously



(a) Real-time Data Transfer (b) Bulk Data Transfer

Figure 37: Wireless Links Selection

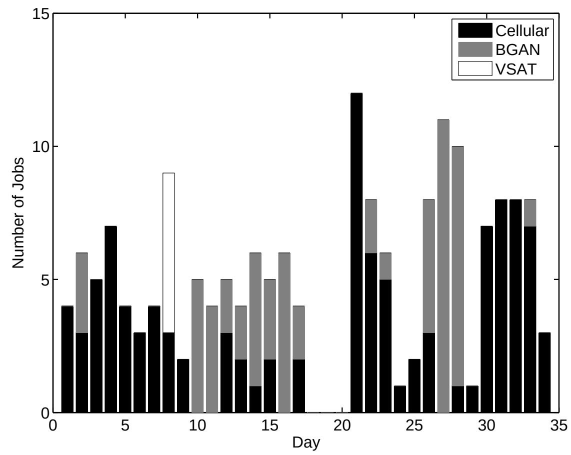
and sent to the server in data center if one of those data links is available. On the other hand, bulk data is generated in terms of files with the size of 1 MBytes regularly. Once such a file is generated, our application automatically tries to upload it to a ftp server. Unlike real-time data, the bulk data files are kept on local storage until they are uploaded. Each ftp transmission's starting time, size and duration are recorded.

For both real-time and bulk data transfers, the selected data link from the selection procedure is used until it becomes unavailable. Then the selection procedure repeats until another choice is found.

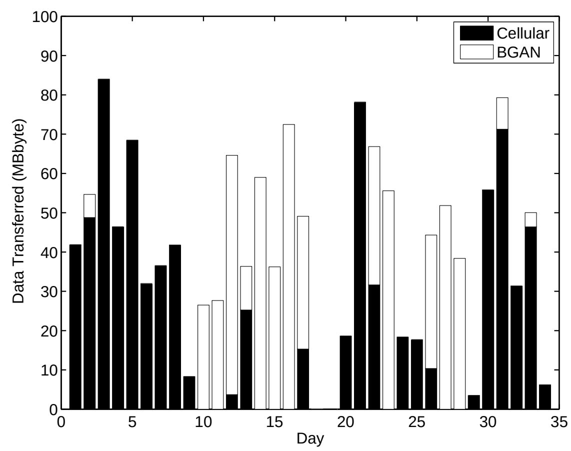
6.1.4 Operation Result from the Pilot Unit

One pilot unit was deployed for field tests at Shreveport District at Northern Louisiana on September 2010. We retrieved logs for an one-month span from Oct. 20, 2010 to Nov. 22, 2010 for performance evaluation. Note that AT&T data modem was used by this pilot unit although Verizon's service shows better coverage. The reason is the latter did not have enterprise level access to our company's intranet until early 2011 after certain business procedures were fulfilled.

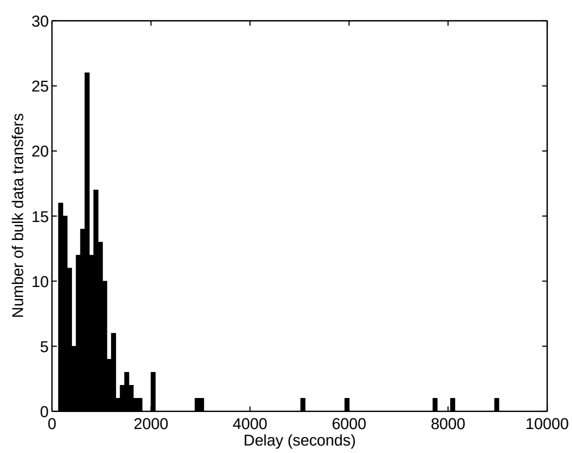
Figure 38a shows the number of real-time transfers over those three data links in each day. Note that among the total more than 170 real-time data transfers in this one month period, VSAT link is only used once. In the meanwhile, the cellular link and BGAN link carry almost all real-time data with cellular link accounts for more than 60%. This result indicates that today's satellite link used in field operations has a poor availability although



