PROTOCOL DESIGN IN WIRELESS NETWORKS: FEATURING CHANNEL ACCESS AND VEHICULAR COMMUNICATIONS

by

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ABSTRACT

Wireless Networks provide a very cost efficient solution for data connectivity over wide areas enabling ubiquitous computing environment through multi-hop relay. The scope of this dissertation encompasses two correlated domains of Wireless Network area, one is the Multi-Radio Multi-Channel Wireless Mesh Network (MRMC-WMN) and the other is Vehicular Ad hoc Network (VANET). The research issues studied here are related to IEEE 802.11 based, multi-hop ad hoc wireless network.

In the first part, we deal with some of the fundamental issues of Wireless Networks, with particular emphasis given on approaches and techniques for channel assignment and delay analysis in multi-radio multi-channel wireless mesh network. A novel channel assignment scheme has been proposed utilizing Partially Overlapped Channel (POC). We also introduced the notion of I-Matrix as a new interference model which takes into account one additional type of channel interference ignored by most researchers. Specifically, our interference model considers the effect of Self-Interference for multi-radio environment in addition to Adjacent Channel Interference(ACI) and Co-Channel Interference. We evaluate the performance of our POC based channel assignment algorithm in terms of capacity by comparing with the one using only orthogonal channels. Our results show capacity improvement as the increased link assignments at an average of more than 15 percent.

The second part presents a spatio-temporal analysis of multi-hop V2V connectivity and network partitioning along with the statistical behavior of urban taxi mobility pattern. We developed two new approaches in analyzing the connectivity. One is the bitwise matrix manipulation for determining multi-hop connectivity and transitive closure. The other is the detection of saturated connectivity based on the k-hop reachability. The proposed algorithm

of generating multi-hop reachability and network partition, though not optimal in performance, is better than traditional BFS approach in terms of space and time complexity. We then apply our algorithm for spatio-temporal analysis of urban taxi mobility pattern. Using the presented empirical analyses, wireless researchers can estimate the capabilities and constraints of vehicular communication from connectivity and mobility patterns as well as government can plan and work on issues related to implementing proper DSRC infrastructure for optimal data connectivity in urban area.

We also propose an innovative application of V2X communication for Intelligent Transportation System (ITS). The application relates to DSRC based taxi hailing system in urban metropolitan area. The proposed system can work in both presence and absence of ITS infrastructure. Our evaluation results show that the system can not only reduce the passenger's waiting time and driver's empty cruise time, but also increase the overall taxi availability using multi-hop communication.

DEDICATION

This dissertation is dedicated to my beloved wife, *Farhana Afroz*. I can never quantify the inspiration and co-operation that I received from her every single moment during my study at the University of Alabama.

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Chapter 1

INTRODUCTION

All wireless networks are subject to capacity limitations due to many issues related to the characteristics of physical media. For example, due to the broadcasting nature of the transmission in physical media, the wireless networks impose additional challanges like channel interference problems which are absent in wired networks. This problem is even more severe in case of multi-hop and multi-radio environment where the interference effect can cause a significant throughput loss in the network. Hence, a common goal for any wireless design is to focus on increasing capacity by applying innovative channel assignment schemes that can minimize the interference while maximizing the overall network throughput. Also, carefully allocating partially overlapped channels with proper interference model can further improve the channel utilization to maximum level. Therefore, one of the objectives of this research is to design an efficient channel assignment scheme that utilizes partially overlapped channels together with an appropriate interference model that can increase the number of simultaneous transmissions in a multi-radio multi-channel wireless mesh network. We introduce the notion of I-Matrix as a new interference model which considers the effect of Self-Interference for multi-radio environment in addition to Adjacent Channel Interference(ACI) and Co-Channel Interference. We evaluate the performance of our POC based channel assignment algorithm in terms of capacity by comparing with the one using only orthogonal channels. Our results show capacity improvement as the increased link assignments at an average of more than 15 percent. We also propose a timing model to characterize the delay components associated with multi-hop relay in ad hoc network.

On the other hand, Vehicular ad hoc network (VANET) is a special form of wireless mesh network which poses some extra challanges on network protocol design due to its unpredictable mobility direction and high speed. In this dissertation, we propose a novel algorithm to determine the multi-hop reachability and saturated connectivity of a vehicular network. We analyze some of the key features of vehicular network using real world GPS traces from taxi cabs. The work presents a spatio-temporal analysis of taxi mobility pattern with the instantaneous velocity profile, distribution of hotspots, multi-hop connectivity, network partitioning and other characteristics like trip duration and empty cruise interval. The empirical data analyses presented here can be a helpful resource for wireless researchers, government organizations, taxi companies and even for the drivers or passengers. While wireless researchers can estimate the capabilities and constraints of vehicular communication from connectivity and mobility patterns, government can plan and work on issues related to implementing proper DSRC infrastructure. Finally, taxi companies and drivers can benefit from maximizing the trip revenue and minimize empty cruise time though balanced loaddistribution and awareness of the hotspots.

We also propose a novel taxi hailing application using DSRC technology. Based on the primary results obtained from real world GPS traces, it can be predicted that, our proposed system can significantly increase the availability of taxi cabs while reducing the wait time for the passenger. At the same time, from the perspective of a taxi driver, it can reduce the cruising time and increase daily trip count and eventually help increase the revenue of the taxi company. This system can make a revolutionary change in the day today urban life, particularly for the crowded metropolitan cities around the world where people spend several exhaustive hours in transportation to and from work places. Our system can reduce the transportation overhead for city people and help them spare more time and efforts in productivity.

The following sections gives an overview of some of the focused areas that are within the scope of this research.

1.1 Channel Assignment Algorithms

One of the major issues concerned with WMN architecture supporting multiple radios and multiple channels (MRMC) is the channel assignment (CA) problem. Particularly for multi-hop networks, it is very complex to design an optimized CA algorithm that makes efficient utilization of available channels and at the same time minimizes the overall network interferences. In general, channel assignment algorithms should facilitate multi-path routing among wireless routers apart from minimizing interference on any given channel or from adjacent channels. Existing channel assignment algorithms designed for multi-radio multi-channel wireless mesh networks (MRMC-WMN) mainly deal with orthogonal or non-overlapped channels. But in reality, the limited availability of orthogonal channel is a major issue where the network is very dense in terms of inter-nodal distances. On the other hand, partially overlapped channels (POC) are currently considered as a great potential for increasing the number of simultaneous transmissions and eventually upgrading the network capacity; especially in case of MRMC-WMN. In chapter two, we address the limited orthogonal channel problem by exploring the usable POCs. The key technique lies in the fact that the interference between adjacent channels has to be considered intelligently in order to increase the overall capacity.

1.2 Delay Analysis

Multi-hop Wireless Mesh Networks (WMNs) are also considered as means for achieving lastmile internet connectivity on the go. Links in such networks are created in a self-organizing manner by participating nodes which relay data packets for other nodes. These types of self-organizing networks introduce several research challenges, among which the problem of determining an optimal route based on end to end delay estimation is prominent. It is of immense importance to measure the performance parameters of Ad Hoc networks, especially the end to end delay which optimizes the overall network performance. Minimizing delay is also one of the vital conditions to ensure Quality of Service (QoS) requirements in these dynamic networks, which necessitates proper estimations and realistic measurement techniques apart from network simulations. Unfortunately, the practical measurement of these wireless ad hoc networks has not received so much attention whereas a large number of studies have been devoted to system stability and throughput maximization. In this experiement, we focus on a practical implementation of intra-node as well as inter-node delay estimation in multi-hop mesh networks using a packet sniffer tool named Wireshark. We also show how the delay estimation varies on network load and connectivity. Finally we provided the performance comparison between single radio and multiple radio environments keeping the other network parameters constant. In a nutshell, our prime achievements on this area are as follows: (i) We successfully conducted the multihop ad hoc communication in windows platform with both single and multiple radios. (ii) We analyzed the total end to end delay as a linear summation of several delay components (intra-node delay, response time and air propagation delay). Also comparison between different experimental setups were illustrated with the use of these components. (iii) All the delay components were measured without time synchronization between the nodes

1.3 Vehicular Mobility and Connectivity analyses

Several interesting works related to taxi mobility patterns has been addressed by the researchers. Most of these works are based on analyzing GPS traces from different taxi cab companies to explore hidden characteristics of urban mobility models. Some of these researchers tend to reveal new mobility models while others focus on clustering and hot spot identification. Piorkowski textitet. al. [99] utilized the Cabspotting data archived over a month to propose a parsimonious mobility model called Heterogeneous Random Walk (HRW) which captures some of the important mobility characteristics observed from the macroscopic level. A key feature of the model is that nodes follow independent and statistically equivalent mobility patterns, despite the presence of long-term clusters. They also evaluate the predictive power of the HRW model in the context of epidemic dissemination, which is one of the most prominent paradigms for routing in DTNs. Their work motivates the vehicular networking community to deeply investigate the taxi mobility traces for further research.

Shin et al [98] used real-life location tracking data collected from the Taxi Telematics system developed in Jeju, Korea. Their analysis aimed at obtaining meaningful moving patterns of taxi cabs .They have extracted some interesting statistical factors such as taxi's driving type, driving time, driving area, pickup rate etc. Lee et. al [97] analyzed a pick-up pattern of taxi service in the same geographical area aiming at clustering the pickup and drop off locations to develop a location recommendation service for empty taxis. The same author in another paper [99] analyzed both spatial and temporal statistics of taxi's waiting spots from the movement history. These works provide an insight to the possible dimensions of utilizing location tracking data for the purpose of taxi industry.

In chapter 3, we present a spatio-temporal analysis of multi-hop V2V connectivity and network partitioning along with the interesting features of urban taxi mobility. We analyze multi-hop vehicular connectivity and network partitions in a different apporach that is achieved through bitwise operation on boolean matrix representing transitive closure. This novel algorithm of generating multi-hop reachability and network partition, though not optimal in performance, is practically better than traditional BFS approach in terms of space-time complexity. Apart from the algorithm development, our major contribution in this area includes:

- Instantaneous velocity profile
- Spatio-temporal distribution of cabs
- Frequency distribution of pickup and drop off
- Identification of hotspots
- Trip duration and empty cruise interval
- Multi-hop V2V connectivity
- Network partitions

1.4 DSRC based Taxi Hailing System

Street hailing was the only option for reserving a taxi until the early eighties of the last century before the introduction of radio paging system in the taxi industry. With the advancement of wireless communication technology, the taxi reservation system has evolved to provide exibility and ease of booking to the customers as well as optimizing the dispatching procedure with the aid of automated systems. In chapter 4, we summarize the existing computer aided taxi booking and dispatching systems that are currently implemented in the industry as well as proposed in literature. Our goal is to point to new opportunities emerging from recent advances in wireless technologies. With this objective, we introduce an innovative taxi hailing system using DSRC technology. We describe our Hailing-Response protocol that can work in either V2V or V2I mode of vehicular communication and also compatible with the state-of-the-art ITS infrastructure deployed by the US Department of Transportation.

Chapter 2

CHANNEL ASSIGNMENTS IN MRMC-WMN

2.1 Characteristics of Efficient Channel Assignment Algorithm

In the literature, solving channel assignment problems have been targeted to meet various design objectives. One of the key objectives that need to be considered while designing a channel assignment scheme is to *minimize the network interference*. This interference minimization goal can either be implemented globally (in case of centralized schemes) or locally (in case of distributed schemes). It has been proved in the literature that the channel interference effects can cause a significant throughput loss in the network, especially if the design includes partially overlapped channels. Hence, most of the channel assignment algorithms should focus on this issue with severe importance. Throughput is often regarded as the primary criterion to evaluate the efficiency of a new scheme. In fact, throughput is maximized by increasing the number of parallel transmission in a network. So, channel assignment algorithms should equally focus on throughput maximizing. The IEEE 802.11 standard specifies multiple non-overlapping channels for use (3 in 802.11b/g, 12 in 802.11a). So the channel assignment scheme should aim into exploiting channel diversity to *maximize spectrum utilization*. Also, carefully allocating partially overlapped channels with proper interference model can further improve the channel utilization to maximum level. Therefore, researchers of wireless mesh networks are emphasizing on increasing channel diversity while designing channel allocation schemes. Adaptation to changing traffic conditions is another important criterion for a well designed channel assignment scheme. An efficient channel assignment algorithm should not only maximize channel utilization but also *distribute the load equally* among different channels. Inefficient channel assignment may lead to network partitions which ultimately deforms the original topology. So, *preserving the topology* by avoiding network partition is also an important goal for channel assignment algorithms.

Table 2.1: Classification of Channel Assignment Algorithms

Classification Criteria	Types of Channel Assignment
Channel Switching Frequency	a) Static/Fixed: b) Dynamic c) Hybrid
Number of Radios	a) Single Radio b) Multiple Radio
Spectrum Utilization	a) Orthogonal Channels (OCs) b) Partially Overlapped Channels (POCs)
Topology Awareness	a) Centralized b) Distributed
Routing Dependency	a) Routing independent b) Routing dependent c) Joint Approach
Infrastructure	a) Access Point based b) Ad hoc based c) Hybrid approach
Granularity of Assignment	a) Per Packet Channel Assignment b) Per link Channel Assignment c) Per Flow Channel Assignment d) Per Component Channel Assignment

2.2 Classification Of Channel Assignment Schemes

The channel assignment schemes can be classified based on different criteria and perspectives. Table 2.1 summarizes the classification followed by the description of each category thereafter. It is noteworthy that, these categories are not necessarily disjoint from each other. A particular type of scheme based on one criterion may fully or partially overlap with another type in different criteria.

2.2.1 Based on Channel Switching Frequency

Skalli et. al. [40] proposed a taxonomical classification of various channel assignment schemes based on the criteria of channel switching frequency where the channel assignment schemes are divided into three main categories: fixed, dynamic and hybrid.

Fixed/Static Channel Assignment

Fixed or Static assignment schemes assign each radio to a channel for a relatively long period of time. The purpose of fixed channel assignment is to control the connectivity of the nodes. Das et. al [53] described some of the key issues related to static channel assignment algorithms. Fixed channel assignment scheme has been further subcategorized into two types: Common Channel Assignment (CCA) is the simplest among all the schemes where the network interfaces of each node are assigned to a common set of channels. The primary advantage of this approach is that the network topology essentially remains identical to that using a single channel assignment scheme, while increasing the network throughput by the use of multiple channels. However, in case where the number of orthogonal channels is greater than the number of radios in each node, the throughput gain may be limited and may lead to inefficient channel utilization. In case of Varying Channel Assignment (VCA), radios of different nodes are assigned to different sets of channels. However, assigning disjoint set of channels to the NICs may lead to network isolation and modified topology. An example of this type of algorithms is Connected Low Interference Channel Assignment (CLICA) [41].

Dynamic Channel Assignment

In Dynamic assignment schemes, any radio can be assigned to any channel where the radios can frequently switch from one channel to another. The advantage of dynamic assignment is that it utilizes multiple channels with few interfaces. However, these approaches have the disadvantage of strict time synchronization requirement between the nodes. Other key challenges constitute of channel switching delays and the need for signalling and coordination mechanisms for channel switching between a pair of nodes. These constraints impose practical challenges for implementation in real networks.

Hybrid Channel Assignment

Hybrid channel assignment strategies combine both fixed and dynamic assignment strategies. Here, some radios are assigned to a static channel whereas others can be dynamically switched between several channels.

2.2.2 Based on Number of Radios

When all the nodes in a WMN are equipped with single radio, these channel assignment schemes are applicable. Advantages of this type are: (i) no complicacy of self-interference, (ii) channel selection algorithm is quite simple as only one channel has to be selected and finally (iii) easy to implement. However, it also has drawbacks like: (i) less channel utilization (ii) no simultaneous transmission possible from a single node (iii) frequent channel switching Currently the channel assignment algorithms are targeted for mesh networks with multi-radio environment. As multiple channels are utilized at a time, channel utilization is much higher. Advantages of multi-radio scheme include (i) less channel switching and (ii) parallel transmissions. However, the channel selection algorithm is complex and interference handling is also more difficult.

2.2.3 Based on Spectrum Utilization

Currently almost all channel assignment algorithms are designed with non-overlapping channels or Orthogonal channels. This does not utilize all the available channel resources allocated for the specific IEEE 802 technology. For example, in case of IEEE 802.11 b/g/n, there are only 3 non-overlapping channels out of 11 channels (in USA). During the network overload period, there are not sufficient spectrum resources available when using only orthogonal channels. This initiates the necessity of designing efficient schemes that can utilize all the available channels in the spectrum. Recently, a substantial amount of research is going on with designing channel assignment algorithms with Partially Overlapped Channels (POC). Some of the researchers already came up with efficient algorithms that could handle the interfering channels. But still questions exist about the feasibility of implementing those schemes into current industry standard. We shall discuss the issues concerning the POCs later.

2.2.4 Based on Topology Awareness

Centralized channel assignment algorithms have the global knowledge about the topology, either through global positioning system or though routing table information. They are mostly useful in case of infrastructure based wireless networks like AP based networks. Centralized algorithms are easy to implement, less overhead required for routing and node connectivity is determined by access points (APs). In other case, centralized channel assignment is also applicable without APs when all the nodes have the global topology information. In most cases, centralized algorithms are either static or quasi-static. Distributed channel assignments are the ideal requirement for Ad hoc networks. The distributed approach is more feasible in realistic environments where the global information for centralized algorithm is not available. Our previous work [55] summarized a classification of MRMC channel assignment and routing algorithms on the basis of centralized and distributed categories.

2.2.5 Based on Routing Dependency

Most of the channel assignment schemes are independent of routing protocol. These schemes work with any type of routing protocol, irrespective of proactive or reactive routing categories. Some channel assignment schemes depend on the type of routing protocol. These algorithms only work with the associated routing protocols. A recent trend is to design joint routing and channel assignment schemes that optimize the route by selecting the channels along the end to end path. In such cases, channel information is also appended in the routing table and broadcasted periodically. In these cross layer designs, efficient routing metric has to be selected incorporating the channel interference characteristics. An example of such joint approach is the KN-CA algorithm, by Xiaoguang Li et. Al. [24], which is an enhancement of AODV protocol.

2.2.6 Based on Infrastructure

Channel assignment schemes that are particularly dependant on infrastructure or based on access point are mostly centralized. In that case the access point has the information of all the nodes and their adjacent channels. In such case, the access point allocates the channel in a manner that minimizes the overall interference and maximizes the throughput and capacity. On the other hand, ad hoc mesh networks lacks the information of global topology. Hence it is difficult to implement a centralized scheme with the limited local information. Such centralized design basically imposes static channel assignment. Again, using distributed approach, the algorithm is prone to inaccurate topological information which results into network partitioning. In hybrid mesh networks, nodes are connected in two ways, one is the direct single hop connectivity with access point, and another way is to route through other nodes to connect to a relatively less traffic loaded access point. This type of schemes is applied to areas where load density is high.

2.2.7 Based on Granularity

Per-packet channel assignment requires more run-time control overhead for scheduling each single packet with particular channel. Hence, algorithms in this type are less efficient for high loads. In [2], [6], Vaidya et. al., described such a CA scheme where the radios switch from one channel to another in a small time scale. In reality, this type of scheme is not feasible for implementation because of the high overhead. In link-based channel assignment scheme, channel is assigned to a link between a pair of nodes, and all packets transmitted between these two nodes use that particular channel for a certain period of time. Some of the algorithms of this type, focus on assigning channels by ensuring appropriate amount of bandwidth for each link according to the expected load. On the other hand, other schemes emphasize on minimizing link interference in the network. Several optimization models are also proposed in the literature for centralized channel assignment in static WMNs, focusing on either maximizing the number simultaneously active links [56] or minimizing the overall interferences among links. In flow-based channel assignment scheme, a single channel is assigned to consecutive links along path from source to destination which defines a flow. As for example, So et al. [19] described a channel assignment scheme that binds separate channels to each of the flows in a single radio multichannel network. Flow based scheme is extended by Sivakumar et. al. in [20] to component-based channel assignment. A component is formed by intersecting flows at a particular node and according to this approach an entire component is assigned a single channel.

2.3 Problems With Multi-Radio Channel Assignment

The IEEE 802.11b/g/n standards provide 3 and 12 non-overlapping channels that can be used in parallel within a mesh network. If multiple radios can be installed on the same node to facilitate the simultaneous use of some of the channels, one can expect increased working bandwidth. The market availability of cheap NIC hardware has made the multi-radio solutions more feasible. Several research works [12, 13, 14] have proved that equipping a node with only 2 radios may increase the network capacity as well as throughput by a factor of 6 or 7. However, beside these benefits, there are a lot of problems associated with multi-radio channel assignment. Throughout the following subsections, we address some of the critical problems related to MRMC design.

2.3.1 Interference Minimization

Although multi-radio wireless nodes can significantly uplift the performance of WMN, there is a critical trade-off to be made between maximizing connectivity and minimizing interference. The key factors to consider are the co-channel and adjacent channel interference due to the close proximity of the radios equipped on a single node, and those due to the transmissions from neighbouring nodes [35]. The co-channel interference prohibits a particular channel to be used more than once by two links within the interference range simultaneously. The adjacent channel interference determines the total number of usable channels within the neighbourhood (defined by the transmission range). In order to minimize the network interference, a suitable interference model has to be designed in accordance with the assignable channel super set. For example, an interference model which is capable of handling the self interference problem may not be suitable for POC based design.

2.3.2 Channel Switching Delay

One of the key challenges in multi-radio environment involve channel switching delay which is typically in the order of several milliseconds. This mandates tight coordination mechanisms for channel switching between nodes. Hence, the frequency of channel switching greatly impacts the efficiency and throughput of the network.

2.3.3 Interdependency with Routing Protocol

As a matter of fact, routing and channel assignment are interdependent. A routing protocol selects a path from the source to the destination, and forwards traffic to each link along the path, while channel assignment determines the individual channel that each link should use. In other words, CA determines the connectivity between two nodes as two radios can only communicate when they are tuned to a common channel. Hence channel assignment ultimately determines the network topology. Again, as we know, routing decisions are dependent on the network topology which implies that channel assignment has a direct impact on routing. Experiments have shown that, dynamically adjusting the channel according to the traffic status can achieve better result, which again proves that routing and channel assignment are tightly coupled.

2.3.4 Issues with Joint Channel Assignment and Routing

In order to maximize the performance gain in MRMC-WMN, joint implementation of routing and channel assignment is very important. Traditional wireless routing protocols [7, 8, 11] may not provide optimized performance without incorporating integration with CA. Wireless researchers focussing on cross layer protocol design mostly deal with integrating routing with CA. Some of these schemes are designed as centralised algorithm [14, 24, 27, 41] while others considered distributed mode [9, 37]. However, there are several challenges in effectively designing algorithms for joint CA and routing, especially in a distributed fashion. More complicacy arises when the network is a heterogeneous type of multi-radio wireless networks. Below we mention some of the critical issues while designing a joint CA and routing algorithm: For any routing protocol whether or not integrated with CA, a routing metric needs to be concretely defined as a quantitative measurement of the performance gain. In case of joint CA and routing, most of these metrics are defined as compound metric derived from other elementary routing metrics. One such algorithm of this type [37] defines a metric named Channel Cost Metric (CCM) that computes the expected transmission cost weighted by channel utilization. CCM quantifies the effect of channel interferences along with the benefit of channel diversity. Another major issue arises in networks with heterogeneous radios operating with different transmission power and frequency. It can be possible that

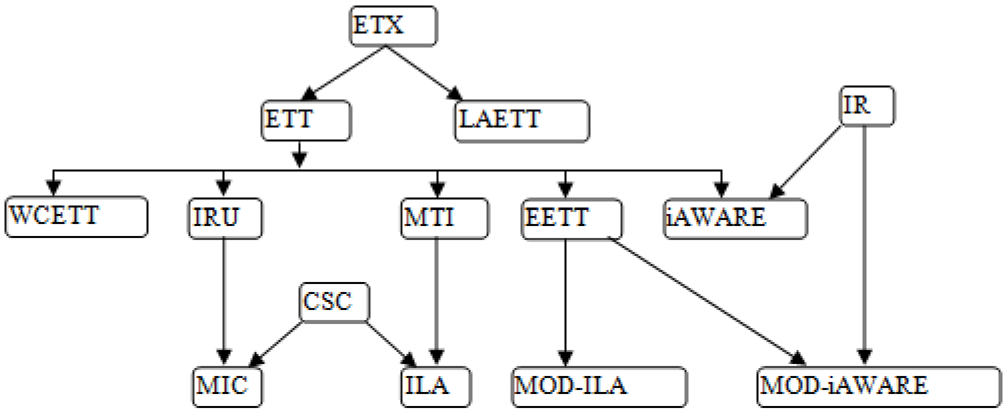

Figure 2.1: Hierarchical representation of routing metrics based on origin

there be no common radio or common channel supported in the whole network for both data transmission and signalling (e.g., routing message), leading to network partitioning. Bhandari and Vaidya [38, 42] revealed many issues particularly applicable for networks with heterogeneous radios. Further, reducing the protocol overhead for a distributed algorithm in such a heterogeneous wireless environment presents significant challenges for the joint implementation of CA and routing.

2.4 Choice of Routing Metric Integrated With CA

2.4.1 Evolution of Routing Metrics

In this section, we discuss the routing metrics that have been widely accepted for mesh networks in a hierarchical representation based on their derivation. Some of the well known routing metrics are: hop count, RTT, ETX [4], ETT [5], WCETT [5], EDR [10], CCM [37], MCR [15], MIC [18], ILA [48] and iAWARE [50]. Addagadda et. al. [47] summarized some of the notable features of these routing metrics and proposed modifications over ILA and

Characteristics	Hop	RTT	ETX [4]	ETT [5]	WCETT [5]	CCM [37]	MIC [18]	EETT [21]	LAETT [49]	ILA [48]	iAWARE [50]	Mod-iAWARE [47]
Multi-channel Support	X	X	X	X	Y	Y	Y	Y	Y	Y	Y	Y
Intra-Flow Interference	X	X	Y	X	Y	Y	Y	Y	X	Y	Y	Y
Inter-flow Interference	X	X	X	X	X	Y	Y	Y	X	Y	Y	Y
Load balancing	X	Y	X	X	X	Y	X	X	Y	X	X	Y
Link loss ratio	X	X	Y	Y	Y	Y	Y	Y	Y	X	Y	Y
Throughput	X	X	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Transmission Rate	X	X	X	Y	Y	Y	Y	Y	Y	Y	Y	Y
Link Capacity	X	X	X	Y	Y	Y	Y	Y	Y	Y	Y	Y
Multi-Radio Support	X	X	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Heterogenous Radio	X	X	X	X	X	Y	X	X	X	X	X	X
Agility	Y	Y	X	X	X	X	X	X	X	X	X	X
Isotonicity	Y	Y	Y	Y	X	X	Y	Y	Y	X	X	Y

Figure 2.2: Summary of characteristics of the routing metrics used in wireless networks

iAWARE. All these metrics are topology-dependent and most metrics were proposed as improvement over some other previous metrics. Figure 2.1 shows a hierarchical representation of the metrics based on their derivation.

We also tabulated some of the interesting characteristics of these metrics as shwon in the figure 2.2. These characteristics gave us a foundation to classify the metrics from two different perspectives, i.e. we categorized the routing metrics based on isotonicity and interference consideration.

2.4.2 Classification Based on Isotonicity

In order to calculate the minimum cost path, most routing protocols follow certain variations of efficient algorithms, like Bellman- Ford or Dijkstra's algorithms. Even if a metric guarantees that its minimum cost route has good performance, there is no assurance

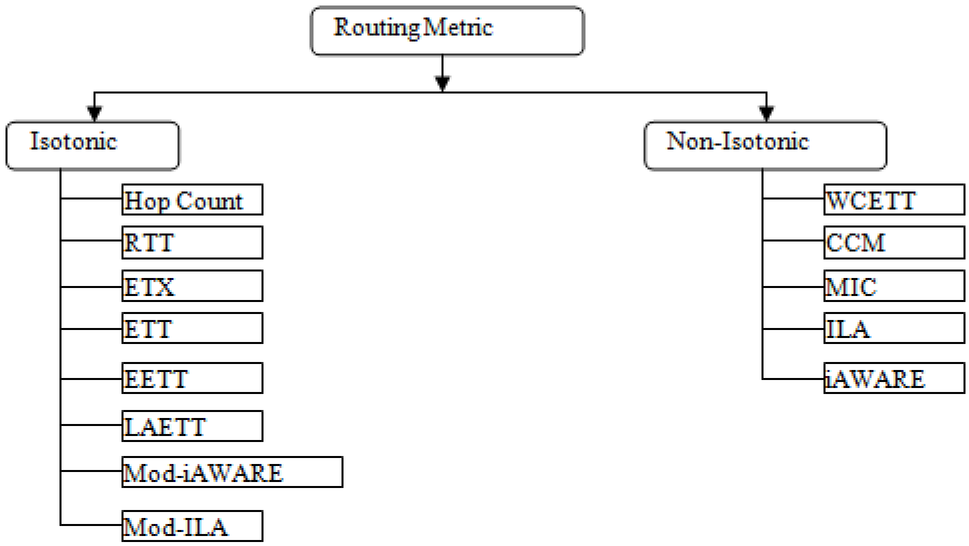

Figure 2.3: Classification of routing metrics based on Isotonicity

of having an efficient algorithm to compute the path cost based on the metric. The property that ensures the existence of such efficient algorithm is called isotonicity [45]. Based on this property, routing metrics can broadly be categorized into two classes, namely i) Isotonic and ii) Non-Isotonic. Figure 2.3 shows the classification of some of the common routing metrics on the basis of isotonicity.

2.4.3 Classification Based on Interference

While designing a routing metric, two types of interferences are needed to be considered in a mesh network: Intra-flow interference occurs while the network interfaces of two or more consecutive links belonging to a single path or flow operate on the same channel. This type of interferences can be mitigated by applying channel diversity; for example, by selecting non-overlapping or orthogonal channels for subsequent links. Typically the interference range is greater than transmission range beyond immediate neighbors. This might result into interference among non-adjacent links operating on same channel in a multi-hop path. Inter-flow interference is caused by interference generated from other flows that are operating

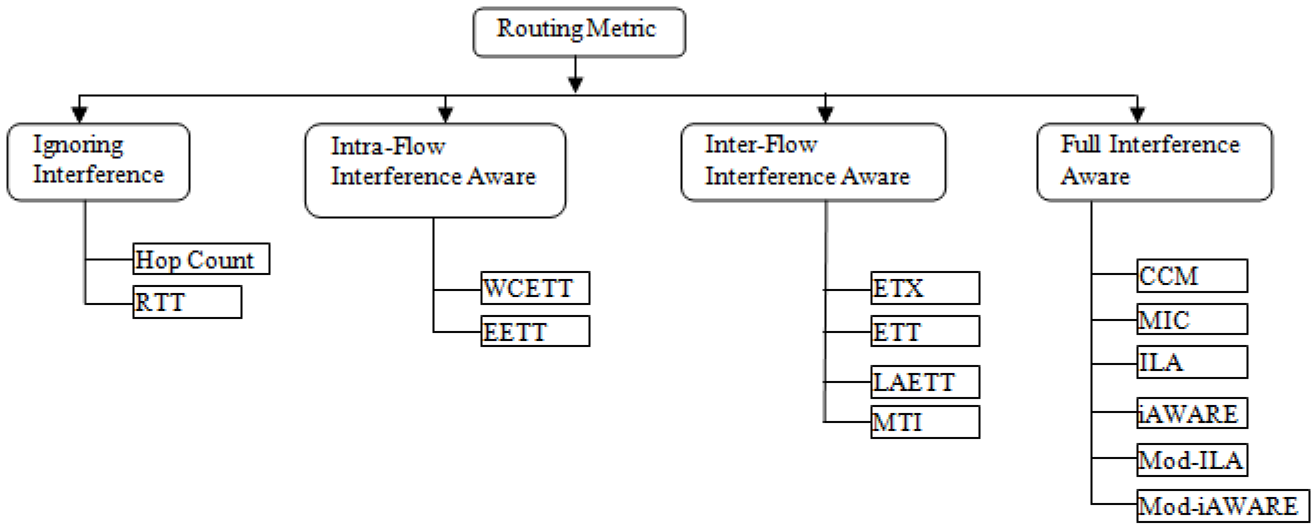

Figure 2.4: Classification based on Interference

on the same channels. Due to the involvement of multiple flows and routes, controlling inter-flow interference is more complicated than intra-flow interference. Based on the consideration of these interferences, routing metrics can be classified to four categories as shown in Figure 2.4.

2.5 Choice of Interference Model in Channel Assignment

A fundamental difference between a wireless network and its wired counterpart is that wireless links may interfere with each other, resulting in performance degradation. As a result, there have been numerous researches on wireless networks considering interference between wireless links. Out of several kinds of interference, handling co-channel interference is relatively simpler because many of the wireless link layer protocols use contention resolution mechanisms like RTS-CTS which easily detects if the transmitting channel is busy or not. On the contrary, adjacent channel interferences (ACI) are difficult to detect using channel contention mechanisms because in most cases these ACIs contribute as background noise and reduce the signal to noise ratio. Below, we mention some of the possible choice and

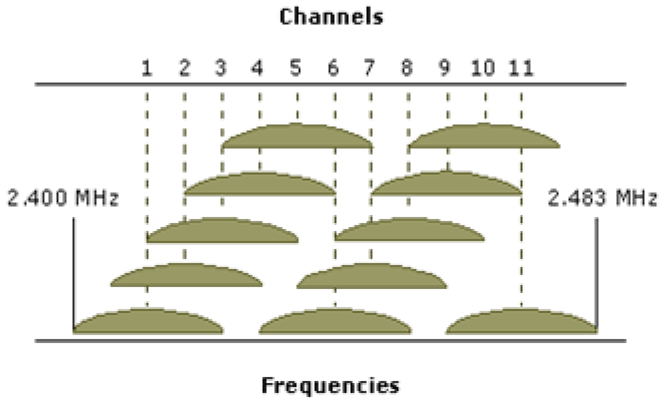

Figure 2.5: Partially Overlapped Channels (POC) in IEEE 802.11b/g

alternatives while considering the interference model in a POC based channel assignment algorithm:

2.5.1 Binary Interference Model

Among all the interference models, the Binary Interference Model is the simplest one. The model defines that two links can be either interfering or non-interfering without quantifying the extent of interference among each other. Hence, this phenomenon can be represented as a binary condition. But researchers have proved that this 0/1 assumption in case of interference is not true for most cases. The network throughput depends on the actual amount of frequency overlap, distance between nodes and signal to noise ratio which quantifies the interference. Therefore, this model is not meaningful while considering the case of POC based design.

2.5.2 Protocol and Physical Interference Model

Gupta et. al [58] proposed two important interference model that has been widely used in wireless communication and information theory. These two models, namely protocol model and physical model, have been studied extensively in the literature by subsequent researchers. In protocol model, a geographical boundary or interference range is defined for each receiver within which a receiver may perceive interference from other potential transmitters residing inside the boundary where the interfering transmissions are also on the same channel. Hence, this model can capture the effect of co-channel interference but not ACI. On the other hand, in physical model, the interference is mathematically calculated from the signal to noise ratio. Here, a transmission is considered successful when the signal to noise ratio perceived by the receiver exceeds a minimum threshold value after accumulating noise signals contributed by all other transmitters. In this model, the choice of threshold is an important tunable parameter for actual interference measurement. Comparing, protocol and physical model, the latter is obviously the more accurate but the computational complexity is too high. On the other hand, protocol model is easy to calculate but may lead to erroneous results due to inability to capture ACI effect.

2.5.3 Channel Interference Cost Function

A channel interference cost function, proposed by Ko et al. [25], provides a measure of the spectral overlapping level between two partially overlapped channels. The interference cost between channel a and b, denoted by $f(a, b)$, is defined as $f(a, b) \geq 0$ and $f(a, b) = f(b, a)$, where a value of 0 indicates that channels are non-interfering. The value of decreases as the frequency separation between the two channels increase. An example of a simple cost function defined using a single tunable parameter δ is:

$$f(a, b) = max(0, \delta - |a - b|) \tag{2.1}$$

where δ can be defined as the minimum channel separation between two non-overlapping channels. For IEEE 802.11b/g, $\delta = 5$. For example, if $a = 7$ and $b = 4$, then $f(7, 4) =$

$max(0, 5-3) = 2$. Again, for $a = 9$ and $b = 2$, the cost function will be

$$f(9, 2) = max(0, 5-7) = max(0, -2) = 0 \quad (2.2)$$

which means no interference at all. Due to the simplicity of this cost function, it is also easy to implement in a channel assignment algorithm as a measure of partial interference.

2.5.4 Channel Overlapping Matrix Model

An innovative Channel Overlapping Matrix Model has been introduced by A. Hamed Rad et. al [28]. The model captures the interference using a channel overlapping matrix. For example, let us consider an MRMC-WMN where N denotes the set of wireless routers where each router is equipped with I NICs. There are a total of C channels available for transmission. For any two routers $a, b \epsilon N$, a $C \times 1$channel assignment vector is defined as $\overline{x_{ab}}$. If router a, communicates with router b over the i-th channel, then the i-th element in $\overline{x_{ab}}$ is equal to 1; otherwise, it is equal to zero. As for example, suppose a router a is linked with router b through the 2nd channel where C = 5. This implies,$\overline{x_{ab}} = [01000]^T$. Let, m and n are two of the available channels within the frequency band. To mathematically model the overlapping effect among different channels, the authors defined a symmetric $C \times C$ channel overlapping matrix W. The entry in the m-th row and the n-th column of W is denoted by scalar w_{mn} and is defined to be as follows:

$$w_{mn} = \frac{\int_{-\infty}^{\infty} F_m(\omega) F_n(\omega) d\omega}{\int_{-\infty}^{\infty} F_m^2(\omega) d\omega} \quad (2.3)$$

Where $F_m(\omega)$ and $F_n(\omega)$ denote the respective power spectral densities on channels m and n.

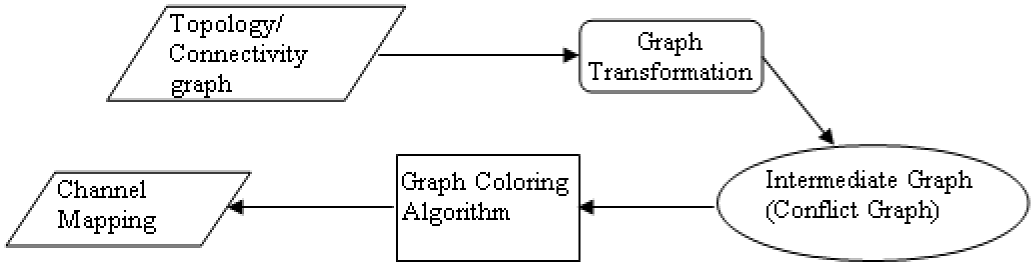

Figure 2.6: Framework for channel assignment

2.6 Graph Theoretical Framework For Channel Assignment

Graph based algorithms have been widely used in many channel assignment algorithms, irrespective of number of radios and channels. The network topology input is generally specified as a connectivity graph. The connectivity graph may be simple undirected graph or multi-graph depending on the number of radios and link topology. This connectivity graph can be converted into an intermediate graph, which generally takes the form of a conflict graph, characterizing the impact of mutual link interferences. For example, when coloring algorithms are used, this conflict graph is fed as input to the graph coloring algorithm which ultimately finds the channel mapping solution for the links. The method is depicted in Figure 2.6.

2.6.1 Graphical Representation of Channel Assignment Problems

Researchers have developed many approaches to design solutions for channel assignment. To formulate the channel assignment problems, different versions of conflict graphs are commonly used to characterize the interference constraints, whereas the application of various graph coloring algorithms has become a popular practice in selecting channels. Below we mentioned some of the graphical models that are very widely used during problem formulation of multi-radio channel assignment:

Figure 2.7: A four node network

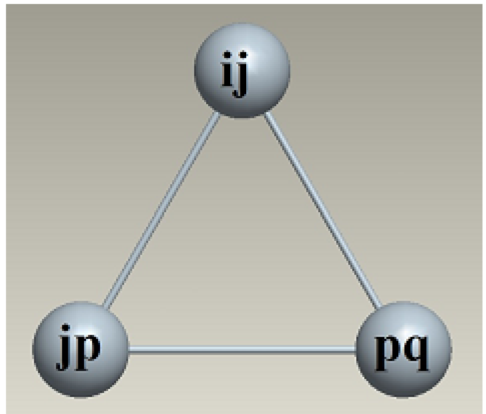

Figure 2.8: Corresponding conflict graph

Simple Conflict Graph

A simple conflict graph $G_c(V_c, E_c)$ is a graph derived from the original network topology graph where each vertex V_c represents a communication link or egde of the topology. There is an edge between two vertices of conflict graph only if the corresponding links in the topology are mutually interfering. An illustration is given in Figure 2.7 and 2.8. Figure 2.7 shows the original network topology where the three links ij, jp and pq are represented as vertices in Figure 2.8. Here, all the three links interfere with each other because of the close proximity and hence all the three vertices in conflict graph are connected.

Weighted Conflict graph

Some researchers represent the interference effect through assigning various weights to the edges of conflict graph. These types of graphs are known as Weighted Conflict graphs. These weights are assigned based on the extent of interference calculated from appropriate

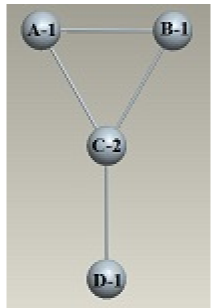

Figure 2.9: A simple network topology

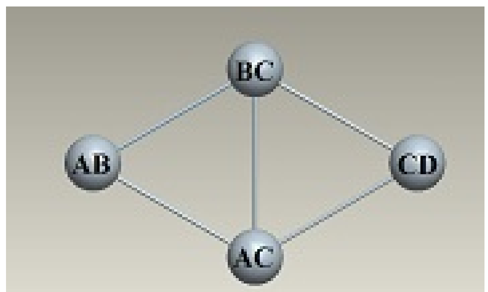

Figure 2.10: Corresponding conflict graph

interference model. Two well known algorithms, CLICA [41] and CoSAP [30] are formulated using these models. Of them, the latter is applicable cognitive radio networks.

Multi-radio Conflict graph

K. N. Ramachandran et al [12], introduced the notion of Multi-radio Conflict graph (MCG). The authors extended the simple conflict graph to model multi-radio mesh routers (Figures **??**). In this model, edges between individual radios are represented as vertices instead of representing edges between the nodes.. Figure 2.9 shows a wireless network with four nodes A,B,C and D where node C is equipped with 2 radios while the rest have single radio. Figure 2.10 is the corresponding simple conflict graph while Figure 2.11 shows the multi-radio conflict graph. In the multi-radio conflict graph, all the links connected to node C are represented with two edges, each for an individual radio.

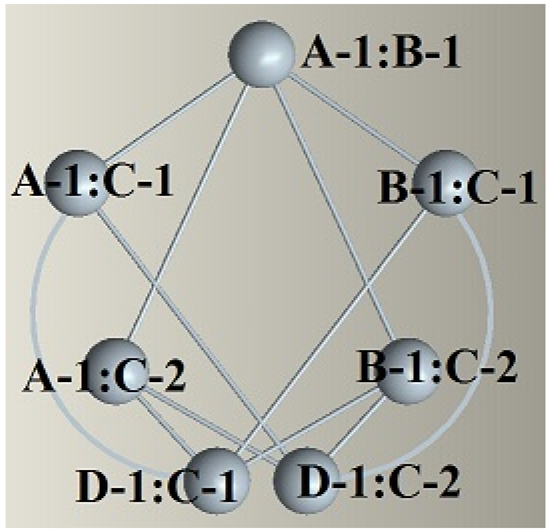

Figure 2.11: Multi-radio conflict graph

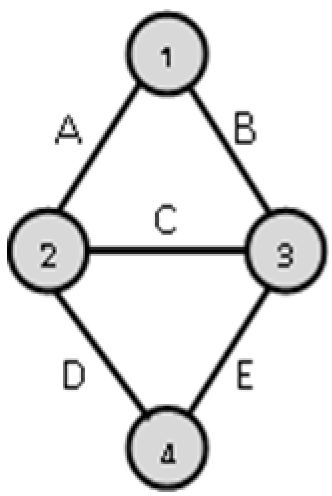

Figure 2.12: A topology of 4 nodes

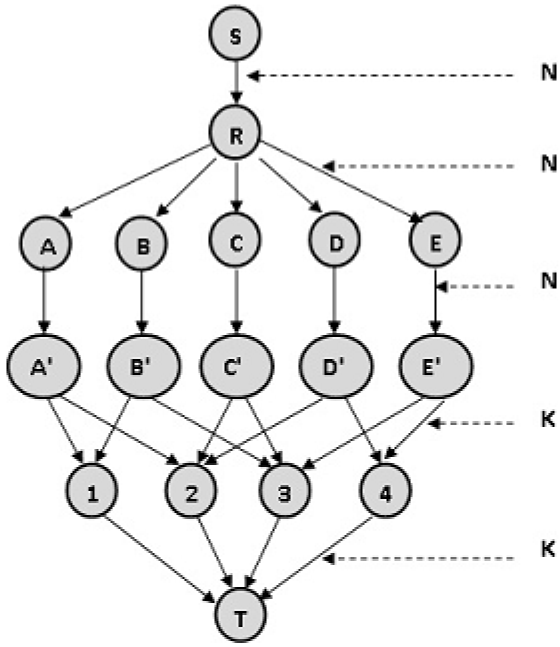

Figure 2.13: Resource Contention Graph

Resource Contention Graph (RCG)

W. Wang et al. [16] proposed the notion of Resource Contention Graph (RCG) which captures various contention regions in the network topology by identifying all the maximum cliques in the interference graph. The authors described a framework that represents the capacity of a multichannel network when the topology is known. The framework is formulated as an ILP problem where the solution of the problem determines the maximum possible spectrum usage for a given topology under channel and radio constraints. For any specific traffic pattern, the framework provides an upper bound on throughput with optimal routing decisions. Initially the resource contention graph is generated from the topology graph. Then a max-flow-like graph is constructed using the resource contention graph. The Max-flow graph is an extended version of the RCG which is generated by adding a source vertex s and a sink vertex t . For example, Figure 2.12 is a topology consisting of 4 nodes. Figure 2.13 illustrates the corresponding network flow model. The edge capacity for the first

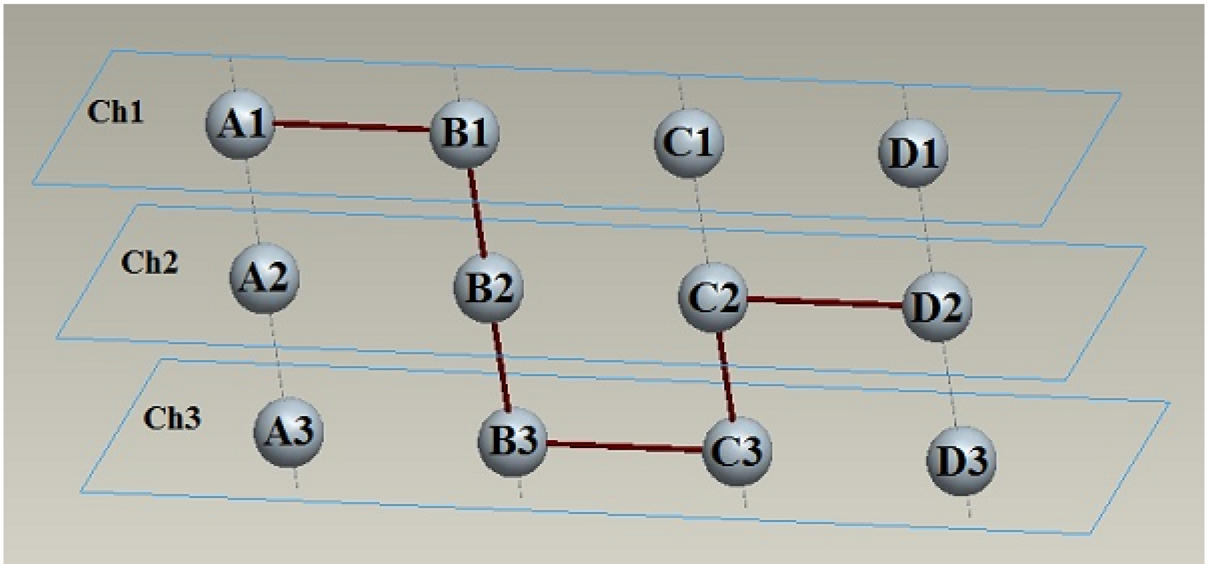

Figure 2.14: Layered graph Model

three levels is N, which is the number of channels and the edges of the last two levels have a capacity of K, which is the number of radios.