(a) Real-Time Data Transfer Per Day



(b) Bulk Data Transfer Per day



(c) Delay of Bulk Data Transfer

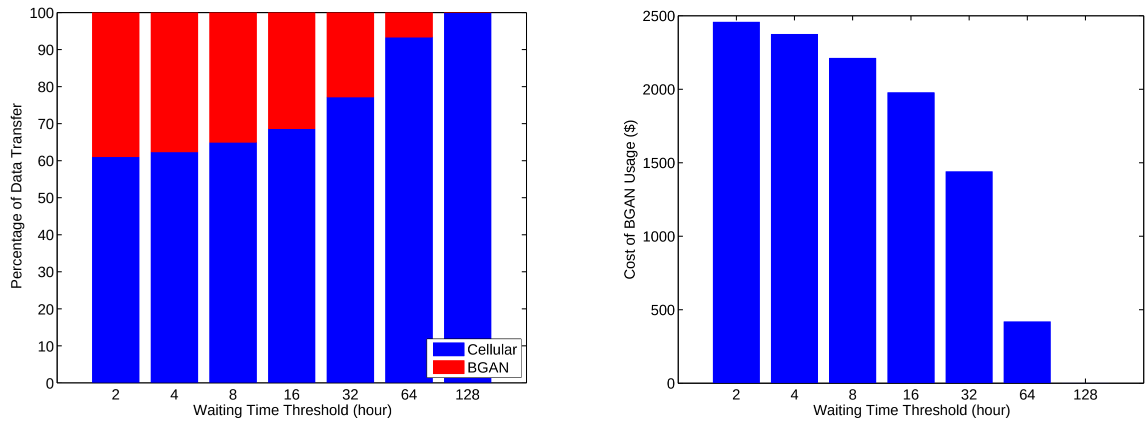
Figure 38: Data Transfer Statistics

it is supposed to have good coverage even at remote areas. Further investigation shows the major factor accounting for this poor availability is the directional antenna with the VSAT modem, which has a diameter of 75cm - 1.2m and weights over 50kg, motor-driven mechanic arms are used to elevate the antenna, track the signal as well as fold the antenna beneath the roof when the vehicle hosting the VSAT system is in motion. As such movement is always on unpaved road, strong vibrations may damage the mechanic part and control system. In addition, this VSAT system requires close attention from field engineers throughout its operation and maintenance, which is not always there in the intensive and fast-paced field operations.

We summarize bulk data transfer distribution in Figure 38b where the y axis represents the amount of daily data transferred over those data links. Note that cellular link handles a big portion (>60%) of bulk data transfer. By comparing the time stamp of each bulk data file's creation and the time stamp of its real transfer, we collect and present the waiting time of each bulk data transfer in Figure 38c. Most of bulk data transfer's delay is less than half an hour with a median value of 731 seconds. The maximum waiting time is 9027 seconds when bulk data transfers can use either cellular or BGAN link.

From network classification point of view, introducing cellular link and BGAN link to oil field operations significantly improves the connectivity in terms of creating space path and space-time path between field sites to the data center. However, unlike license free 802.11 or bluetooth links discussed and evaluated in most research works on wireless and mobile networks, using cellular and BGAN links has associated operational costs. BGAN link has tiered pricing models and the service used in our study costs USD 5/MByte. Cellular data service's pricing model is a simple flat one: USD 100 per month with 2G Bytes usage cap. In this one month time period, more than 500 MByte data is sent via BGAN link and it costs nearly USD 2,500. In the same time period, around 850 MByte data is sent via cellular link. If we only used cellular link to transfer bulk data, some bulk data files may have longer delay as the cellular link might not be available at the moments when they were sent via BGAN link. However, the potential reduction of operational cost is significant.

The tradeoff of latency and operational cost can be shown by emulations over the same trace collected in late 2010. In these emulation, we intentionally delay the data transmission of the expensive satellite link for a certain amount of time. If a cellular data transfer



(a) Percentage of Link Usage

(b) Operational Cost Reduction

Figure 39: Tradeoff of Latency and Operational Cost

opportunity occurs during these delays, the cellular link is used instead of the satellite link. As the allowance of delay increases, the cost of data transmission reduces significantly as more data is transferred using inexpensive cellular service. As a matter of fact, if the application allows a latency of 5 days, which is feasible for operations such as general equipment record archiving, the USD 2500 operational cost is completely eliminated.

6.2 Wireless Link Characterization at Oil Field Locations

With positive results from the pilot unit, we deploy more units in 2011. Due to the high cost of using BGAN link in pilot unit, we only upload bulk data on cellular links in 2011. Besides the usage of uploading job data, our application check the connectivity over each data link every 30 seconds. Measurement results are recorded with time stamp in local database on the laptop. We developed scripts to retrieve essential information from database records as log files and upload them to a ftp server from time to time.

In this section, we present measurement results from four crews stationed at Shreveport, Louisiana. They are named as SLA1 to 4 in our discussion. Measurement study was also conducted at one crew stationed at Williston, North Dakota which is named as WIL1. Normally, each crew operates within an area of thousands of square kilometer around the city where it is stationed. Between January 26, 2011 to March 20, 2011, AT&T link was used instead of Verizon service at SLA1 and measurements during this time is collected in an independent data set named “SLA1 ATT”. At the end of March, all units started using Verizon data service. We present analysis of link availability, TCP throughput and end-to-end latency from measurement results collected at those five crews. To our knowledge, this is the first side-by-side comparison between cellular data link and satellite links at remote areas with more than 300 days’ measurement. Our studies target an answer to the question of whether we can cost-effectively improve the connectivity from remote oil field locations to the Internet, in other words, transform currently challenged network connecting field crews and the data center.

6.2.1 Availability

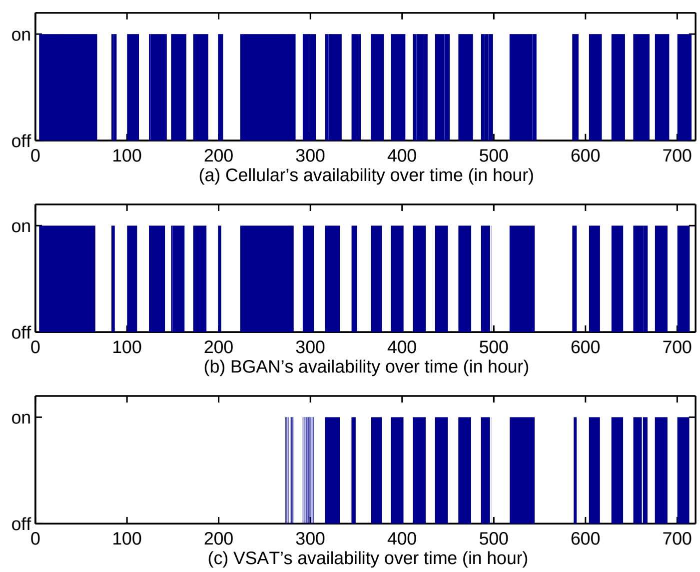


Figure 40: Availability comparison at SLA2 in April 2011

Data link availability via cellular, BGAN and VSAT over time for each crew is the first metric of interest in our measurement study. We find out this metric is affected by the work shift pattern of each crew. Figure 40 shows the link up and down sequences of SLA2 crew in April 2011. This crew is a day crew which stops operation and shuts down all equipment at night. SLA2 and SLA3 belong to this category and thus their link availability is always interrupted by such operation halts. SLA1 and SLA4 are 24-hour crews which operate continuously at field locations. All crews normally move to next field location after working 5 to 10 days at one place. The job location transition may take 1 to 3 days during which all equipment is powered off.

We retrieved Windows OS's native logs containing PC power on/off events from different crews. With this type of information, we reprocessed availability logs of cellular and satellite interfaces so that the probability that a link is available is only calculated when the equipment is powered on. Therefore, we eliminated the effect of job transition/equipment down schedule on availability evaluation of those data links.

Difference on costs associated with usage of satellite data links (USD 5/MByte) and cellular one (USD 100 per month with 2 GByte cap) indicates a potential cost reduction if a cellular link instead of a satellite link is used when data communication happens. Therefore, we not only calculate $P(X)$, probability that link X is available, but also the $P(X|Y)$, conditional probability that link X is available given link Y is available. Higher value of $P(X|Y)$ represents more opportunities of using link X instead of Y.