Layered Graph Model

C. Xin et al. [17] proposed a layered graph model to jointly optimize routing and channel assignment. In their model, each layer corresponds to a particular channel. The entire topology is represented using multiple layers of nodes where the number of layer is equal to total number of channels. A single network node is shown as a collection of virtual nodes residing in each layer. Vertical edges between layers connect the virtual nodes. The weights of the virtual edges are typically set with a low cost which makes the routing protocol prefer a path with dynamic channel switching. Practically, the cost of the vertical edges should be equal to the cost of channel switching delay. The horizontal edges that belong to the same layer (channel) are the actual cost of air propagation delay. Figure 2.14 illustrates a simplified layered model of three channels with four wireless nodes A, B and C, in which A and D are a communicating pair. The routing path switches from channel 1 to channel 3 at node B and again switches from channel 3 to channel 2 at node C.

2.6.2 Coloring Algorithms

Utilizing the different forms of conflict graphs described in the previous section, colors (i.e. channels) have to be assigned to the vertices of the conflict graph (which correspond to the links in the connectivity graph) so that an objective function is optimized. Typical objective functions range from minimizing the difference between the largest and the lowest used colors while avoiding interference to minimizing interferences using a given number of colors. For arbitrary networks, the resulting vertex coloring problems are computationally intractable (i.e., NP-hard). Therefore, the channel assignment problem is usually addressed by means of heuristic approaches, like genetic algorithms, taboo search, saturation degree, simulated annealing etc. Some researchers [52] tend to use polynomial time approximation schemes in greedy approach. Some of the common coloring or partitioning algorithms used to solve the channel assignment problems are Max K-Cut algorithm [32], MIN-MAX k-PARTITION [53], Distance-2 Edge Coloring/Strong Edge Coloring [43] etc.

2.7 POC based Channel Assignment Scheme

2.7.1 Frequency Distribution of IEEE 802.11b/g

Consider a wireless mesh network operating with the interface devices built on IEEE 802.11b/g technology. Fig. 2.5 gives an overview of the frequency spectrum of this category which works in the 2.4 GHz frequency band having a total of 11 channels available for communication. The frequency bandwidth of each channel is 44 MHz and the dotted lines correspond to the centre frequencies of corresponding channels. The distance between the centre-frequencies of two consecutive channels is 5 MHz. Increasing channel separation for simultaneous transmissions corresponds to decrease in spectrum overlapping which lead to less interference. If two channels have a separation of 5 channels or more, then they work as orthogonal channels. For example, channel 2 is orthogonal with respect to channels 7 and above. The maximum number of available orthogonal channels in IEEE 802.11b/g is 3. These are channels 1, 6 and 11.

2.7.2 How POCs can improve performance

The reason why partially overlapped channels (POCs) are neglected is because they create a significant amount of interference which is often difficult to handle. On the other hand, as the number of orthogonal channels is very limited, it now becomes infeasible to design an efficient channel assignment algorithm without the aid of POCs for MRMC environment. Recent works show that a systematic approach to exploit POCs can lead to better spectrum utilization and maximize network capacity and throughput. Experiments by Mishra et al in [82] have proved that two simultaneous transmissions with a channel separation of 3 can give the same level of throughput derived from two orthogonal channels. Their research also reflects that the effect of interference from adjacent channels is reduced as the geographical distance is increased. Therefore, instead of prohibiting the usage of channels with overlapped spectrum, POC based design makes a smart compromise between geographical positioning of neighboring nodes and interference tolerance level of radio interfaces. The primary idea is to provide nodes with full access of all working channels in the available spectrum let it decide whether a specific channel is usable or not. This increases channel diversity and upgrades overall network capacity. In this way, network capacity can be improved up to 90 percent if all the 11 channels can be utilized in 802.11b. [78]

2.7.3 Related Work on POC

Early work that closely relates to ours includes modeling interferences and capacity improvements of POCs and designing channel allocation and scheduling schemes using POCs.

The first systematic model of the POC based network design was introduced by Mishra, et al. in [82] and [83]. Their discovery showed that POC based design can improve network capacity up to three times in IEEE 802.11b-based networks compared to using only orthogonal channels. However, the authors did not mention any particular algorithm for channel assignment using POCs. In [91], Garcia et. al, presented a new frequency management scheme as well as channel assignment algorithm for IEEE 802.11b that minimizes interference and increases the throughput. Their algorithm takes both co-channel and adjacent channel interference into account, and makes use of all available channels instead of only 3 orthogonal channels. The results obtained from their simulations, justified the use of POCs for channel assignment. The usability and performance improvements by POCs in WLAN were also experimented using real test-beds by Feng et al. in [80] and [81]. They proposed two separate optimization models for one hop and multi-hop networks for POC-based design. They are the first to identify one of the most vital constraints for channel assignment in multi-radio multi channel WMN, that limit the number of parallel transmissions. We referred to this constraint in our research as self-interference constraint. We also utilized their experimental results on interference range in our paper as an input to our algorithm for constructing I-Matrix. A few more existing works focused on designing POC-aware channel allocation and scheduling schemes by applying variants of classic network resource allocation schemes. In [79], Liu et al. proposed a genetic algorithm scheme for joint channel allocation and link scheduling using POCs in single radio based wireless mesh networks. Their simulation results also showed that POC works better in denser networks. The authors mentioned the extendibility of their algorithm in multi-radio environment, but they failed to mention about the different types of interference issues (like self-interference) that arises while considering MRMC networks. Hence their algorithm, though improved system throughput for single radio environment, may not be feasible in multi-radio environments. In [78], Rad, et al., formulated the joint channel assignment and link scheduling problem in multi-radio environment as a linear mixed integer problem. Their simulation results showed that there was a significant performance improvement in terms of a higher aggregate network capacity and a lower bottleneck link utilization when all the POCs were used. But unfortunately, their algorithm also lacks the concept of self-interference.

Our study utilizes the promising results from the early work about the potential of POCs in increasing network throughput, and applies them to the channel assignment scheme for multiple radio and multiple channel networks. Our algorithm integrates all the related interference issues which are missing in most previous works.

2.7.4 Challanges for POC based Channel Assignment

The fundamental problem to be addressed in an MRMC mesh network architecture is the channel assignment problem that involves mapping channels to radios with a goal to achieve maximum channel utilization with minimum interference. The distance within which two transmissions interfere with each other is called the interference range. Due to adjacent channel interference, a transmission on channel 4 will interfere with channel 3 or 5 if they are within the interference range. In order to avoid such interference, network designers usually tend to use only non-overlapping channels in their wireless network.

The interference range of a transmission depends on the transmission power used. Therefore, the choice of transmission power also determines the amount of spatial re-use of the same channel. In channel allocation schemes that only use orthogonal channels, it is often unavoidable to assign neighboring nodes with the same channel due to limited number of orthogonal channels. The co-channel interference restricts the nodes from parallel communication. Though POCs can also interfere with each other, it is observed that the interference range of POC is often much smaller than the typical co-channel interference range. Such reduced interference range of POCs enables more parallel transmissions and lead to increased network capacity.

A number of challenging issues have to be tackled in our POC-aware channel assignment algorithm. Generally speaking, the "goodness" of a channel assignment rests on two factors: connectivity and interference. With multiple radio interfaces operating on different channels, two nodes a & b can communicate only if a) they are within the transmission range; and b) each of them has an interface assigned to a common channel (let this common channel be i); On the other hand the most significant issues related to interference include:

Co-channel Interference

Co-channel intereference refer to the interefernce generated from concurrent use of the same channel. To overcome this problem: none of the two communicating nodes (a & b) can use the common channel i for any other adjacent links.

Self-Interference

One of the most critical challenges is to overcome self-interference problem. Links connected to a single node cannot be assigned to channels with overlapping frequency bandwidth due to this problem. This important issue, addressed by Feng et al in [80], has been taken into account very well in our work. To overcome this problem:

- The maximum number of parallel transmission from a single node must be restricted to the number of maximum orthogonal channels available, which is 3 in our case.
- To ensure that within a single node the channels assigned to the incident links are mutually orthogonal.

Adjacent-channel Interference (ACI)

ACI refers to the interference perceived by node a or b from any of their neighboring nodes communicating on a channel which has partial overlapping with channel i. Fortunately, POCs do not have the same interference range as co-channel interference. As experimented by previous research works, the effect of interference from adjacent channels is reduced as the channel separation or geographical distance is increased. This is the basis of our POC based design. To utilize the property that ACIs of POCs reduces with the increase of channel separation and geographical distances in our algorithm, we introduce an innovative concept of Interference-Matrix (which we shall hereafter refer to as I-Matrix) to measure the ACIs among different POCs. The details about the I-Matrix and the algorithm are given in the following sections.

2.7.5 Interference Model

The I-Matrix at each node is the ultimate measurement that helps our channel assignment algorithm in determining whether a channel is assignable or not. It measures the interferences from all the possible channels for each channel with the node's current radio usage. We describe here the steps that lead to generate the matrix. They include the calculations of the interference factor, interference vector and the I-Matrix.

Interference factor

We define the interference factor, $f_{i,j}$ to provide a measure of the effective spectral overlapping level between channels i and j. This interference factor takes into account both the geographical distance and the channel separation between the two transceivers using these two channels. Our definition of interference factor refers to the effective interference from adjacent channels considering the Interference Range as a reference distance metric. To be noted, our definition of interference factor is different from the normalized I-Factor defined by Mishra et al in [82]. The I-Factor measures the extent of overlap between channels i and j given by the fraction of a transmitted signal's power on channel i that will be received on channel j. On the other hand, we quantified our metric as a ratio of interference range and geographical distance between the operating radios. If the geographical distance is greater than the interference range associated with the channel separation, we consider the two channels i & j as non-interfering, even though they have spectrum overlapping. This gives us the opportunity of better spatial reuse of channels with overlapping bandwidths. Since the interference range depends on the signal strength of the receiver, we may say, in a broad sense, that ours is a derived metric from the I-Factor mentioned in [82].

A good number of prior experiments have been done to measure the interference ranges (IR) for different channel separations. For our algorithm, we utilized the experimental results showed by Zhenhua Feng and Yaling Yang [80] & [81]. The IR table used for our algorithm is as follows:

Table 2.2: Interference Range

δ	0	1	2	3	4	5
$IR(\delta)$	13.26	9.21	7.59	4.69	3.84	0

Here $IR(\delta)$ refers to the interference range for a channel separation of δ, where $\delta = |i-j|$. Let, d refer to the distance between the two radios operating on channels $i\&j$. If the two radios tuned to channels i & j belong to the same node then the value of d will be zero. We define the interference factor as follows: 1) $f_{i,j} = 0$: when δ>5 or d>$IR(\delta)$ When channels i & j do not have overlapping spectrum or their operating distance is beyond the interference range; the corresponding value of interference factor is equal to zero, which implies that channels i & j are non-interfering. 2) $1 < f_{i,j} < \delta$: when $0 < \delta < 5$ and $d < IR(\delta)$ When two radios communicating on channels i & j are within the interference range and the channel separation is less than 5, they interfere with a factor inversely proportional to the distance between two operating radios. In this case we calculate the interference factor from the following equation:

$$f_{i,j} = IR(\delta)/d \tag{2.4}$$

Equation 2.4 indicates that $f_{i,j}$ decreases as the geographic distance increases. 3) $f_{i,j} = \infty$: when $0 < \delta < 5$ and $d = 0$. Due to the self-interference problem discussed in the previous section, two parallel transmissions on channels i and j within the same node will fully interfere with each other if their channel separation is less than 5.

Interference Vector

After calculating the interference factors for all the distinct 11 channels with respect to a specific channel within a particular node, we tabulate the values as below (Table 2.7.5) which we refer to as an interference vector. Clearly, an interference vector signifies the effect of interference from each of the 11 channels with respect to a particular channel i. The table also keeps track of the distance (d_i) to the nearest radio operating on channel i from the current node. Therefore, if the node itself has a radio tuned on channel i then di will be equal to zero. Table 2.7.5 below shows the interference vector corresponding to channel 3.

Table 2.3: Interference Vector

		Interference Factor										
Ch#	d_i	1	2	3	4	5	6	7	8	9	10	11
3	d3	$f_{3,1}$	$f_{3,2}$	∞	$f_{3,4}$	$f_{3,5}$	$f_{3,6}$	$f_{3,7}$	0	0	0	0

I- Matrix

Combining all the interference vectors for each channel, the I-Matrix is formed (Figure 2.15). Each node keeps track of its own I-Matrix. Either a column or a row corresponding to channel i refer to the interference effects from all other channels. After each link assignment, each node updates the I-Matrix for the newly assigned channel.

Ch#	d_i	Interference Factor										
		1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*
1	d_1	∞	$f_{1,2}$	$f_{1,3}$	$f_{1,4}$	$f_{1,5}$	0	0	0	0	0	0
2	d_2	$f_{2,1}$	∞	$f_{2,3}$	$f_{2,4}$	$f_{2,5}$	$f_{2,6}$	0	0	0	0	0
3	d_3	$f_{3,1}$	$f_{3,2}$	∞	$f_{3,4}$	$f_{3,5}$	$f_{3,6}$	$f_{3,7}$	0	0	0	0
4	d_4	$f_{4,1}$	$f_{4,2}$	$f_{4,3}$	∞	$f_{4,5}$	$f_{4,6}$	$f_{4,7}$	$f_{4,8}$	0	0	0
5	d_5	$f_{5,1}$	$f_{5,2}$	$f_{5,3}$	$f_{5,4}$	∞	$f_{5,6}$	$f_{5,7}$	$f_{5,8}$	$f_{5,9}$	0	0
6	d_6	0	$f_{6,2}$	$f_{6,3}$	$f_{6,4}$	$f_{6,5}$	∞	$f_{6,7}$	$f_{6,8}$	$f_{6,9}$	$f_{6,10}$	0
7	d_7	0	0	$f_{7,3}$	$f_{7,4}$	$f_{7,5}$	$f_{7,6}$	∞	$f_{7,8}$	$f_{7,9}$	$f_{7,10}$	$f_{7,11}$
8	d_8	0	0	0	$f_{8,4}$	$f_{8,5}$	$f_{8,6}$	$f_{8,7}$	∞	$f_{8,9}$	$f_{8,10}$	$f_{8,11}$
9	d_9	0	0	0	0	$f_{9,5}$	$f_{9,6}$	$f_{9,7}$	$f_{9,8}$	∞	$f_{9,10}$	$f_{9,11}$
10	d_{10}	0	0	0	0	0	$f_{10,6}$	$f_{10,7}$	$f_{10,8}$	$f_{10,9}$	∞	$f_{10,11}$
11	d_{11}	0	0	0	0	0	0	$f_{11,7}$	$f_{11,8}$	$f_{11,9}$	$f_{11,10}$	∞

Figure 2.15: Interference Matrix (I-Matrix)

Threshold Interference (Th)

We define a threshold (Th) value which specifies the tolerance level of interference for the radios. By limiting the value of Th to 1, we can disregard any channel within IR(?) from being considered for assignment. If we want to increase the tolerance level, we may specify Th ¿1.

2.7.6 Proposed Channel Assignment Algorithm

Our channel assignment algorithm uses the knowledge of offered traffic load. The offered load is specified as an input file to the algorithm which describes all the links that need to be assigned with suitable channels. The input links are assigned to specific radios of both the incident nodes. Then the nodes are sorted in descending order of the degree of the nodes so that the channel assignment starts with the most constrained node having maximum neighbors and links to be assigned. The I-Matrix of each node are initialized with zero. During the channel assignment procedure, the I-Matrixes will be updated accordingly. For each node, whenever any link incident to that node is found unassigned, a suitable channel is sought for assignment based on the information from the I-Matrix. To check whether a channel c is assignable to a link or not, the algorithm visits the two I-Matrixes of the incident nodes of this link, and sums up the total interference factors corresponding to the channel c. For example, if a link e connecting nodes u and v needs to be assigned a channel c, it computes the total interference factor with respect to channel c for both the nodes. The process repeats for all 11 channels. Whichever channel gives the minimum value of total interference factor will be selected for the assignment. If this value is less than the threshold value (Th), the channel is finally assigned to the link. After each link assignment, the interference vectors corresponding to the assigned channel are updated for each node. To update the I-Matrix, each of the nodes computes the distance from the node with the newly assigned link. With this distance (d), the interference factors are calculated for each channel with respect to the newly assigned channel (c), based on the conditions specified in earlier section. Then the values of I-Matrix are updated as follows.

$$F_{c,i}^{new} = F_{c,i}^{prev} + f_{c,i} \tag{2.5}$$

where c is the newly assigned channel..

Channel Assignment Algorithm

for each Node n in the sorted list:

    for each link e incident to Node n:

        if e is not assigned then:

```
ch = Get_Channel (e);
if (ch=Valid channel)
   e ->Assign_channel(ch);
   for all nodes: Update I-Matrix(ch);
else cannot assign channel;
```

Algorithm for Get_Channel(e)

```
Get two adjacent nodes of link e: n1 & n2
Initialize min=INFINITE;
For each channel i from 1 to 11:
     Calculate total I-Factor for channel i for both n1 & n2:
     if min >[ n1.total_i_factor(i) + n2.total_i_factor(i)]
        min = n1.total_i_factor(i) + n2.total_i_factor(i);
     if (min <Threshold_Interference)
        ch = i;
return ch;
```

2.7.7 Performance Evaluation of Proposed Scheme

Our evaluation studies the workability and efficiency gain for the POC based channel assignment scheme. We compare the two sets of usable channel inputs, one is the conventional orthogonal channels (denoted as OC) only; the other is all the channels (denoted as POC). To maintain consistency, we specified the threshold interference value, Th = 1 for both the schemes. This implies that we disregarded any partially interfering channel within the interference range (IR) from assignment. We are interested in the influence on the channel assignment algorithm from radio resources (implying feasible traffic load) and node density. Very low traffic load demands less channels, thus, could be sufficiently handled by OCs. Very high traffic load will saturate the media, leading to high interference at POC channels, thus can provide less help. The area dimension for our topology is within 100m 100m. Nodes are equipped with multiple radios of similar capability. Each node has the information of physical distance from each of its neighbors. We considered different types of node placements for our simulation. The total number of nodes is varied in the simulation. And we test two cases, 2 and 3 for the number of radios. According to our traffic load assignment scheme presented early, we assign sets of links for channel assignment as input load. We use the number of the links as a baseline to measure the improvement offered by POCs. In measuring the performance, we use the percentage of assigned link for a given link load.

Illustrations of Channel Assignment Outputs

Fig. 2.16 shows the channel assignment output for a random topology with 45 nodes and 54 total links, where maximum load is 3. Our results show that, POC based scheme is capable of assigning 35 links with 11 different channels whereas OC based scheme could only assign 29 links. This gives an overall capacity improvement of more than 20%. Similarly Fig. 2.17 shows the output for a random topology with 35 nodes and 30 links, where maximum load is for a node is 2. In this case POC based scheme was able to increase the number of assigned links from 19 to 25, which corresponds to 31% increase in the overall network capacity.

Total Link Assignment vs. NodeNumber

The performance of POC improves as the number of node increases. Fig. 2.18a and 2.18b demonstrates the total link assignment comparison between OC and POC scheme for different number of nodes with load 2 and 3. For both the cases, the figures show that

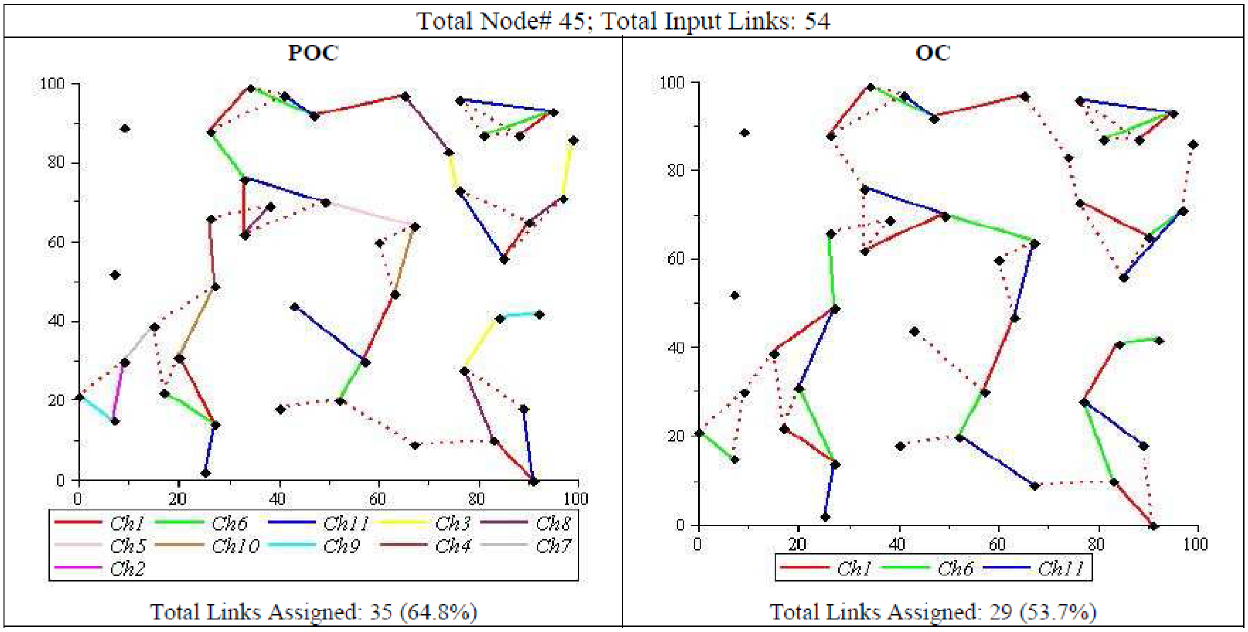

Figure 2.16: Channel Assignment Output for Random Topology (Input load=3)

increasing the number of total nodes results in increase of link assignments. The figures also show that saturation exists, after which the network is unable to assign more links even with POC. This saturation point occurs early in case of load 3. But there is not a single point where the POC based scheme is exceeded by OC scheme.

Percentage Link Assignment vs. Node Density

Fig. 2.19 shows the comparison of the percentages of the link assignments for both types of inputs. As our system can handle maximum 3 concurrent links in order to negotiate with the self interference problem, it is interesting to notice that an input link set with load =2 is capable of assigning channels with a higher percentage than that with load=3. But the POC still assigned more links in load=3 as seen in Fig. 4a and 4b.

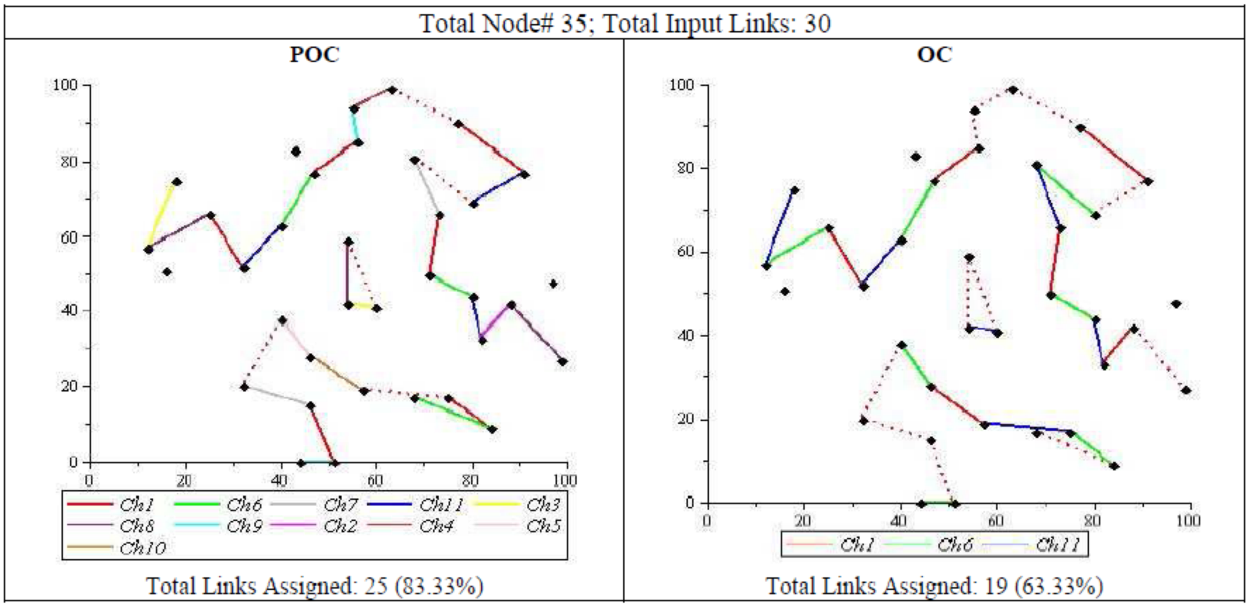

Figure 2.17: Channel Assignment Output for Random Topology (Input load=2)

Capacity Improvement

If we assume each link with equal bandwidth then the more number of links is assigned with channels, the higher capacity is gained. This capacity improvement is directly proportional to the difference of number of links assigned between POC and OC. We present the percentage of capacity improvement in Figure 2.20. It is measured with respect to the OC based scheme. From Figure 2.20 we can see the variation of capacity improvement for different node densities and loads. This is due to the randomness in the topologies. On average, with either load=2 or 3, our POC based algorithm can give an increase of capacity by more than 15%. In summary, our POC based channel assignment algorithm shows significant increase in channel assignment outputs for different random networks varying the number of total nodes and input load.

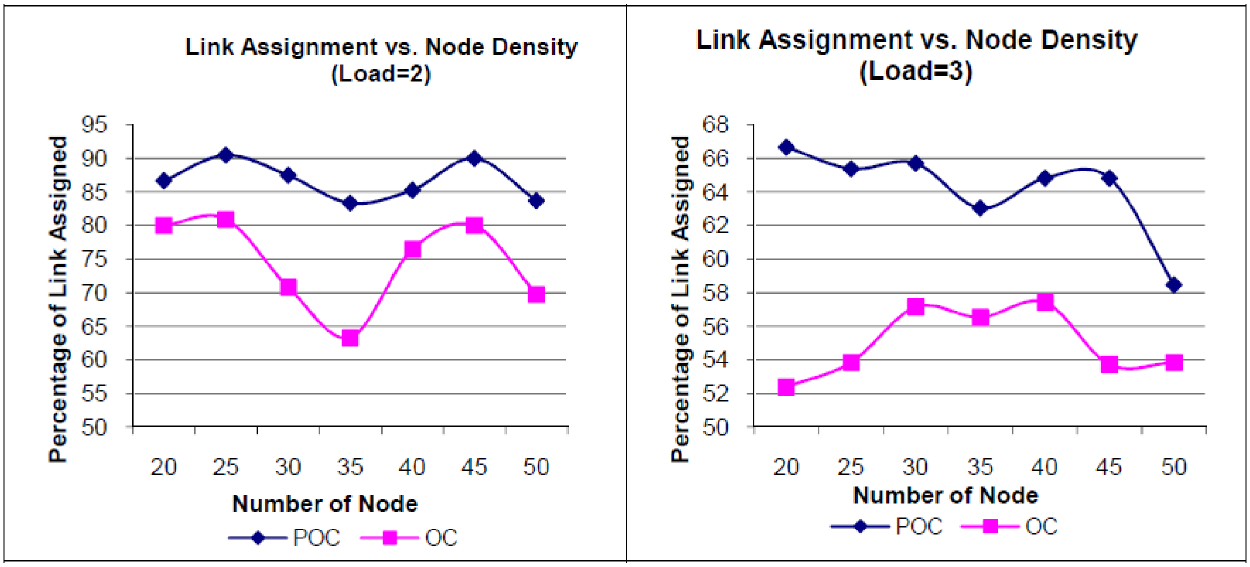

Figure 2.18: Comparison of Link Assignment Percentage: (a) Load=2 and (b)Load=3

2.8 Delay Analysis in Channel Access

It is of immense importance to measure the performance parameters of Ad Hoc networks, especially the end to end delay which optimizes the overall network performance. Minimizing delay is also one of the vital conditions to ensure Quality of Service (QoS) requirements in these dynamic networks, which necessitates proper estimations and realistic measurement techniques apart from network simulations. There are several classes of techniques discussed in the literature for determining end to end delay as well as one way delay. One class of technique, named internal measurement technique, adopts distributed method to deploy measurement agents on some internal nodes and calculate per hop delay by direct measurement. This information is then transferred to the central server node where the measurement data are processed and analyzed to optimize the overall network performance. The other class which is external network measurement technique (e.g. NT: Network Tomography technique) uses the measurement data sample of End-to-End to infer internal link performance parameters without the collaboration among internal nodes, which is also

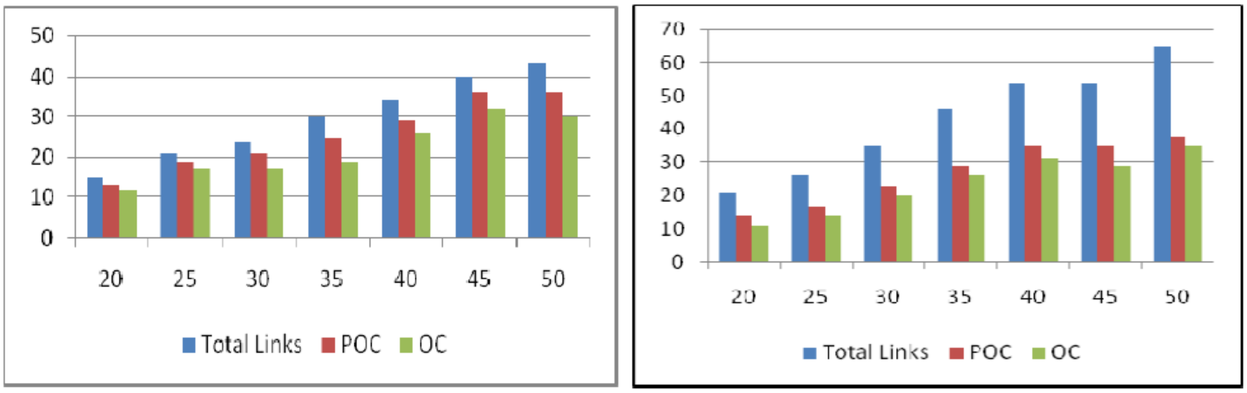

Figure 2.19: Number of link assignments for (a) load=2 (b) load=3

not concerned with network protocols. For this reason, some researchers [67, 76, 77] consider this technique apparently adaptable for quantifying link performance parameters in Ad Hoc network measurement.

For measuring one way delay, adding timestamp, sending probe packets and packet pair technique (PP) are three useful methodologies that are commonly practiced. With the first method, one could either add timestamps to each packet before it is sent and subtract the reception from the transmission time. If timestamps can be added to a packet directly before it is transmitted, this method allows determining the packet delay very easily and accurately without generating additional measurement overhead. The downside of this method is that the clocks of the stations have to be synchronized which is a challenge for any real-world implementation, as hardware clocks are in general neither synchronized nor equally fast. Clocks can be synchronized via the Network Time Protocol (NTP) or GPS, but both methods are more suitable for test bed setups than in a productive indoor environment.

The probing method does not need synchronized clocks, as the sender of a probe only need to record the time until the packet returns. Unfortunately, this method has several disadvantages: firstly it assumes that the receivers can response immediately to the probe packet which is not possible in real world. Our experimental measurements also prove this

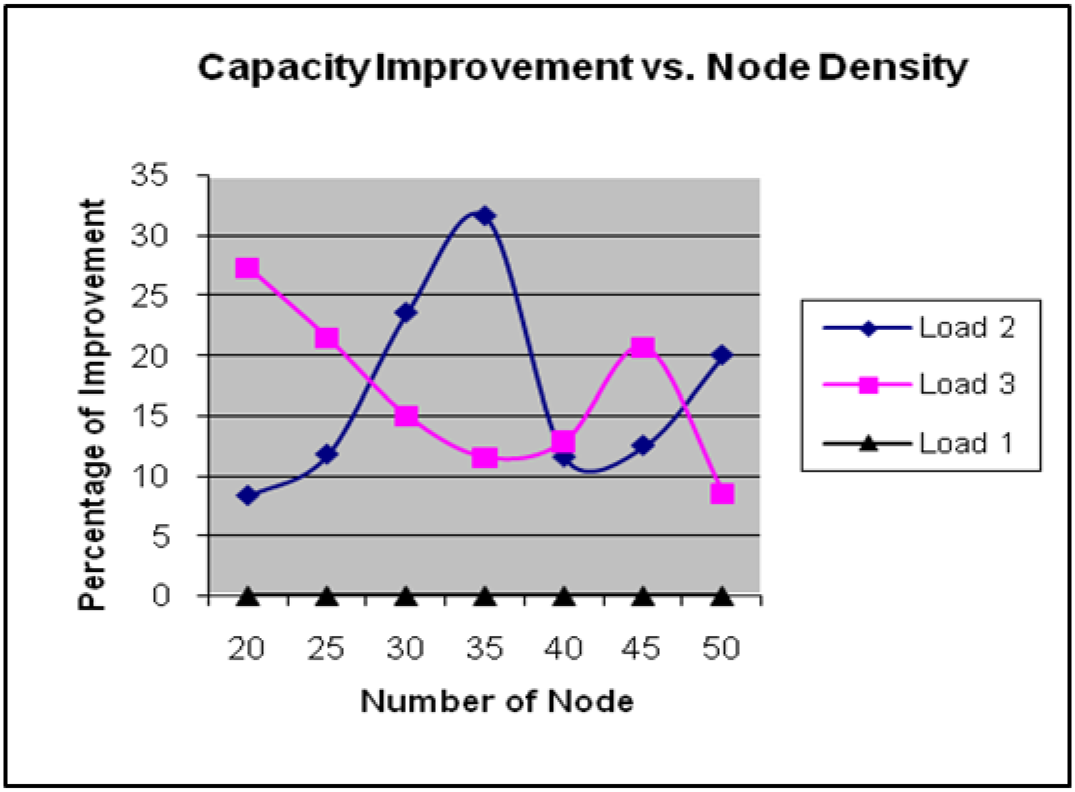

Figure 2.20: Capacity Improvement in POC based Channel Assignment Scheme

fact. Another major disadvantage is that it assumes the links are symmetric which gives unreliable measurement of one-way delay in wireless networks with asymmetric.

Packet Pair (PP) was a little bit sophisticated technique proposed by Keshav [74]. In this technique, two packets are sent directly after each other, the time dispersion between the reception time of these two packets measure the transmission time. Two particular implementation of packet pair concept has been attempted by Kapoor et al.[73] and Sun et al. [75]. An experimental study using both RTT and PP for estimating the link quality has been presented by Draves et al. [77].

Motivated by the APHD mechanism [68], Staehle et al. in their implementation of TOM [66] addressed the problems of above techniques and made utilization of an IP option field to accumulate the per hop delay estimate. Unfortunately their model also had a flaw of unpredictability due to hardware abstraction layer. In our experiment we did not face this problem as we got the hardware timestamp from WinPcap driver integrated with Wireshark tool.

In brief, all the above methodologies refer to end to end delay or one way delay measurement problem. But the concern of measuring per hop delay still lacks efficient techniques. That is why our primary focus of this research is on intra-node delay (sometimes referred to as internal node delay) within each intermediate node along the route from source to destination. The secondary goal is to estimate the air propagation delay between two consecutive nodes along the path or simply inter-node delay (hereafter referred to as airtime).

2.8.1 Network Model

Our network model includes three wireless nodes: *Source node, Relay node* and *destination node.* The radio configuration of the *relay node* is varied depending on the operating mode, that is, the relay node operates either in single radio mode or multi radio mode. But in all cases, the *source node* and *destination node* is fixed to single radio mode. While operating in multiradio, the *relay node* is equipped with an external USB network interface card that belong to IEEE 802.11b/g category. All other internal on board NICs support IEEE 802.11a/b/g. The distance between the three nodes are kept constant throughout the experiment so that there is no impact of distance variation into the delay measurement. To impose more interference in multiradio environment, we kept the distances between the neighbor nodes fixed at 1 meter, which implies the end to end distance between source and destination nodes were 2 meters.

Using the timing model described in the later subsection, an analytical dissection was done for the round trip delay. The three major delay components analyzed individually in our experiments are *Intra-Node delay, Inter-Node delay* and *Response time.* These terms are defined below:

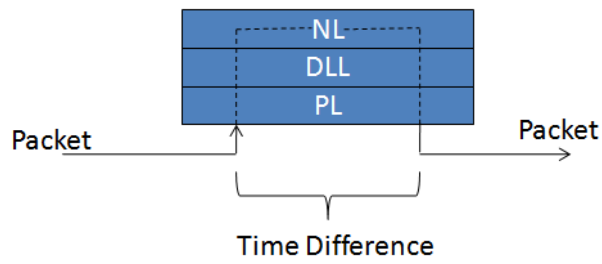

Figure 2.21: Intra-node Delay

Intra-Node Delay

The Intra-node delay can be simply viewed as the internal packet forwarding delay inside the relay node. Thus by this component we identified the delay period associated with packet header processing, route table lookup, queueing of packets to forwarding destination inside the relay node. Theoretically, this delay is equivalent to passing the packet through the bottom three layers. Figure 2.21 depicts the Intra-node delay diagrammatically.

Inter-Node Delay

This is the air propagation delay between two consecutive nodes along the path which is generally calculated by subtracting the reception timestamp of the receiver from the transmission timestamp of the sender. But as this mechanism requires the synchronization among the communicating stations, we designed an alternate technique (described in the timing model section) that can calculate the inter-node delay without synchronization between the clocks. In our experiment we also calculate the total $AirTime$ by summing up the Inter-node delays for all hops along the round trip path for each packet.

Response Time

This delay incurs at the destination node where the packets are passed to the application layer and a reply packet is send towards the source as acknowledgement packets. This delay is comparatively more significant than the intra-node delay due to the fact that it requires response from the application layer.

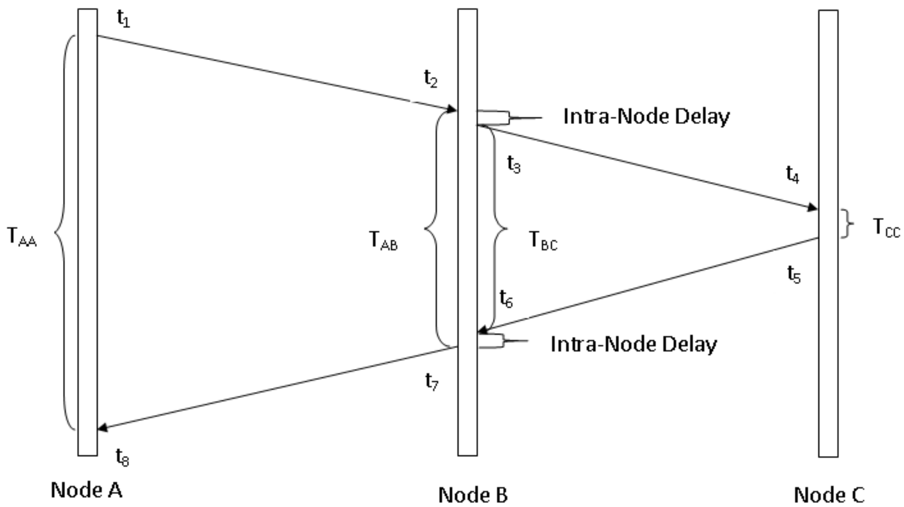

Figure 2.22: Timing Model for Network Measurement

2.8.2 Timing Model

Figure 2.22 illustrates our timing model. For any successful packet transmission from node A to node C, traffic generator application of node A generates a packet specifying node C as destination and node A as source. Routing table of node A decides that all packets towards node C must be routed through intermediate node B. When packet is transmitted to the air, the WinPCAP driver associated with Wireshark attaches a timestamp t_1 with the packet which is captured by Wireshark. At Node B, when one of the radios receive the packet at timestamp t_2, extracts the destination IP, looks at routing table to select route and sends it towards node C at timestamp t_3. Node C receives the packet at timestamp t_4 and sends it to the application layer. The receiver application prepares an acknowledgement packet for the received data packet specifying node A as destination and node C as source. Routing table of node C routes the acknowledgement packet to node B which is transmitted at timestamp t_5.

Node B again receives acknowledgement from C at timestamp t_6 and extract the destination IP and forward to node A at timestamp t_7. Node A receives acknowledgement at timestamp t_8. Node A, B and C do not have synchronized clocks.

The timing model proposed in this chapter (Figure 2.22), can estimate the delays without clock synchronization between the nodes. Timestamps t_1 and t_8 are synchronized as they are captured at node A, timestamps t_2, t_3, t_6 and t_7 are synchronized as they are captured at node B and timestamps t_4 and t_5 are synchronized as they were captured at node C. So response time of node C, T_{CC}, is simply the difference between timestamp t_4 and t_5. Node B sends data at timestamp t_3 to node C and receives acknowledgement at timestamp t_6 from node C (difference between t_3 and t_6 is marked as T_{BC}.) Both data and acknowledgement propagation delay, $T_{B-C}^{(D+A)}$, between node B and node C is the difference of T_{BC} and T_{CC}. Node B receives data at timestamp t_2 from node A and sends acknowledgement at timestamp t_7 to node A (difference between t_2 and t_7 is marked as T_{AB}). So the Intranode delay for data $T_{IntraDelay}^{D}$ is the difference of t_3 and t_2 and Intranode delay for acknowledgement $T_{IntraDelay}^{A}$ is difference of t_7 and t_6. The details equations for calculating the different delay components are provided below.

$$RTT = T_{A-B}^{D} + T_{B}^{D} + T_{B-C}^{D} + T_{C}^{R} + T_{C-B}^{A} + T_{B}^{A} + T_{B-A}^{A} \tag{2.6}$$

$$T_{AA} = t_8 - t_1 \tag{2.7}$$

$$T_{AB} = t_7 - t_2 \tag{2.8}$$

$$T_{A-B}^{(D+A)} = T_{AA} - T_{AB} \tag{2.9}$$

$$T_{BC} = t_6 - t_3 \tag{2.10}$$

$$T_{CC} = t_5 - t_4 \tag{2.11}$$

$$T_{B-C}^{(D+A)} = T_{BC} - T_{CC} \tag{2.12}$$

$$T_{IntraDelay}^{D} = t_3 - t_2 \tag{2.13}$$

$$T_{IntraDelay}^{A} = t_7 - t_6 \tag{2.14}$$

2.8.3 Experimental Setup

This section describes design and implementation of our experimental set up. We have used three Laptops as nodes, Wireshark to capture Ethernet protocol trace and traffic generator tools (Client/Server) to generate continuous traffic of variable packets size. We have done our experiment in Windows platform. We also used an external USB Radio to configure multi radio intermediate node. Data was collected with respect to 4 different scenarios.

Single and Multiple radio environment

We created a mesh network between three laptops (Figure- 2.23). For single radio environment, the touting table of node A was modified and a new route with node C, static IP was created which redirected it to node B. We did exact same thing at node C and created a new route for node A via node B.