	$P(C)$	P(B)	P(V)	$P(C\|B)$	$P(C\|V)$
SLA1	98.50%	71.29%	66.42%	98.99%	98.99%
SLA2	97.03%	83.95%	52.86%	99.52%	99.48%
SLA3	93.76%	88.15%	56.99%	98.12%	97.78%
SLA4	89.73%	88.90%	44.79%	91.89%	99.28%
C: Cellular; B: BGAN; V: VSAT					

(a) Measurement results in April

	$P(C)$	P(B)	P(V)	$P(C\|B)$	$P(C\|V)$
SLA1	96.86%	26.96%	87.10%	99.67%	98.31%
SLA2	96.07%	80.40%	75.19%	99.05%	99.07%
SLA3	97.28%	91.21%	63.86%	99.27%	99.02%
SLA4	76.11%	75.68%	50.89%	98.03%	97.79%

(b) Measurement results in May

Table 6: Normalized link availability comparison

Table 6 shows the availability analysis of SLA1 to 4 in April and May 2011. Note that cellular data link has high availability comparable to the BGAN data link at those measurement locations. The drop on BGAN's availability at SLA1 in May is caused by a device mis-configuration which was corrected after a few weeks. Note that the existing data link solution using VSAT is not as reliable as the other two links as we discussed earlier in section 6.1.4.

High conditional probabilities in Table 6 indicate that a cellular link is always available when satellite links are at locations around Shreveport, an geographical region with good cellular service coverage. The same conclusion might not hold at other regions.

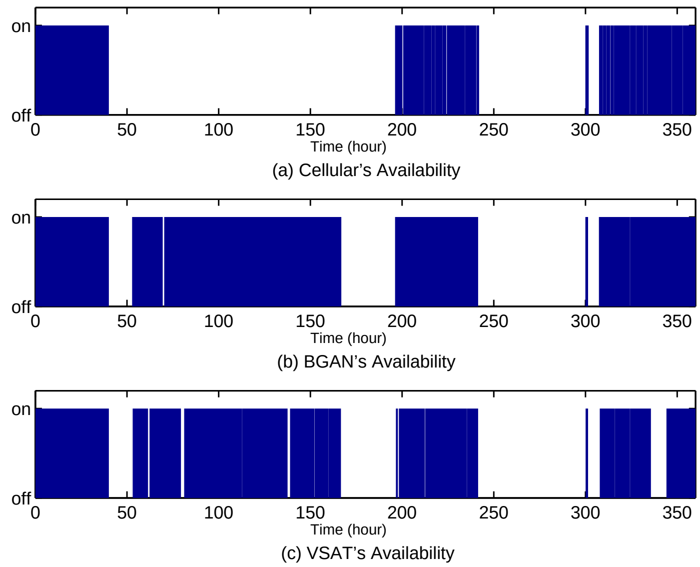


Figure 41: Availability comparison at SLA4 in Aug. 2011

SLA4 crew traveled to southern Texas and operated there for two weeks from Aug. 10 to Aug. 25, 2011. Side-by-side link availability comparison in Figure 41 shows that cellular link was down for a 5 day time period when satellite links were available. Therefore, $P(C|B)$ and $P(C|V)$ are 54.31% and 53.33% in those two weeks. In the meanwhile, P(B) and P(V) are 90.24% and 84.84%.

Measurement results in Table 6 and Figure 41 indicate that no ideal data communication solution can be provided by a single type of data links in our evaluation. A multi-interface system with data link management policy should be developed based on financial consideration and link availability.

Both Figure 40 and 41 show regular availability interruptions on those data links. These interruptions may last for hours or even days. There are two reasons for such long interruptions: 1) The crew is working at a field location with no coverage for a few days; 2) The job location transition takes a few days to finish.