For the multiple-radio environments, node B has two radios R1, R2. It was connected to node A with radio R1 and connected to node C with radio R2. Two different peer to peer networks are created for the link between node A and node B and the link between node B and node C, respectively. The network between A and B has no idea about the network between B and C and vice versa. We modified routing table of A, added a new route for the ad hoc network B - C using radio R1 of node B as gateway. Routing table of node C was also modified and a new route was added to pass packets through B towards A using R2 radio of node B as gateway.

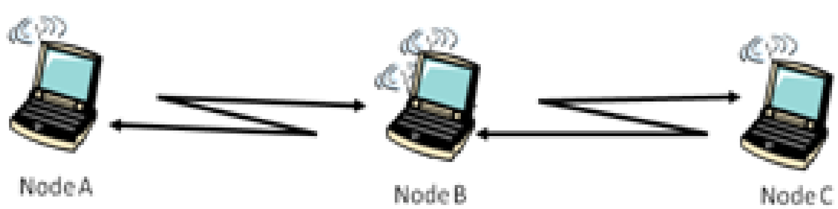

Figure 2.23: Network setup for multiple radio environment

Traffic Generation

To impose traffic, we used an open source traffic generator tool. We also tested other applications like FTP, ICMP, RTP which were tested for special scenarios. For measurement of delay, we installed packet sniffer tool Wireshark in every node. We used unidirectional and bidirectional traffic to investigate the impact of the two-radio and two-channel scenraio. For the one way traffic load, data transfers from Node A continuously with payload of (100, 500, 1000, 1500 and 2000 Bytes) to node C via node B. Then we transferred data between node A and node C via node B in double handshake mode. Node A and node C sent continuous traffic of (100, 500, 1000, 1500 and 2000 Bytes) payload simultaneously. In both scenario we captured Ethernet trace of couple of thousands packet transmission. Wireshark was running in all the nodes to capture trace from radio. In Node B, two Wireshark was active, one for Node A and another for Node C.

2.8.4 Results and Analysis

In the following subsections, we present the analysis of two major components of round trip delay: Intra-Node Delay and Inter-Node delay.

2.8.5 Measurement of Intra-Node Delay (Relay Time)

Here we show the effect of packet size and number of radio on intra-node delay. We also describe a seemingly interesting behavior of the intra-node delay which follows a periodic pattern.

Effect of packet size and number of radio

The comparative analysis of data relay time between single radio and multiradio environment can be visualized from figure 2.24. Figure 2.25 shows the frequency distribution of Intranode delay for particular payload size of 500 bytes in a multiple radio environment.

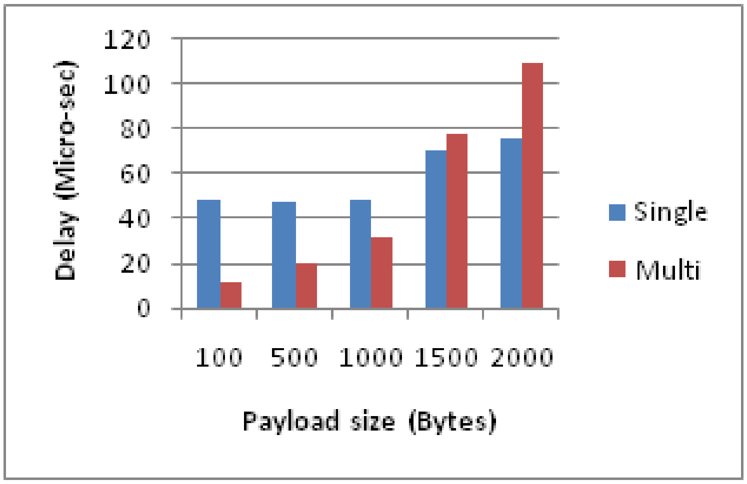

Figure 2.24: Effect of packet size and number of radio on Intra-node delay

From the graphs (Figures 2.24 and 2.25) below, it is evident that multi radio ad hoc netwrok outperformed upto packet size 1000 byte but later single radio is the winner. This is the case where the processing time for fragmentation is taking place. Our hypothesis is, as for large packets in multi radio, fragmentation is a usual phenomenon (observed from Wireshark) and contributing more time in processing data and generation acknowledgement. But in the single radio this is not the case because fragmentation not take place (observed from Wireshark). There is also one more thought about the single radio, the total experimental set up was with one single network, the packet fragmentation was not mendatory in the physical level for ad hoc network, during packet transmission for upto 2000 byte packet size.

Periodic pattern of Relay Time

One of the most interesting findings from our experiments was to identify a periodic pattern of relay time in every setup irrespective of payload size or number of radios. The cause behind this phenomenon was possibly due to internal scheduling of operating system which may follow a periodic scheme for process scheduling. It can be clearly observed in Figures 2.26,2.27,2.28,2.29 that there is some kind of internal processing time of some

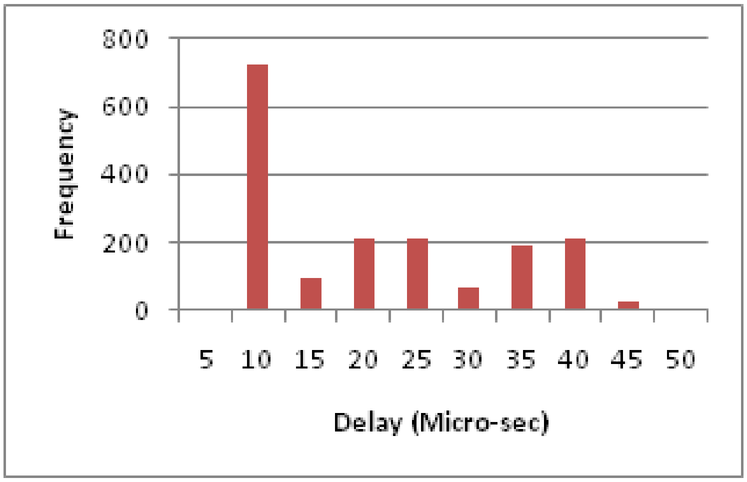

Figure 2.25: Frequency Distribution for Intra-Node Delay

applications engaging the CPU usage periodically and resulting the intermittent nature of the Relay-Time as mentioned before. It may be mentioned that the Relay-Time calculation and graphical representation was totally based on data relay, not based on acknowledgement relay. This is because of the fact that, acknowledgement packets are always of a fixed size even though the data payload was changed, which does not give the opportunity to measure the variation due to change of packet size.

Frequency distribution of Relay Time

We have measured the Intra-node delay (Relay Time) for both single radio and multiple radio environent by varying the payload size. In figures 2.30 and 2.31, we can find the frequency distribution of relay time for different payload size in both single radio and multiple radio environment. Quite interestingly, the single radio graphs take the shape of a damped oscillation where the skewness varies with the payload size. But in case of multiple radio, this was not noticed. Another major difference between the two figures is that, the mode of relay time for multiple radio has shifted leftwards compared to the single radio environment. This

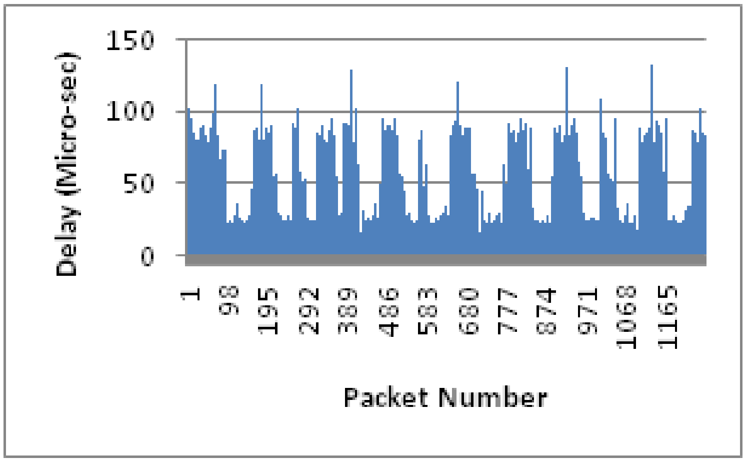

Figure 2.26: Periodic Delay pattern for payload size 100

implies that, most of the packets in multiradio transmission take less time (about 9 micro-sec) compared to single radio environment (22 micro-sec). This scenario is also validated from the graph in Figure 2.24 which shows that the relay time for single radio is higher than multi-radio communiaction due to the flexibilty of parrallel transmission in the later case.

Measurement of Inter-Node Delay (AirTime)

We present the Inter-Node delay (AirTime) for different scenarios here. In order to measure the AirTime, first, the end to end time was collected from the Wireshark at Source Node A whereas the relay time was measured at node B and the response time was measured at node C. Then, after deducting the relay time and response time from the end to end delay the total Air time was found. Having a close observation in the relay time, it was observed that the internal process scheduling at the intermediate node B resulted a periodic nature for the relay time. With regards to the response time at destination Node C, note that this duration reflects the processing delay between receiving a data packet from the Node B and sending acknowledgement towards the source node A.

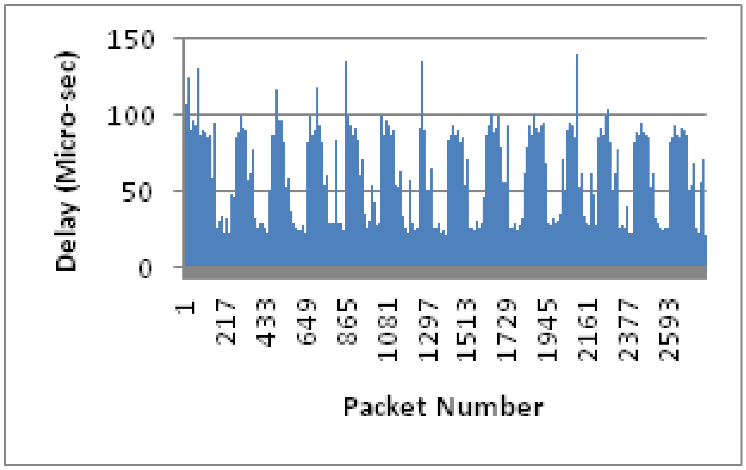

Figure 2.27: Periodic Delay pattern for payload size 500

In addition, we show comparisons between the natures of packet transmission with single radio and multiple radio with respect to couple of points. In a multiple-radio ad hoc network, the packet transmission takes less time than a single-radio ad hoc network for all packet sizes. From Figure 2.32 it can be seen that multiple radio setup has outperformed the single radio setup, which is quite natural. The reasons behind this fact are that, in multiradio environment, a node can receive and transmit simultaneously, also the two different networks use different channels so that 802.11 carrier sensing and ransom access delay are eliminated. In all, the overall airTime associated with round trip delay is reduced. Figure 2.33 shows the frequency distribution histogram of AirTime for a particular setup.

Statistical Analysis of Delay Components

In order to identify the statistical correlations we performed multivariate linear regression analysis (Figure 2.35) to model the relationships between end to end delay and other delay components. From the regression analysis, we validated that the end to end delay is linearly related to all the delay components through the values of regression co-efficients calculated to be 1. We can also verify from the correlation coefficients (Figure 2.34) that end

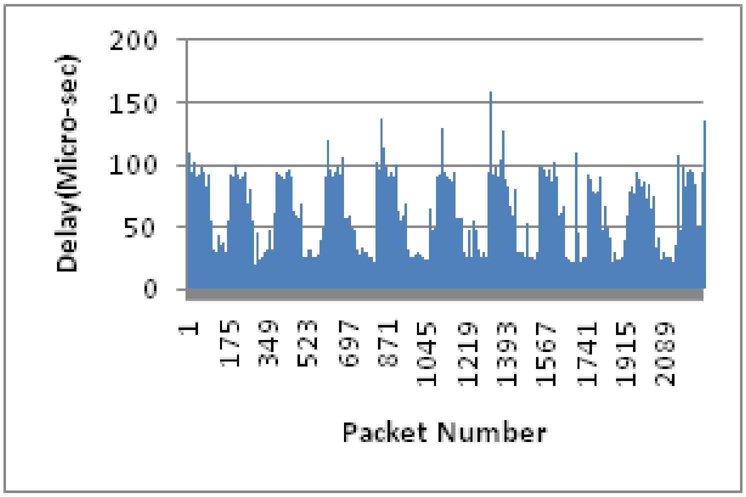

Figure 2.28: Periodic Delay pattern for payload size 1000

to end (E2E) delay is 98% correlated with total AirTime. A general descriptive statistics (Figure 2.36) is also given for the overview of data. The descriptive statistics shows the mean, median, mode, standard deviations, variances, skewness etc. for each of the delay components.

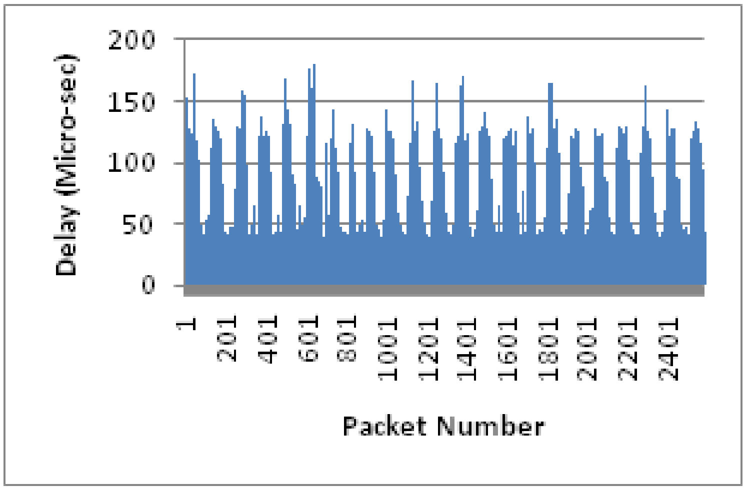

Figure 2.29: Periodic Delay pattern for payload size 1500

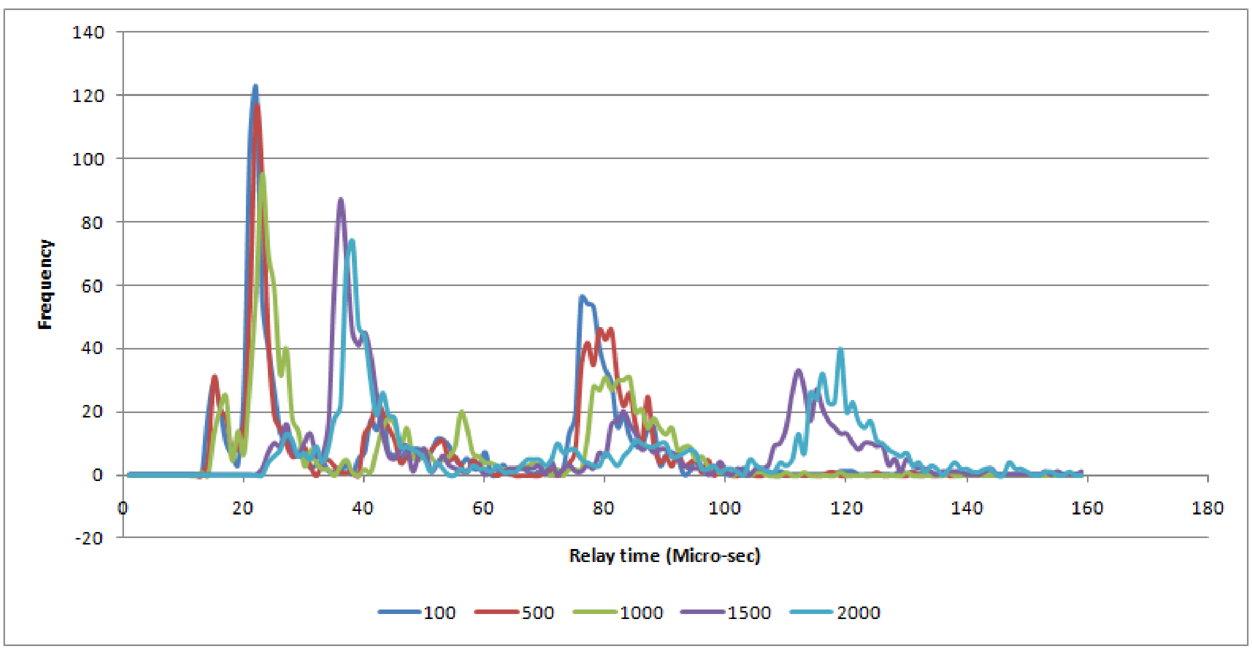

Figure 2.30: Frequency Distribution for Relay Time (Single Radio)

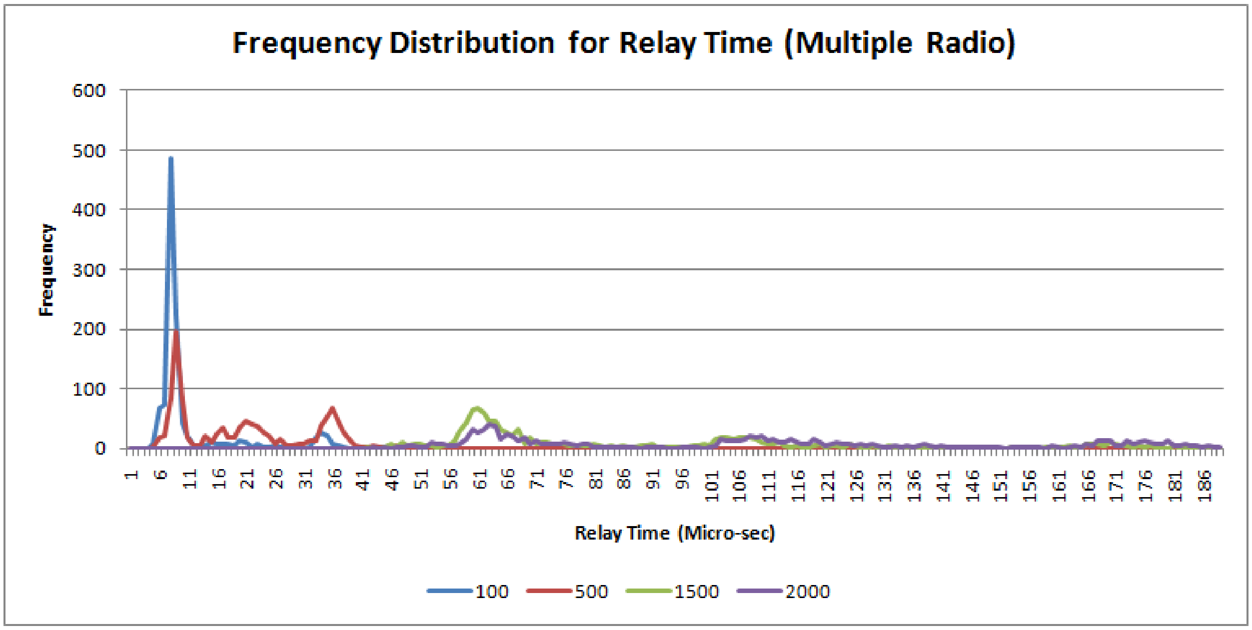

Figure 2.31: Frequency Distribution for Relay Time (Multiple Radio)

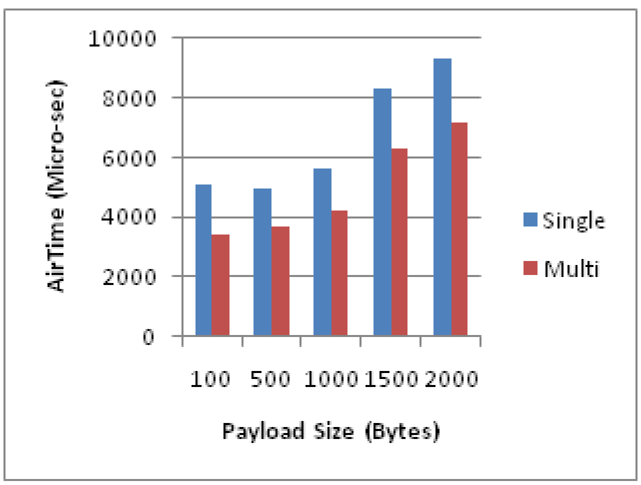

Figure 2.32: Effect of packet size and number of radio on round trip delay

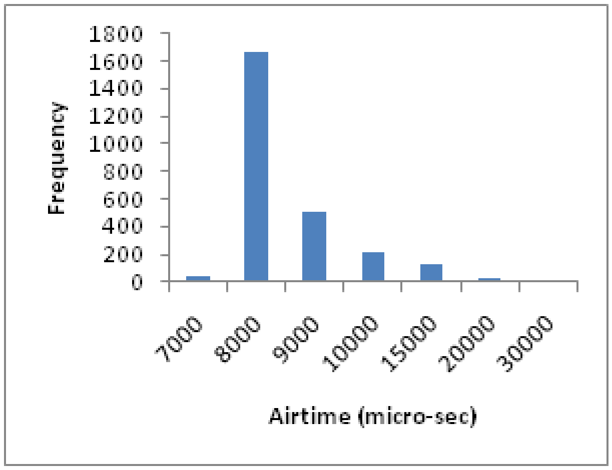

Figure 2.33: Frequency Distribution for Air Propagation Delay

	E2E	*Data_Relay*	*Ack_Relay*	*Total-Relay*	*Response*	*AirTime*
E2E	1					
Data_Relay	-0.002319614	1				
Ack_Relay	-0.004007315	0.874252184	1			
Relay	-0.003295873	0.965923521	0.970114339	1		
Response	0.195094366	0.008588875	0.013009168	0.011228674	1	
AirTime	**0.981299445**	-0.038401068	-0.041120174	-0.04111666	0.005913	1

Figure 2.34: Correlation between Delay Components

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	-1.63709E-11	3.76972E-13	-43.4273	0
Relay	1	5.44601E-15	1.84E+14	0
Response	1	1.69829E-16	5.89E+15	0
AirTime	1	4.14408E-17	2.41E+16	0

Figure 2.35: Regression Analysis of Delay components

	E2E	Data_Relay	Ack_Relay	Total-Relay	Response	AirTime
Mean	8656.942967	70.36454721	45.83044316	116.1949904	332.8458574	8207.902119
Standard Error	35.95493945	0.711256524	0.522577462	1.212106487	8.467037482	34.70960719
Median	8159	56	38	89	232	7742
Mode	7896	36	21	58	219	7278
Standard Deviation	1831.585695	36.23221994	26.62069295	61.74608929	431.320563	1768.147046
Sample Variance	3354706.156	1312.773762	708.6612934	3812.579543	186037.428	3126343.977
Kurtosis	57.7296419	-1.393657505	-1.313155267	-1.490529465	215.6565789	64.97756364
Skewness	6.115788567	0.36558812	0.471169531	0.382303724	11.40397393	6.559222543
Range	29812	158	122	224	11498	29684
Minimum	6867	22	13	39	204	6450
Maximum	36679	180	135	263	11702	36134
Sum	22464767	182596	118930	301526	863735	21299506
Count	2595	2595	2595	2595	2595	2595

Figure 2.36: Descriptive statistics of Delay components

Chapter 3

MOBILITY AND CONNECTIVITY ANALYSES IN VEHICULAR NETWORK

3.1 Introduction

Vehicle to Vehicle (V2V) communication is one of the two fundamental communication modes of DSRC technology that provide a flexible and real-time information dissemination mechanism through various ITS applications. Achieving seamless connectivity through multi-hop vehicular communication is a challenging issue particularly in sub-urban or rural areas with sparse networks. It can be envisioned that in near future, enterprise business applications or commercial applications might be developed on top of DSRC platform targetting a particular class of vehicles in a specific geographical terrain. For example, a taxi cab company may use an internal fleetwide business application using V2V communication platform. Other examples of this type of selective multicast applications include commercial applications targetting vehicles of specific manufacturer or government entities trying to draw attention of a specific class of travellers etc. Irrespective of the application scope, we attempt to analyze the feasibility of implementing such kind of selective multicast applications by quantifying the connectivity of vehicles through multi-hop communication. In this analysis we had used real world GPS traces from San Francisco yellow cabs to investigate the fleetwide data dissemination using V2V connectivity.