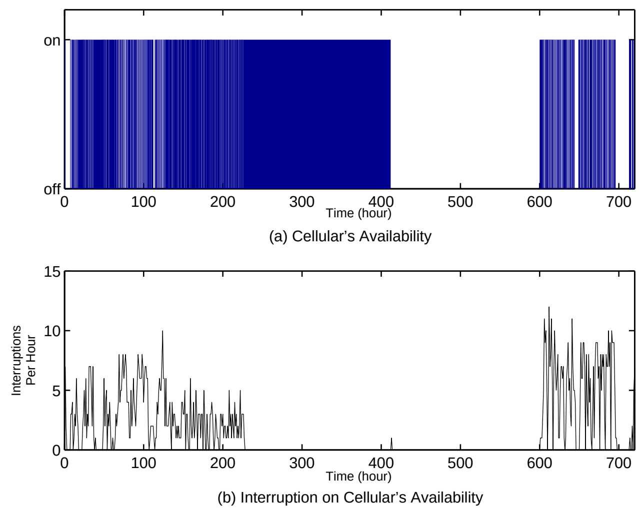


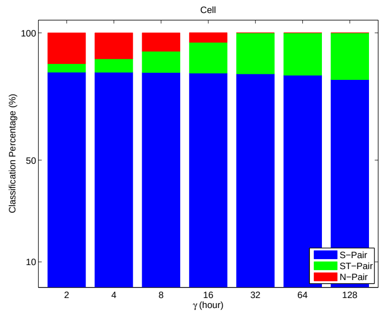
Figure 42: Interruptions on cellular link availability at WIL1

In the meanwhile, interruptions on those wireless links caused by weak signal can be very frequent. We present cellular link's availability from data collected at WIL1 during August in Figure 42. In this month, over 1100 interruptions occurred with a peak rate of more than 10 times per hour.

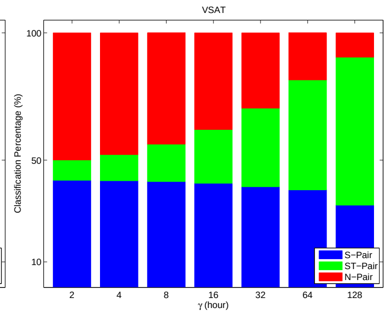
Overall, data access from field location to the Internet is a delay-tolerant network scenario [39]. Applications running over these data links at field locations should include disruption/delay-tolerance features to handle intermittent link availability as mentioned in [12].

6.2.2 Classification of Different Links

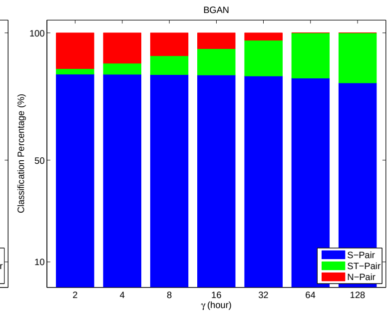
We can also compare these links using the connectivity based classification framework. In our deployment scenario, there is only one node pair as such data link is used to connect the field crew with the data center. Therefore, we show the node pair classification results over the contact traces collected in April, 2011 and August, 2011 respectively in Figure 43. Note that even satellite links are not able to provide space paths all the time from remote area to our data center. Therefore, real-time application is not expected to be feasible all the time. However, for certain applications allow latency for a few hours or even days, inexpensive cellular service is enough to provide the data link between the field crew and the data center. And a BGAN link would be a good supplementary to cellular link when



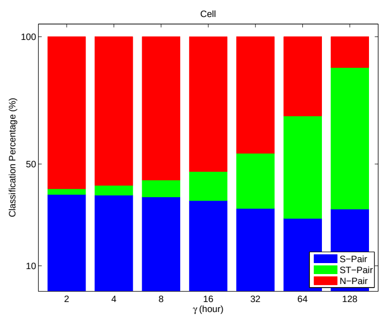
(a) Cellular Link, April



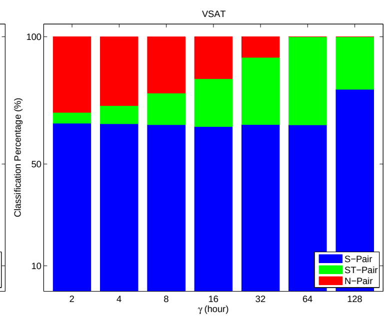
(b) VSAT Link, April



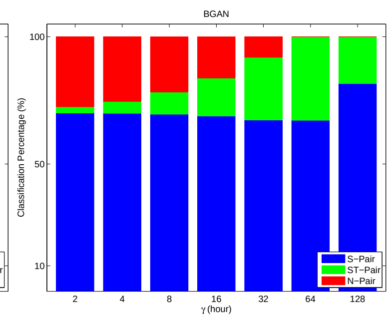
(c) BGAN Link, April



(d) Cellular Link, August



(e) VSAT Link, August



(f) BGAN Link, August

Figure 43: Node Pair Classification Results

the the coverage of the latter is questionable, e.g., in the August's operation.