The GIS based computer aided taxi dispatching (CAD) systems provide an easy way to track the movement of each individual taxi and monitor the occupancy status of the vehicle. In order to distribute the load fairly among the fleet, it is nevertheless important for the taxi companies to have a prior idea about the demand and availability statistics based on historical data that can be generated from the archived GPS trace records in their systems. On the other hand, to maximize daily trip revenue and minimize empty cruise time, it is also necessary for the drivers to have a sound idea about the geographical distribution of taxi hotspots for passenger pickup and drop off which varies along time. More important, the historical archived data of mobility traces can provide significant information, such as geographical distribution and time varying density of the road traffic, for helping vehicle communications, for implementing Intelligent Transportation Systems applications, and for planning of deploying DSRC infrastructure. Recent research have shown studies on many interesting facts related to Vehicular Ad hoc Network (VANET) like urban mobility models, vehicle-to-vehicle (V2V) connectivity etc.

A remarkable initiative of San Francisco Exploratorium [94] is the Cabspotting project [95], which is intended as a living framework to use the activity of commercial cabs to explore the economic, social, political and cultural issues that are revealed by the realistic GPS traces. In this chapter, we present our analysis on the traces available through this project provided by San Francisco Yellow Cabs [93]. Our analysis dealt with 536 cabs generating over 10 million mobility traces over a period of one month. Our results show new interesting factors about taxi cab mobility, passenger data and communication potentials. The main contribution of this research is twofold. First, investigating the time varying nature of multihop vehicular connectivity and dynamic network partitioning in an urban environment. Second, exploring interesting facts from taxi mobility pattern like velocity profile, spatial distribution of hotspots and other characteristics like trip duration, empty cruise interval etc.

The subsequent sections are organized as follows: We discuss related work in Section 3.2, followed by our analysis model and data collection methodology in Section 3.3. Sections 3.4 presents the mobility analysis results for a single cab as well as for the whole fleet. Section

3.5 and 3.6 provides a detail analysis on vehicle connectivity and partitioning of the mobile nodes. Finally, we conclude in Section 3.7.

3.2 Related Work

Even though vehicular connectivity problem is one of the most interesting research area for the community, but not much work has been done from the perspective of analyzing network partitioning and multi-hop connectivity using real world traces. However, several interesting works related to taxi mobility patterns has been addressed by the researchers. Most of these works are based on analyzing GPS traces from different taxi cab companies to explore hidden characteristics of urban mobility models. Some of these researchers tend to reveal new mobility models while others focus on clustering and hot spot identification. Piorkowski *et. al.* [99] utilized the Cabspotting data archived over a month to propose a parsimonious mobility model called Heterogeneous Random Walk (HRW) which captures some of the important mobility characteristics observed from the macroscopic level. A key feature of the model is that nodes follow independent and statistically equivalent mobility patterns, despite the presence of long-term clusters. They also evaluate the predictive power of the HRW model in the context of epidemic dissemination, which is one of the most prominent paradigms for routing in DTNs. Their work motivates the vehicular networking community to deeply investigate the taxi mobility traces for further research. Shin et al [98] used real-life location tracking data collected from the Taxi Telematics system developed in Jeju, Korea. Their analysis aimed at obtaining meaningful moving patterns of taxi cabs .They have extracted some interesting statistical factors such as taxi's driving type, driving time, driving area, pickup rate etc. Lee et. al [97] analyzed a pick-up pattern of taxi service in the same geographical area aiming at clustering the pickup and drop off locations to develop a location recommendation service for empty taxis. The same author in another paper [99] analyzed both spatial and temporal statistics of taxi's waiting spots from the movement history. These works provide an insight to the possible dimensions of utilizing location tracking data for the purpose of taxi industry.

3.3 System Model and Data Collection

The Cabspotting project tracks San Francisco's taxi cabs as they travel throughout the Bay Area. The data is transmitted from each cab to a central receiving station once in every minute, and then delivered in real-time to dispatch computers via a central server. This system broadcasts the cab call number, location and whether the cab currently has a fare. The cab locations are not stored by Yellow Cab, but only used in real-time to aid dispatch. Cabspotting server communicates to the Yellow Cab server and stores the data in a database, encoding the call number for privacy. The patterns traced by each cab create a living and always-changing map of city life. This project is intended for researchers to explore these issues in the form of a small experiment, investigation or observation. One of the most important component of this project is the API [100] that allows real time tracking information of individual cabs. Two other mentionable applications belonging to this project is the CabTracker [101] which averages the last four hours of cab routes into a map and the Time Lapse [102]which reveals time-varying patterns such as rush hour, traffic jams, holidays and unusual events.

3.3.1 Trace Record

Each mobility trace record contains the following fields:

1. *Latitude & Longitude:*Two floating point values of the current GPS position of the cab.

2. *Occupancy status:* A binary value indicating the passenger occupany status. A value of 0 indicates that the cab is free while 1 means hired by passenger.

3. *Timestamp:* Unix timestamp of the trace reception time.

Figure 3.1: Euclidian distance vs. actual geographical distance

3.3.2 Accumulation of Trace Records

Using the API we accumulated real time traces of these cabs over a time frame of more than 24 hours starting from July 17, 2011 11:01:09 PM to July 18, 2011 11:57:08 PM. A total of 2063trace records were captured within this time frame. We also collected previously archived data for a period one month from CRAWDAD [103] that was acquired though the same procedure. The archived records summed up to a total of more than 10 million traces organized in individual ascii files for each of the 536 licensed yellow cabs. These trace files were simulated using our own developed application. We analyzed the traces both from the perspective of a single cab as well as from the perspective of the whole fleet.

3.3.3 Calculation of Geographical Distance

Previous work with GPS trace data and distances mostly considered Euclidian distance between two points. However, this calculation completely ignores the fact that the earth is round yielding incorrect results. The difference between Euclidian distance and a correct approach can be described in Figure 3.1. According to the Euclidian distance, the distance between two points P1 and P2 would be equal to the cord P1P2, whereas the actual distance would be along the circular arc.

In our work we investigated two algorithms, namely, the Spherical Law of Cosines and Equi-rectangular approximation, in calculating a geographical distance between two trace locations. Our implementations and usage of the two schemes suggests that, for more accurate precision level, the spherical cosine is better than the Equi-rectangular approximation. But for faster system performance the latter is preferred. In our mathematical analysis,

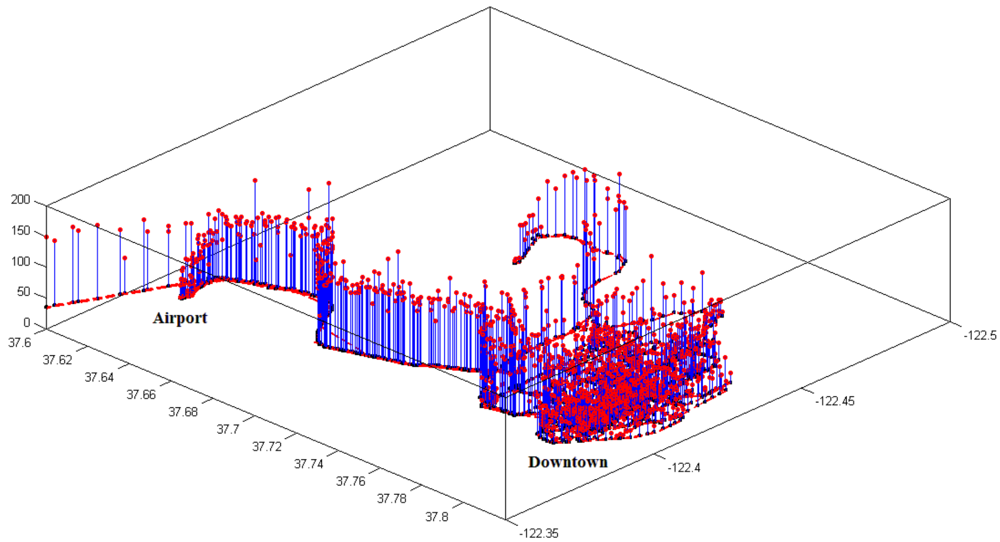

Figure 3.2: Velocity profile of a single taxi cab in one day

we used the latter in case of averaging one month's data for all the cabs, which contained over 10 million records. While working with a single cab over 24 hour time span we used Spherical Cosine Law to get an accuracy level of less than one meter. Below we mentioned the mathematical equations for both the approaches.

1. Spherical Law of Cosines

$$d = cos^{-1}(sin(lat_1).sin(lat_2) + cos(lat_1).cos(lat_2).cos(long_2 - long_1)).R \qquad (3.1)$$

2. Equirectangular approximation

$$x = \Delta lon.cos(lat) y = \Delta lat d = R.\sqrt{x^2 + y^2} \qquad (3.2)$$

3.4 Taxi Mobility Analysis

We analyzed the mobility pattern of individual taxi cabs as well as the spatio-temporal distribution in order to investigate the feasibility of implementing business applications that can be developed using the vehicular ad hoc network formed by the fleet of taxi cabs. Velocity profile of the a single cab within a daylong duration gives an idea of the variation of speed with respect to geographical location. This analysis can provide a metric to decide the amount of time that can be spared for establishing data connection with the road-side units.For spatial distribution of hotspots, we have analyzed archived data for a duration of one month containing traces of all 536 cabs. Some of the key findings are mentioned in the following subsections.

3.4.1 Instantaneous Velocity

Figure 3.2 shows the velocity profile of a single cab within a day. Vertical axis shows the calculated instantaneous speed of the cab in km/hour. Two axis along the horizontal plane denote latitude and longitude. The figure demonstrates some logical findings from the urban traffic perspective.The average speed in downtown area is calculated to be less than 40 km/h or approximately 25 mile/hour. On the other hand, average speed on the freeways is above 100 km/hour or more than 65 mile/hour. The averages speed of the taxi cab over the whole day calculated from the trace records was 43.81 km/h.

3.4.2 Trace Locations and Direction of Mobility

Figure 3.3 shows the geographical locations of trace points where we calculated instantaneous velocity and moving directions of the taxi cab within a time frame of one day. Here we only show a partial plot near the San Francisco downtown area. The black dots denote the location points where trace records were generated by the taxi cab and received by the GPS satellite. The average distance between two trace points were found to be 253.27 meter

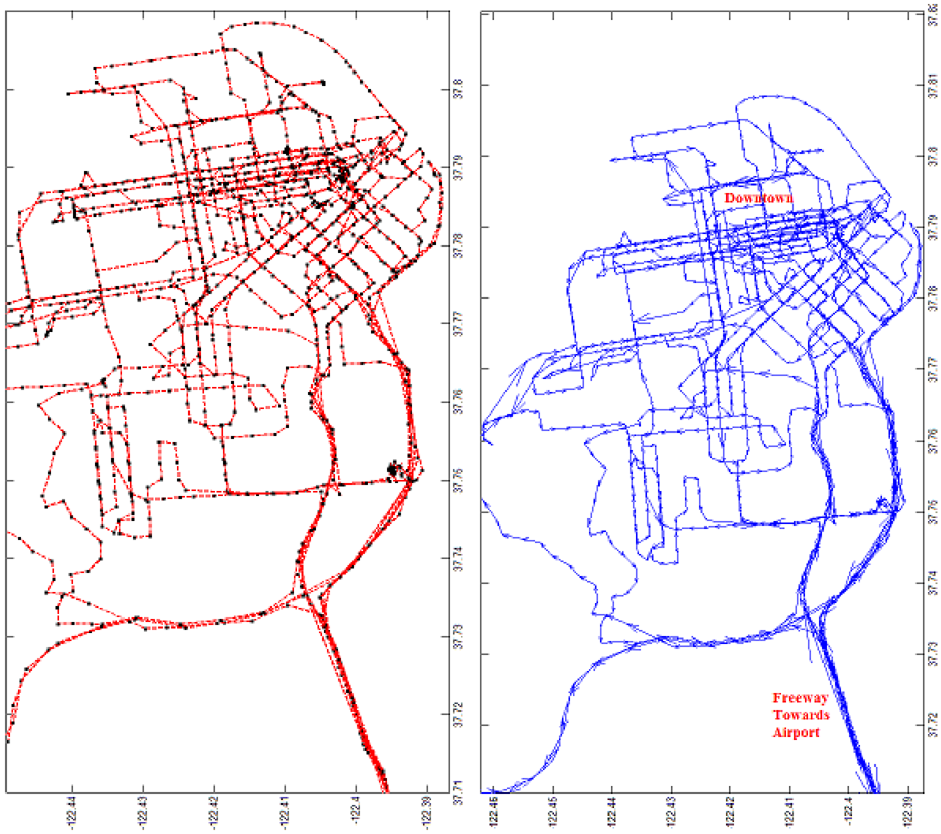

Figure 3.3: (a) Spatial distribution of trace locations for a single taxi cab over 24 hours (b) Instantaneous direction of mobility and velocity

which is close enough to derive the direction of the movement. Within the downtown area the gap is mostly less than 100 meter due to slow traffic, whereas in the freeways these trace points are more than 1 km apart. The maximum distance found between two trace points was 1.79 km. The average time gap between two trace records wascalculated about 43.34 sec.

3.4.3 Passenger Trip Duration and Driver's Cruise Time

Table 1 shows the frequency distribution of passenger trip duration over one month where almost 48% trips take less than 10 minutes and about 4% trips take above an hour. Table 2 shows the frequency distribution of driver's empty cruise time which is defined as the time gap between consecutive drop off and pickup event. The statistics shows that almost more than half of the times drivers manage to get another passenger within 10 minutes of previous drop off.

Table 3.1: Frequency Distribution of Passenger Trip Duration

Trip Duration	Frequency	Cumulative %
5	97821	21.33
10	122133	47.97
15	77198	64.80
20	49753	75.65
25	33318	82.92
30	20794	87.45
35	13436	90.38
40	9035	92.35
45	6374	93.74
50	4689	94.76
55	3562	95.54
60	2695	96.13
More	17754	100.00

Table 3.2: Frequency Distribution of Cruise time

Cruise Time	Frequency	Cumulative %
5	124765	36.75
10	65519	56.05
15	36944	66.94
20	24861	74.26
25	17247	79.34
30	11797	82.82
35	8318	85.27
40	6216	87.10
45	4908	88.54
50	3892	89.69
55	3206	90.64
60	2827	91.47
More	28961	100.00

3.4.4 Passenger pickup and drop off locations

Figure 3.4 describes the frequency distribution of pickup and drop off over the whole month. Vertical axis shows number of pickup and drop offs in the geographical location. Frequency of pickup and drop off is much higher in downtown and airport area than residential area. Figure 3.5 shows the spatial distribution of pickup locations where a single red dot corresponds to a single pickup incident. Figure 3.5 is initially plotted using MATLAB on white background and then superimposing on Google Map.

3.5 Analysis of Wireless Connectivity

This section describes some of the features of wireless connectivity and network partitioning analyzed from the GPS traces using our own algorithm. We have used both short term and long term analysis to investigate some of the dynamic properties of VANET. Before presenting the results, we introduce the notion of Degree of Connectivity and network partitioning. Then we describe the algorithm to determine the k-hop connectivity and network partitioning.

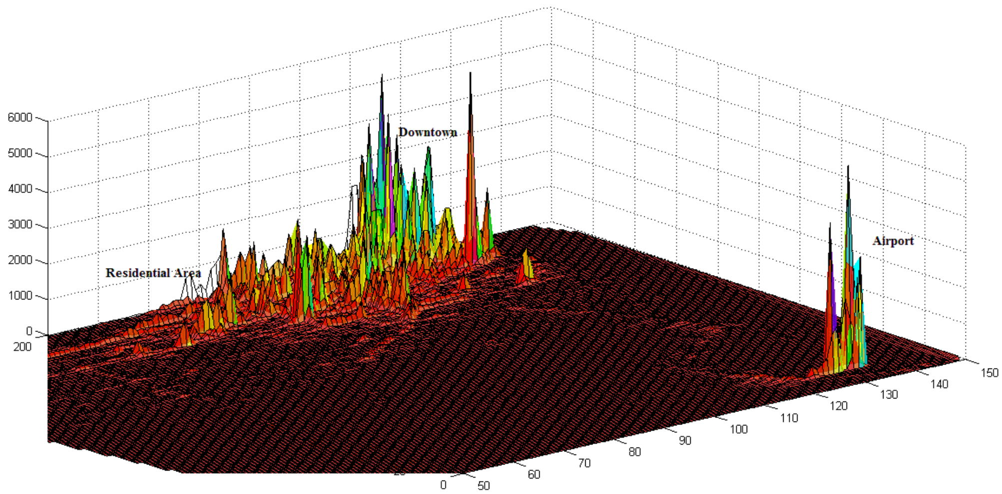

Figure 3.4: Frequency Distribution of passenger pickup and drop off locations

3.5.1 Degree of Connectivity

We define the Degree of Connectivity (DoC) as the total number of nodes reachable from a particular node via any wireless path not longer than a given number(k) of hops. The Average Degree of Connectivity (ADoC) is the metric that characterizes the reachability of any random node with the network. Mathematically, ADoC specifies the average number of reachable nodes from a single source within a given path length.Hence, ADoC of a vehicular network with n nodes is defined by,

$$ADoC = \frac{\sum_{i=0}^{n} DoC}{n} \tag{3.3}$$

3.5.2 Network Partitioning

We define the Network Partition as a connected component where any node can communicate with another node in the component through multi-hop communication. In other words, we can say that, there exists at least one path from any particular node to each of the other nodes within a partition or connected component. Obviously, the path length can

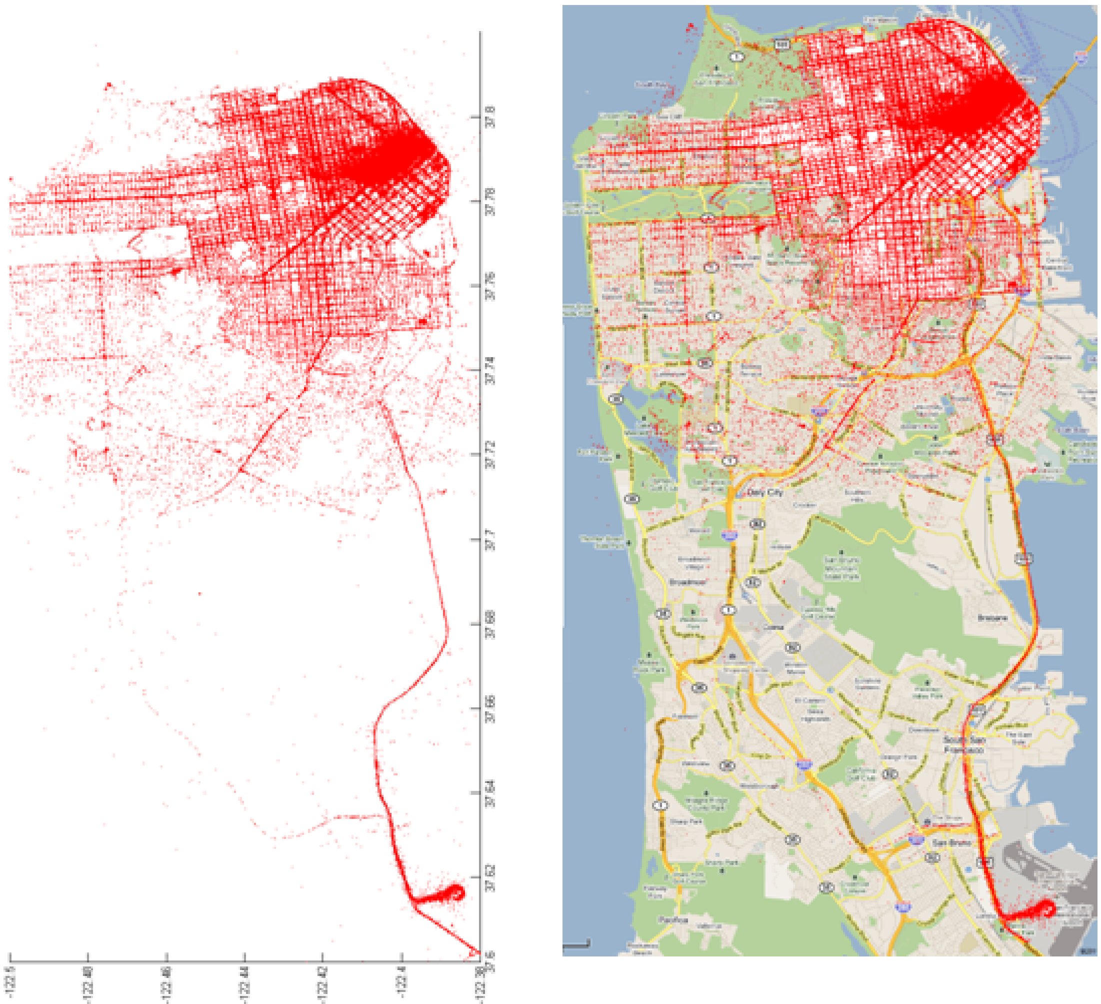

Figure 3.5: Spatial distribution of taxi hotspots

never exceed the total number of nodes in that component. The size of the partition is determined by number of nodes in that partition. If the entire topology is connected, we get only one partition within the network. On the other hand, if any node is totally isolated from other nodes, this will be a partition of size one. Less number of partitions will lead to better connectivity and information dissemination.