6.2.3 Throughput Profiling

By uploading thousands of bulk data files from our units, we obtained substantial number of samplings of average TCP throughput over cellular data link. There were 200 to 1000 FTP uploads via Verizon's cellular links in each SLA crew during April 2011. Another 2000 FTP uploads were finished in data set SLA1 ATT. In addition, a BGAN link was used for more than 600 FTP uploads from SLA1 crew from October 2010 to November 2010. No FTP upload was conducted on VSAT link in our measurement study since this link is strictly managed and only business applications with recorded and approved bandwidth consumption profile may access it.

Figure 44 illustrates Cumulative density functions (CDFs) of average TCP throughput in those data sets. We notice the significant variation on average TCP throughput over cellular links. This is caused by fluctuation of signal quality as field locations are normally far from cellular towers or by contentions of spectrum usage, which will be discussed

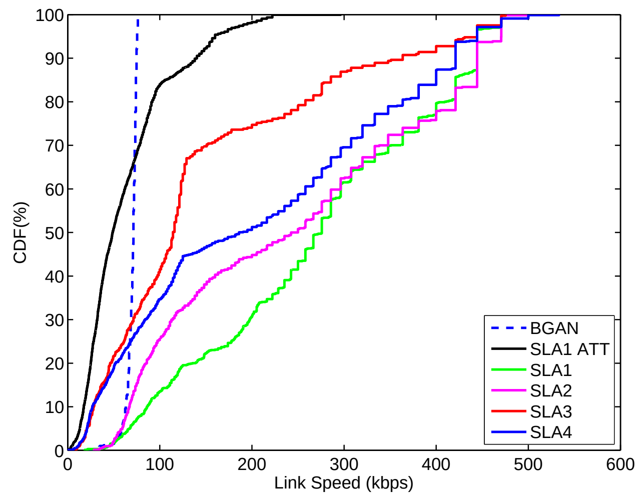


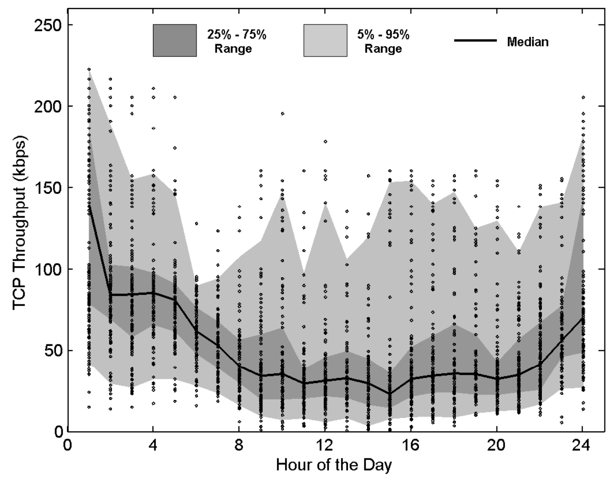
Figure 44: CDF of average TCP throughput

later in this section. Verizon's cellular service provides higher maximum achievable uplink speed (500kbps) than AT&T's (250kbps) but is associated with bigger variations. The average TCP throughput is stable over the BGAN link as it is tightly managed and has less background traffic fluctuation due to limited accesses.