3.5.3 Algorithm for determining Degree of Connectivity (DoC) for k-hops

1. Process input raw trace files into a data structure containing all node information.
   Data structure, *Nodes= Get_Input (Trace file directory);*

2. Calculate the node positions for a given timestamp from the data structure using interpolation method.
   Node position vector, *L=Node_pos(Nodes, Timestamp);*

3. Determine adjacency matrix from the node position vector for a specific transmission range.
   Adjacency Matrix, *M=AdjMatrix(L, TX_Range);*

4. Determine the k-hop reachability matrix, M^k from adjacency matrix, M.
   k-hop Transitive Closure, $M^k = \prod_{j=1}^{k} M^j$;

5. Compute the k-hop degree of connectivity (k-hop reachability), DoC^k from M^k.
   DoC^k for node i, $(DoC_i)^k = \sum_{j=1}^{|V|} M^k(i,j) - 1$

3.5.4 Description of the algorithm

Step 1: Processing raw input

The GPS traces are organized into a set of ASCII text files, where each file corresponds to a single taxi cab. Each file contains different number of trace records with variable sampling

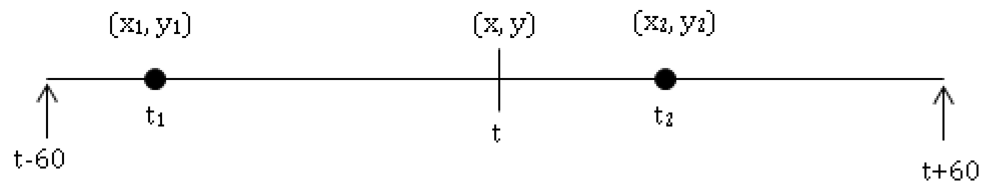

Figure 3.6: Interpolation of two sample points

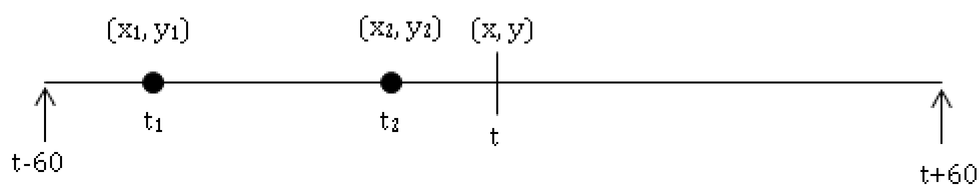

Figure 3.7: Extrapolation of two sample points

frequency of broadcasting GPS data to the central repository. Each trace record comprises of several fields of data separated by a delimiter. The function Get_Input(Trace file directory) extracts each individual record from the directory of trace files and stores them into a data structure of nodes, where each node represents a taxi cab.

Step 2: Determining node position vector

This step calculates the individual geographical positions (Latitude, Longitude) of each node for a specific time of interest. As the nodes generate traces randomly with an average sampling rate of around 30 seconds or less, we use a method of interpolating the closest samples to find the approximate position of the node at the specific time of experiment. We check for the samples one minute backward and forward and depending on the available samples we take the average of different interpolated and extrapolated values. Below we mention the possible different cases:

Case 1: In case, two samples are available during the total interval of 2 minutes, as shown in figure 3.6 and 3.7, we compute the interpolated (if two sample points are located

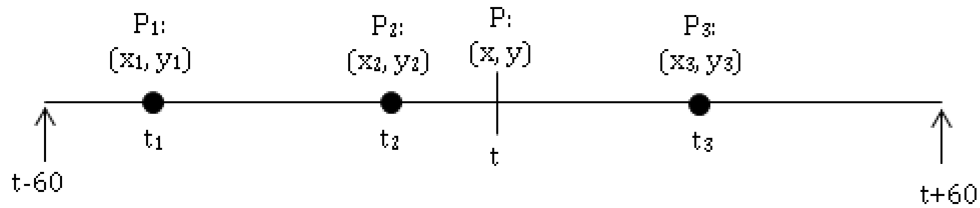

Figure 3.8: Calculating average position from more than two sample points

in opposite side of the experimental timestamp) or extrapolated (if two sample points are located in same side of the experimental timestamp)position using the below formula:

$$x = \frac{x_2 - x_1}{t_2 - t_1} t - t_1 \tag{3.4}$$

$$y = \frac{y_2 - y_1}{t_2 - t_1} t - t_1 \tag{3.5}$$

Case 2: If more than 2 samples are available within the interval (figure 3.8), we calculate the average of the different interpolation/extrapolation position acquired from several pairs of points. For example, in the above scenario where we have three consecutive point P1, P2 and P3, we calculate the position of P by:

1. interpolating P1 and P3;
2. interpolating P2 and P3 and
3. extrapolating P1 and P2

Finally we take the average of the three values to minimize the error probability in the approximation.

Case 3: In case, less than two samples are available during the total interval of 2 minutes, we extend the sample searching interval in either or both direction to get at least one sample point in either direction from the experimental timestamp t.

```
Procedure AdjMatrix (Node position vector(L), TX_Range(R))

n=|V|;
for i=1 to n-1
        for j=i+1 to n
                if (GeoDistance(L_i, L_j) ≤ R)
                        M[i][j] =  M[j][i] = 1;
                else
                        M[i][j] =  M[j][i] = 0;
return M;
```

Figure 3.9: Algorithm for determining adjacent matrix

Step 3: Determining the Adjacency Matrix

In this step, we determine the adjacency matrix of the nodes from the node position vector and a specified transmission range. For our analysis of determining the k-hop reachability, we just consider the connectivity issue ignoring the actual physical distance as we are not determining the best routing path between two nodes; rather we are determining the existence of a path between two nodes. Hence we only manipulate a binary matrix in each of the step henceforth. Figure 3.9 describes the algorithm for determining the binary adjacent matrix. From the algorithm, we can see the loop executes $\frac{n(n-1)}{2}$ times. Hence, the time complexity of determining the adjacency matrix is $O(|V|^2)$. While calculating the geographical distance between two node-positions, we consider the spherical cosine law which gives an accuracy within 1 meter. Also, as we are considering undirected graph, so $M[i][j] = M[j][i]$.

Step 4: Determining the k-hop reachability matrix

We get the k-hop reachability matrix, $M^k = \prod_{j=1}^{k} M^j$. For each of the matrix multiplications, normally it would require $O(V^3)$ operations. So for k-1 multiplications required to determine M^k, in the worst case it would require $O(kV^3)$. But our algorithm reduces the number of operation in several steps that can minimize the average complexity from typical matrix multiplication. Below we discuss the step by step complexity reduction for the matrix

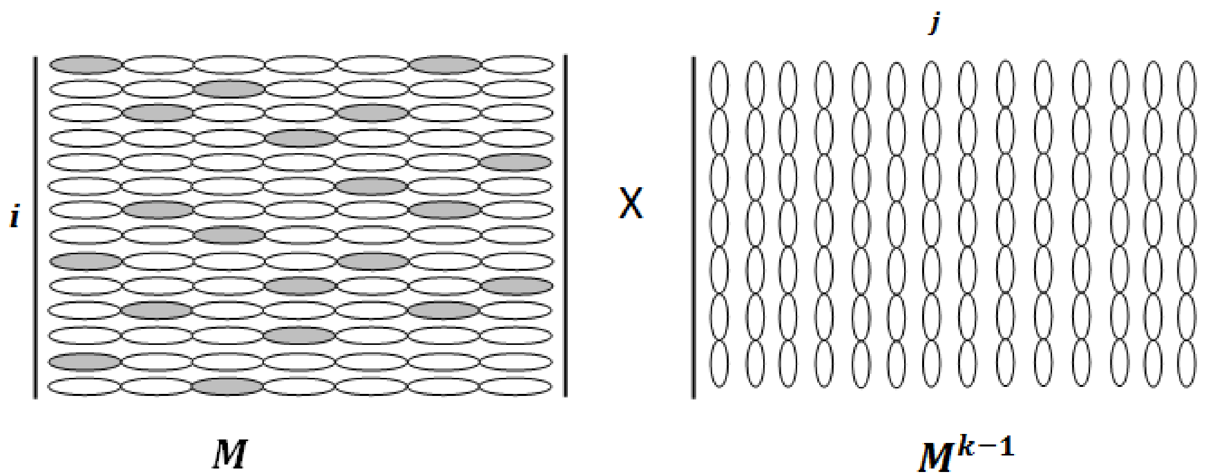

Figure 3.10: Algorithm for bitwise matrix multiplication

multiplication:

1. As the matrix is a Boolean matrix, we can use logical operation AND instead of multiplying two integers. As processors can execute logical operation faster than multiplication this reduces the hardware time consumption.

2. Instead of considering each elements as a single integer value, we use 32-bit integers to represent 32 consecutive Boolean elements of the matrix in a row. This makes the space complexity of the matrix reduce by a factor of 32. For 64-bit integers, the space requirement reduces by a factor of 64. Moreover, a single bitwise AND operation of two 32-bit integers can now be equivalent to previous 32 logical AND operations. Hence, considering blocks of size b reduces both space and time complexity by a factor of b.

3. We use a data structure to keep track of those bit-blocks in matrix M which have at least 1 bit set within the 32 bits. With the help of this data structure, we only manipulate with non-zero bit blocks. This means the number of blocks for manipulation would be at most $|E|$, where $|E|$ is the total number of direct links (or edges) in the topology. In practice, this number would be much less than $|E|$, because many of those

blocks would have more than one bits set, as it is very unlikely that all the bits that are set would be distributed over distinct blocks. In the worst case, this number of non-zero bit-blocks in M would be equal to $|E|$ where as in best case this would be $|V|$ as each node would have at least one bit set due to self connectivity. In the figure 3.10, we represent the shaded blocks as valid blocks for manipulation.

4. Likewise, instead of manipulating each of the valid blocks of M with $|V|$ columns of M^{k-1}, we keep track of the altered blocks of M^{k-1} from previous steps using another data structure, which practically discards many of the blocks from consideration in the current step, in a sparsely connected network.

5. Further, if there are several valid blocks in a row i of M, we manipulate with column j of M^{k-1} until we get the first non-zero block after AND operation. This means we can determine the element (i,j) of M^k whenever we get a non-zero result from AND operation. This also implies that, in best case there will be only $O(V^2)$ operation needed for one multiplication step.

Step 5: Computing DoC for k-hops

Using the following simple calculation, the k-hop degree of connectivity can be determined for each node. DoC^k for node i,

$$DoC_i{}^k = \sum_{j=1}^{|V|} M^k(i,j) - 1$$

Hence, the average DoC for the network with maximum k-hops =

$$\frac{\sum_{j=1}^{|V|} DoC_i{}^k}{|V|}$$

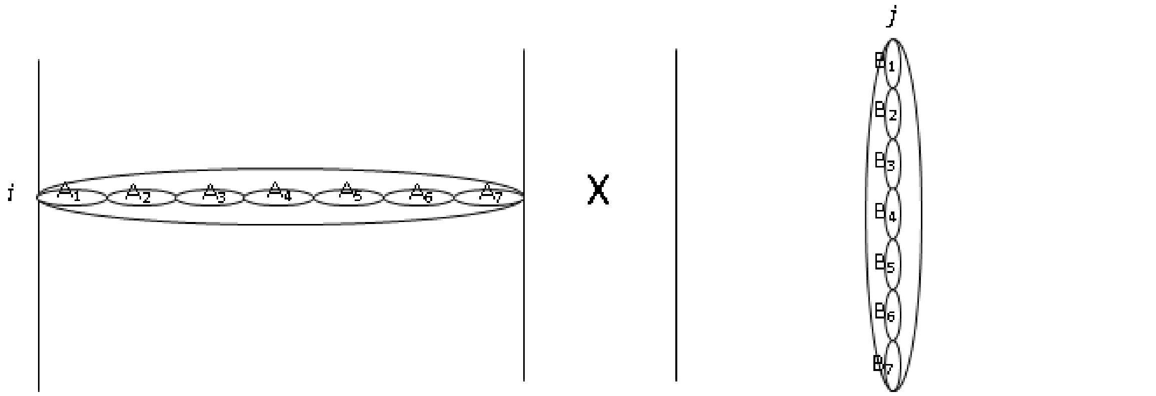

Figure 3.11: Matrix Multiplication

3.5.5 Complexity analysis

In general, the total number of operations required to compute one element $M^k(i,j)$ in the matrix product M^k is as follows (figure 3.11):

Number of operations to compute $M^k(i,j) = \sum$ Number of non-zero blocks in row i of M + $\sum$ Number of altered blocks in column j of $M^{k-1} = {N_i}^r + {N_j}^c$

Considering all rows of M, $N^r = \sum_{i=1}^{|V|} {N_i}^r$

where, N^r is bounded by $|V| \leq N^r \leq |E|$.

Again, considering all columns of M^{k-1}, $N^c = \sum_{j=1}^{|V|} {N_j}^c$

where, N^c is bounded by $0 \leq N^c \leq (DoC^{k-1} - DoC^{k-2})$

Hence, the total number of operations required to complete the product matrix in each step is $= N \times (N^r + N^c)$

where, $N = \frac{|V|}{b}$

Therefore, the total number of operations required to compute $M^k = (k-1) \times N \times (N^r + N^c)$

In our analysis, we are basically interested to observe the connectivity up to a certain number of hops (less than 30). Therefore, considering k as a small constant value we can see that the best case complexity to find M^k is $O(V^2)$ and the worst case would be $O(V(V+E))$.

3.5.6 Determining Network Partitions

The steps of determining the network partition is very much similar to determining the k-hop transitive closure. The only thing is to find the minimum k for which $M^{k+1} = M^k$. At that point, M^k will give the full transitive closure of the topology. This minimum value of k, which we define as *Cutoff Hop*, can be a very important property of the wireless network because it determines the exact point when the degree of connectivity for the network gets saturated. After achieving this saturation point, no more nodes can be reached by any node even if the hop number is arbitrarily increased. This cutoff hop also determines the steepness of the curve that reflects the rate of DoC change with respect to hop increase. In order to get the partition information from the full transitive closure, M^k, we extract the rows from the matrix where the total number of distinct row pattern gives the total number of partition and the arithmatic sum of the corresponding row will give the size of the partition. This algorithm of determining the network partition is a novel approach.

3.6 Results of Spatio-Temporal Analysis of Traces

In this section, we describe some of the key findings of our GPS based trace analysis to determine the probability of seamless connectivity within the taxi fleet. First we consider a node positioning scenario that corresponds to a particular time. Then we attempt to explore the time varying characteristics of the connectivity. Figure 3.12 describes the geographical node positioning of taxi cabs (as observed from sattelite) at a random experiental time for which we analyzed the V2V connectivity. The experimental time chosen for this snapshot was at 2:30 pm on June 5, 2008 which was a working day.

3.6.1 Average Degree of Connectivity for a specific time

Figure 3.13 depicts the impact of transmission range and hop on average degree of connectivity for the mobile taxi network at a specific time (2:30 pm) on a working day.It is

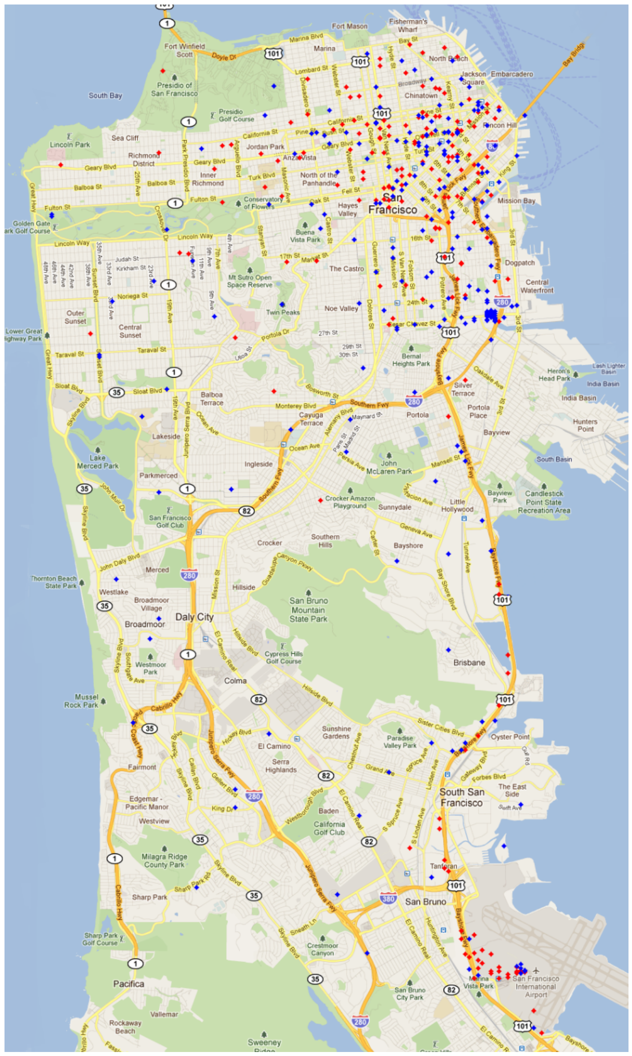

Figure 3.12: Taxi Node Positions at a particular experimental time

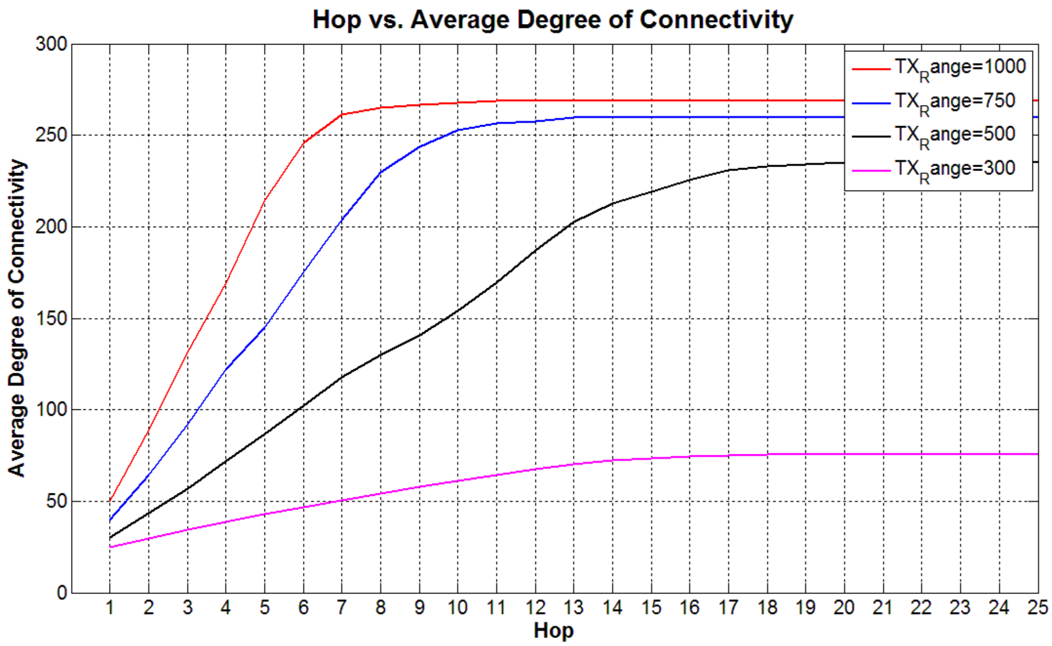

Figure 3.13: Impact of path length and transmission range on ADoC

obvious that, increasing the wireless transmission range will have a significant impact on the Degree of Connectivity. The ADoC graph shown here corresponds to the snapshot of the whole taxi fleet at the said experimental time (Figure 3.12).

From figure 3.13, it can be clearly observed that the average degree of connectivity is minimum for single hop connection, while longer transmission range corresponds to higher degree of connectivity. As we gradually increase the path length (hop count), more and more source-destination pairs become reachable via multi-hop communication which ultimately increases the ADoC of the network. All the curves show a near-linear rate of connectivity increase with the increment of path length up to a certain point when the curve becomes horizontal. This corresponds to the state when no more nodes can be explored with further hop increase. We refer this point as the saturation point. However, the slope of the curve depends on the transmission range, which implies that the longer the range the less number

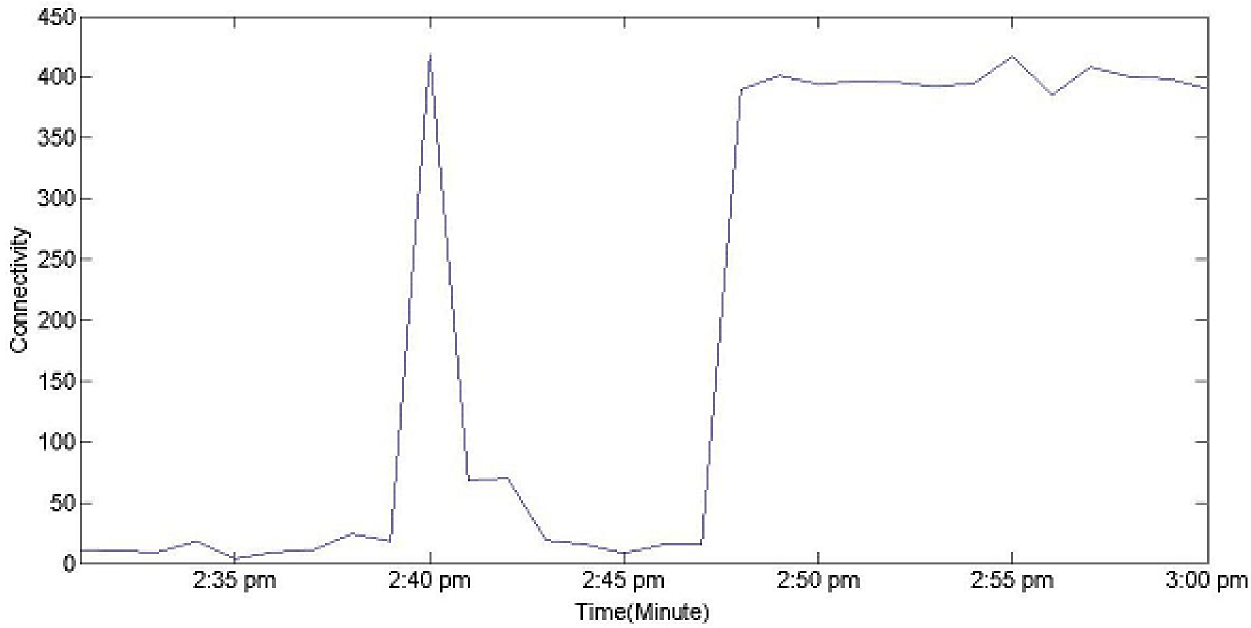

Figure 3.14: Change of Connectivity with respect to time for an individual node.

of hops are required to achieve maximum possible connectivity. The ADoC of a network after saturation indicates the portion of the fleet that can be reached from an arbitrary source node using multi-hop communication. The graph can also describe the percentage of the wireless coverage after a specific number of hops for any transmission range which may provide an estimate for the QoS provisioning of delay-sensitive applications.

3.6.2 Change of Connectivity with Time

In this subsection, we will show the variation of V2V connectivity with respect to time. For that, we have considered two different span of intervals, one is relatively short span which is the variation within 30 minutes and another is relatively long spanning over the whole day.