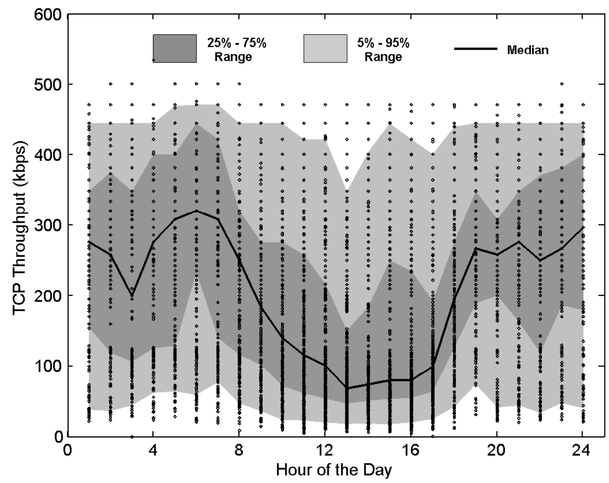
Temporal correlation/predication of TCP throughput over wireless links in small time scales of tens of seconds are investigated in previous work [35, 105]. We are interested in average TCP throughput over cellular links and we conduct our study in a much larger time scale.

We show the average TCP throughput of each upload from the SLA1 ATT data set according to the hour when it starts in Figure 45a. Each dot represents one average TCP throughput measured at a certain hour. We also draw the range bounded by 5 percentile and 95 percentile of all values at each hour. Although 5% to 95% ranges are similar across different hours as link quality fluctuates all the time, the 25% to 75% range is narrow which indicates that a significant portion of TCP throughput measurements at each hour are around the median value.

Average TCP throughput is generally low during busy hours of the day and high otherwise. We believe this is related to contention of spectrum usage towards the cellular tower from other cellular devices at the same field location or the diurnal congestion on cellular



(a) SLA1 ATT data set



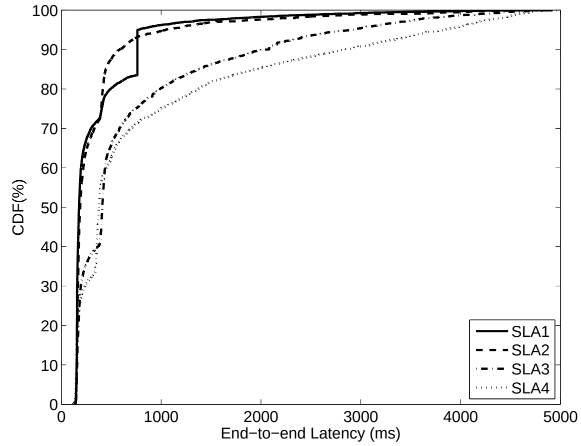
(b) SLA1-4 Verizon data set

Figure 45: TCP throughput at each hour of the day

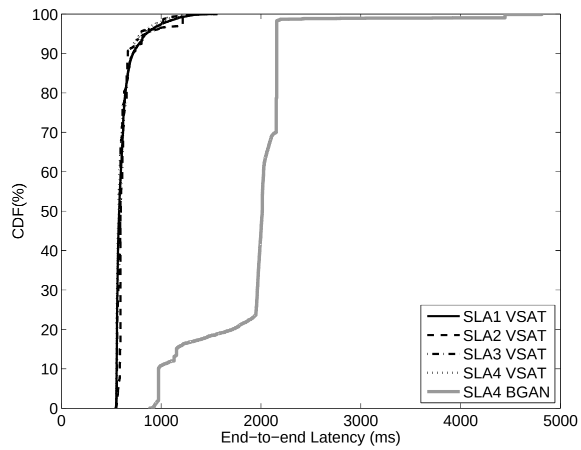
service providers' backbone. As median values change significantly from hour to hour, collecting statistics for each hour of the day would help TCP throughput predication in the same hour of the day. Similar hourly-shifted pattern can be found in Figure 45b, which illustrates results from the data set consists of over 6000 TCP throughput measurements over Verizon's service from SLA1 to 4 in April and May, 2011.

6.2.4 End-to-end Latency

End-to-end latency is the link metric which essentially affects TCP stack's performance and determines service quality experienced by many applications. To collect measurement of this metric, ping packets are sent over SLA1-4's cellular link and VSAT link periodically with an interval of 5 minutes and 15 minutes respectively. Ping packets are also sent over SLA4's BGAN link with an interval of 15 minutes.



(a) Measurements over Cellular Links



(b) Measurements over Satellite Links

Figure 46: End-to-end Latency via Ping

Figure 46 shows those measurements in August 2011. Note that VSAT link's end-to-end latency is stable around 500 ms. In the meanwhile, the latency on BGAN link is significantly longer with a lower bound of 1000 ms and 80% measurement results are around 2000 ms. Compared with satellite links, cellular links have a better lower bound around 200 ms. However, measurements of latency on cellular links are heavy-tailed which means long end-to-end latency may occur from time to time.

Although BGAN and cellular links may have higher availability than the VSAT link according to previous discussions, they might not be used by applications having a tight latency requirement. On the one hand, this indicates multiple network interfaces should be jointly used to provide effective data communication at remote areas; on the other hand, significant differences on end-to-end latency characteristics could make the link management a challenging task as one more criteria should be evaluated besides the cost and availability mentioned in previous discussion. Furthermore, an application's data communication may switch between different interfaces when availability interruptions occur.

CHAPTER VII

CONCLUSION

7.1 Research Summary

This thesis focuses on characterizing and mitigating challenges in wireless and mobile networks, including frameworks to quantify challenges associated with connectivity and energy provisioning, studies of routing protocol integration, experiences in identifying and solving challenges in building a real wireless and mobile network system. The major contribution of this thesis work can be summarized as follows:

- **Network Classification Frameworks.** This thesis work will present a WAM continuum framework in contrast to previous approach of providing solution to distinct network categories. A wireless and mobile network is characterized by its position in this continuum. Certain network equivalence classes can be defined over subsets of this WAM continuum and this classification can be used to determine network design and operation.
  - **Connectivity based Classification Framework.** We show one instantiation of the WAM continuum framework on network connectivity classification and apply it to traces from both real deployments and mobility models.
  - **Energy Sufficiency based Classification Framework.** This thesis work will first define the issue of energy sufficiency in WAM network and then develop a classification framework based on how energy provisioning and power management scheme affects network characteristics related to routing and traffic handling.
  - **Collaboration Advantage based Classification Framework.** This thesis work will extend the connectivity based classification framework to evaluate

the interaction between mobile computation implementation and underlying network's connectivity characteristics.

The results of this work can be used to characterize various challenges in wireless and mobile network and provide guidance on how to mitigate such challenges effectively.

- **Development of a WAM System Working in a Challenged Environment.** We will report the process of data communication provisioning at oil field operations. We introduce new access links to mitigate challenges associated with existing system after a comprehensive measurement study.

- **Integration of Routing Protocols.** We will describe the integration of MANET routing protocol with message ferrying in scenarios where heterogeneous connectivity exists. Interactions between protocols from different routing paradigms are reported.

7.2 Future Directions

In this thesis work, we study issues related to characterizing and mitigating challenges in wireless and mobile networks. Following is the list of potential research directions.

Clustering in Network Classification. Current network classification results are the generalization of results from each node pair or node in the network. As the network of interest scales up, the required amount of computation increases quickly. On the other hand, clustering is a natural phenomenon in wireless and mobile network instances. Therefore, if we are able to identify such clustering in the classification process, the whole classification result might consist of two parts: characterization among nodes in the same "cluster" and the inter-cluster characterization. This would improve the scalability of the classification framework and provide guidance on operations at different areas of the WAM network.

Joint Control Framework in WAM Networks. As illustrated by our classification framework, the connectivity characteristic of a WAM network is determined by contacts among node pairs, which affects the way data is delivered in the network. Controllable mobility is able to introduce extra contacts and thus improve network classifications. On the other hand, the effective utilization of those contacts is limited by energy availability and the power management scheme in WAM networks. Data delivery in WAM networks is a procedure to use available contacts with different routing protocols. It is worth evaluating feasibility of a control framework in WAM networks which adjusts nodes' behavior considering the joint effect of routing protocol, power management and controllable movement.

Cost Management in WAM Networks. In many WAM network deployments, the usage of data link is associated with financial cost. Without a management scheme, such usage can cost a lot as shown by examples in our study. Unlike power management schemes which are based on a simple yet reasonable assumption: there is no energy consumption when a node's radio interface is shut down, there are various charging models on data link usages. In our study, there are usage based model, e.g., BGAN link, and time based model, e.g., monthly charges of cellular link and VSAT link. Finding an cost-effective way to manage usages over such links would be as challenging and exciting as research work on power management schemes in WAM networks.

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