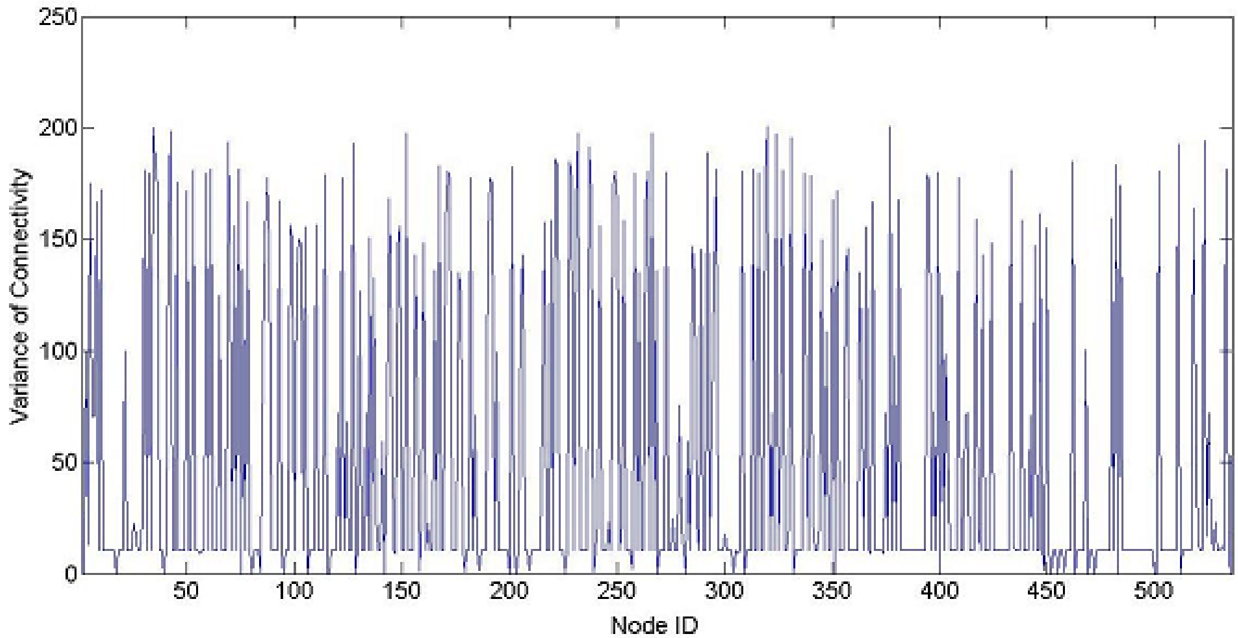

Figure 3.15: Variance of Connectivity for all the 536 nodes within half an hour

Short Duration(30 Minute)

In this case, we took a total of 30 sample snapshots within a half an hour duration, where the time difference between each successive snapshot is one minute. The selected time is from 2:30 pm to 3:00 pm on a business day. First we plot the change of connectivity from the perspective of a single node. Figure 3.14 shows the change of connectivity for a random node with a transmission range of 300m restricted by a maximum path length of 25 hops. This gives an idea about the rapid fluctuation of V2V connectivity for an individual node.

If we measure the standard deviation of connectivity change within this 30 minute interval for all the 536 nodes, we get an irregular scenario as described by Figure 3.15. Here many of the nodes have high variance of connectivity while some others have less variance.

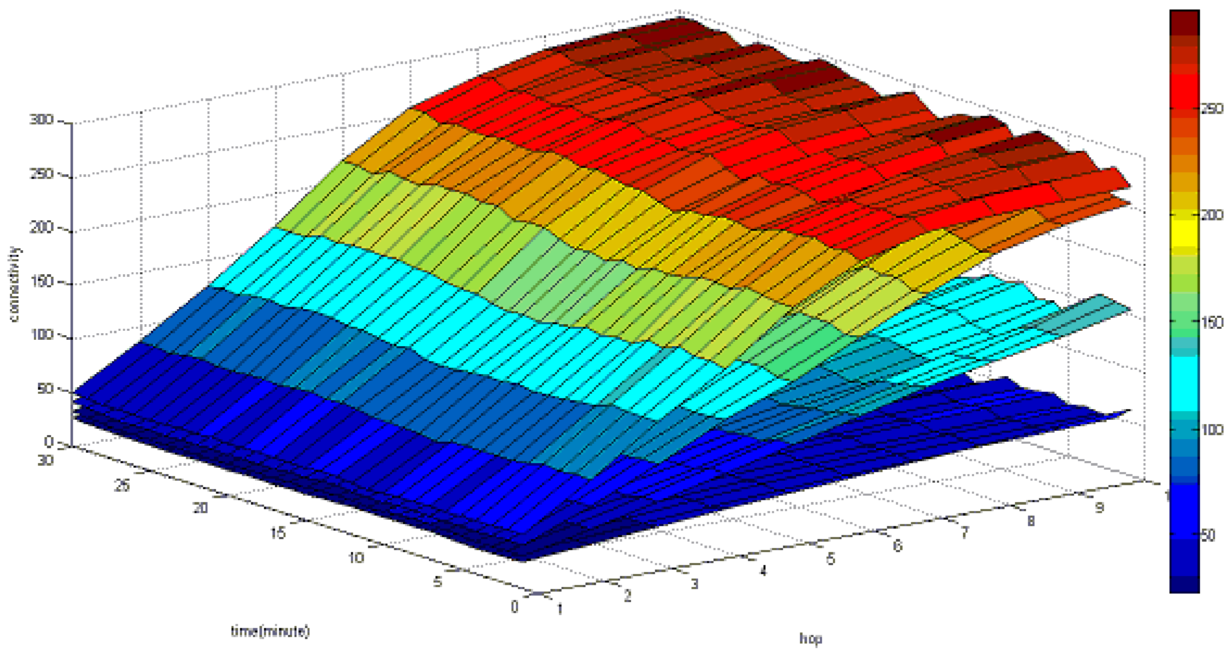

Figure 3.16: Change of Average Connectivity with respect to time for different TX ranges.

On the other hand, Figure 3.16 shows the change of average connectivity with respect to time for different transmission ranges. This figure is a 3D projection of figure 3.13 where the topmost layer corresponds to transmission range of 1000m and the bottommost layer represents the shortest transmission range of 300m. From this figure, it can be observed that within a short span of time, the change of average connectivity is not significant even though a vehicle can move away more than a mile in the freeways within a minute. Even if the connectivity of individual node is varying a lot but when we take the average over all nodes it remains almost constant. The reason behind this phenomena is because, some cabs may lose connectivity while traveling out of the downtown or airport area while other cabs get connected when they get near a dense area. The bottom line is the average change of connectivity over the whole fleet almost remains stable within a short duration interval.

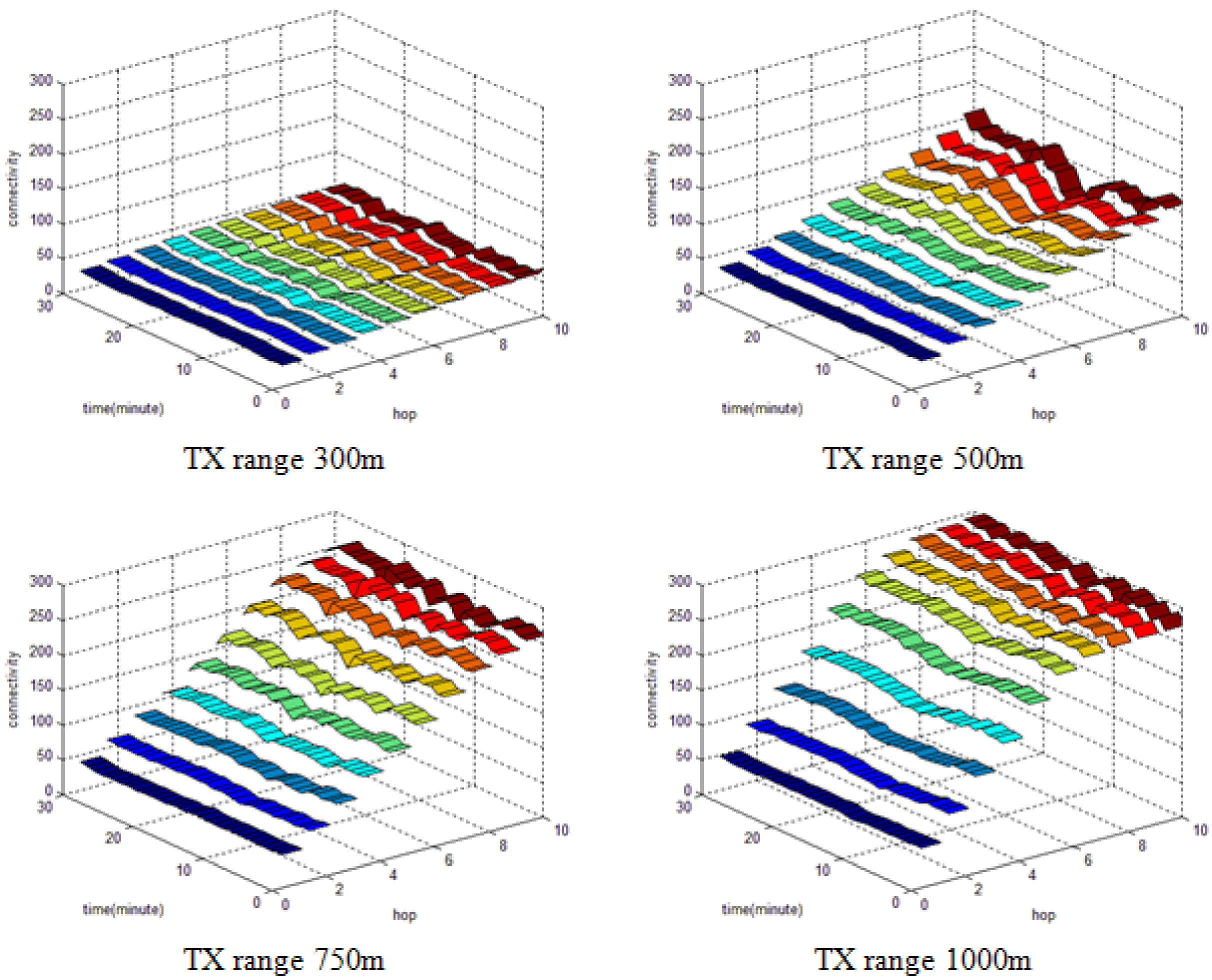

Figure 3.17: Change of Average Connectivity with respect to hop for different TX ranges

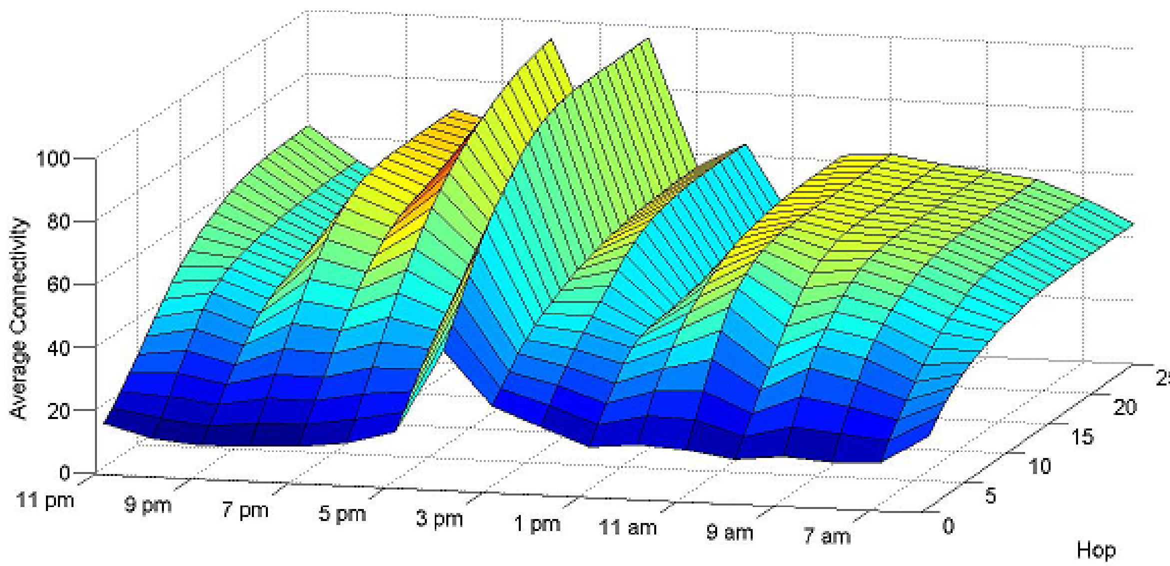

Figure 3.18: Change of Average Connectivity with respect to time for 300m TX range

Figure 3.17 describes a little bit more details of the above figure, where we can closely observe the change of average connectivity for each different transmission range and also measure the variation of connectivity with respect to time and hops. Each of the ribbons (stripes) correspond to a particular hop number which restricts the total path length within that number of hop.

LongDuration (Whole Day)

In contrast with the short interval, a long duration average connectivity analysis results into reasonable fluctuation over the course of a day. This is quite natural because the fleet is not entirely utilized evenly throughout the day and also because of the impact of rush hours. From Figure 3.18 and 3.19, we can easily observe that the maximum average connectivity is achieved during the afternoon and evening rush hours (4 pm and 6 pm). At this time most of the cabs can be found within the vicinity of downtown area for after office trips. For the transmission range, we considered a range of 300 m due to the reason that, in downtown

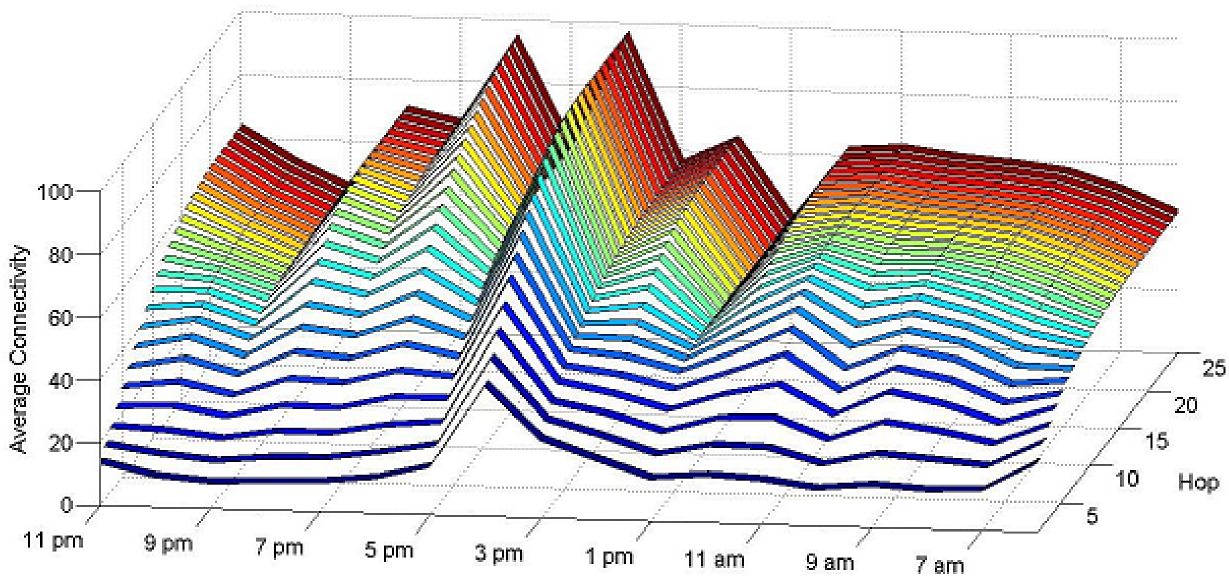

Figure 3.19: Change of Average Connectivity with respect to hop for 300m TX range

area it might not be possible to reach too far because of the obstacles of high rise buildings and skyscrapers.

3.6.3 Network Partitioning Results at a Specific Timestamp

We attempt to identify the network partitions of the whole fleet of cabs based on the instantaneous positions at a certain time. Using the same topology snapshot as the previously analysis, the mobile taxi nodes distributed all across the city of San Francisco can be partitioned into various partitions based on their wireless connectivity between other nodes. For a specific transmission range of 300m, it was found that, out of total 536 nodes, more than 20 percent of the nodes were isolated or disconnected from any other node. 16 partitions were found having 2 nodes and 9 with 3 nodes. The largest partitions found included 155 nodes, which is located in the downtown area. The second largest partition with 120 nodes was found in the airport vicinity.Table 3.6.3 shows the distribution of nodes in various sizes of partitions for 300m transmission range

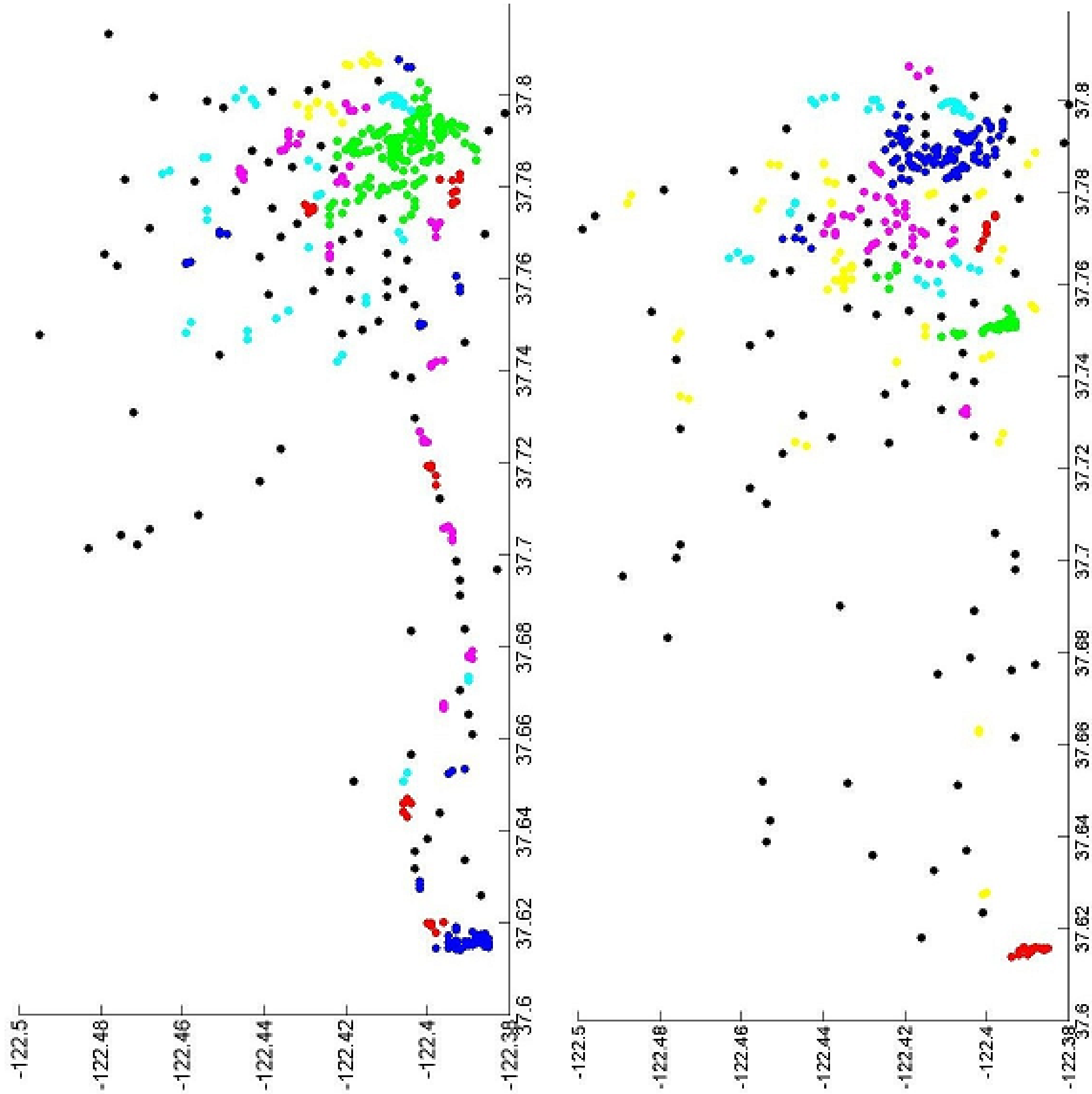

Figure 3.20: Change of Network Partitions with respect to time. The left figure corresponds to noon (12 PM) and the right corresponds to midnight (12 AM).

Table 3.3: Partitioning of Nodes for 300 Meter TX Range

Partition Size (# of nodes)	Number of Partitions	Total Nodes
1	110	110
2	16	32
3	9	27
4	1	4
5	3	15
6	1	6
11	1	11
22	1	22
34	1	34
120	1	120
155	1	155
Total	145	536

3.6.4 Change of Partitioning over Time

In order to capture the change of partitions over time we took two samples-one during mid-day (Figure 3.20 - Left) and another at mid-night (Figure 3.20 - Right). The nodes with the same color belongs to the same connected component or partition. In both the two parts of the figure, black dots represent isolated nodes that are not connected with any other node. If the plots are superimposed on the map of San Francisco, we can see that during the night the taxis are more scattered in the suburban area than during the daytime when taxis concentrate near the downtown or airport area. The dense upper right portion corresponds to the downtown area and the bottom cluster corresponds to airport.

3.6.5 Change of Partitioning with Transmission Range

As the Degree of Connectivity varies along with transmission range, the partitioning also changes. Table 3.6.4 shows the distribution of nodes in different sizes of partitions for different transmission ranges. It is quite natural that, the number of isolated nodes (partitions with size 1) decreases as the transmission range increases. Also the total number

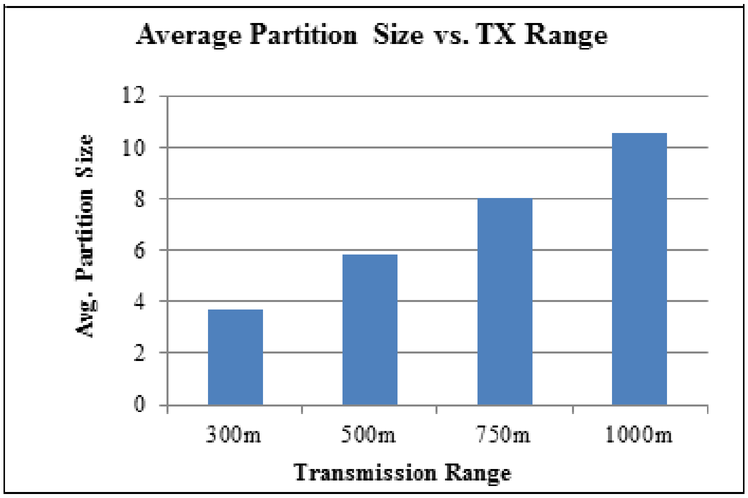

Figure 3.21: Average size of partitions for different transmission ranges

of connected components is reduced at the same time. Figure 3.21 shows the average size of partitions for different transmission ranges. The average partition size is less than 4 in case of 300m range whereas in case of 1000m it goes above 10.

Figure 3.22 shows the difference between two partitioning results for the same time with different transmission range. On the left, due to a transmission range of 1000m, we have very large partitions which almost connects the whole city. On the right, due to shorter transmission range of 300m, we can see lot of smaller partitions for the same node positions. Both the plots correspond to time of 11 AM for a business day.

3.6.6 Dimension of Largest Connected Component

Figures 3.23 and 3.24 show the comparison of partition size for the largest connected component in two different transmission range. For a range of 300m, the largest connected component within the taxi network consist of 150 to 200 nodes on the average. Whereas in case of 1000m transmission range, we can see bigger partition with around 400 nodes in the largest partition.

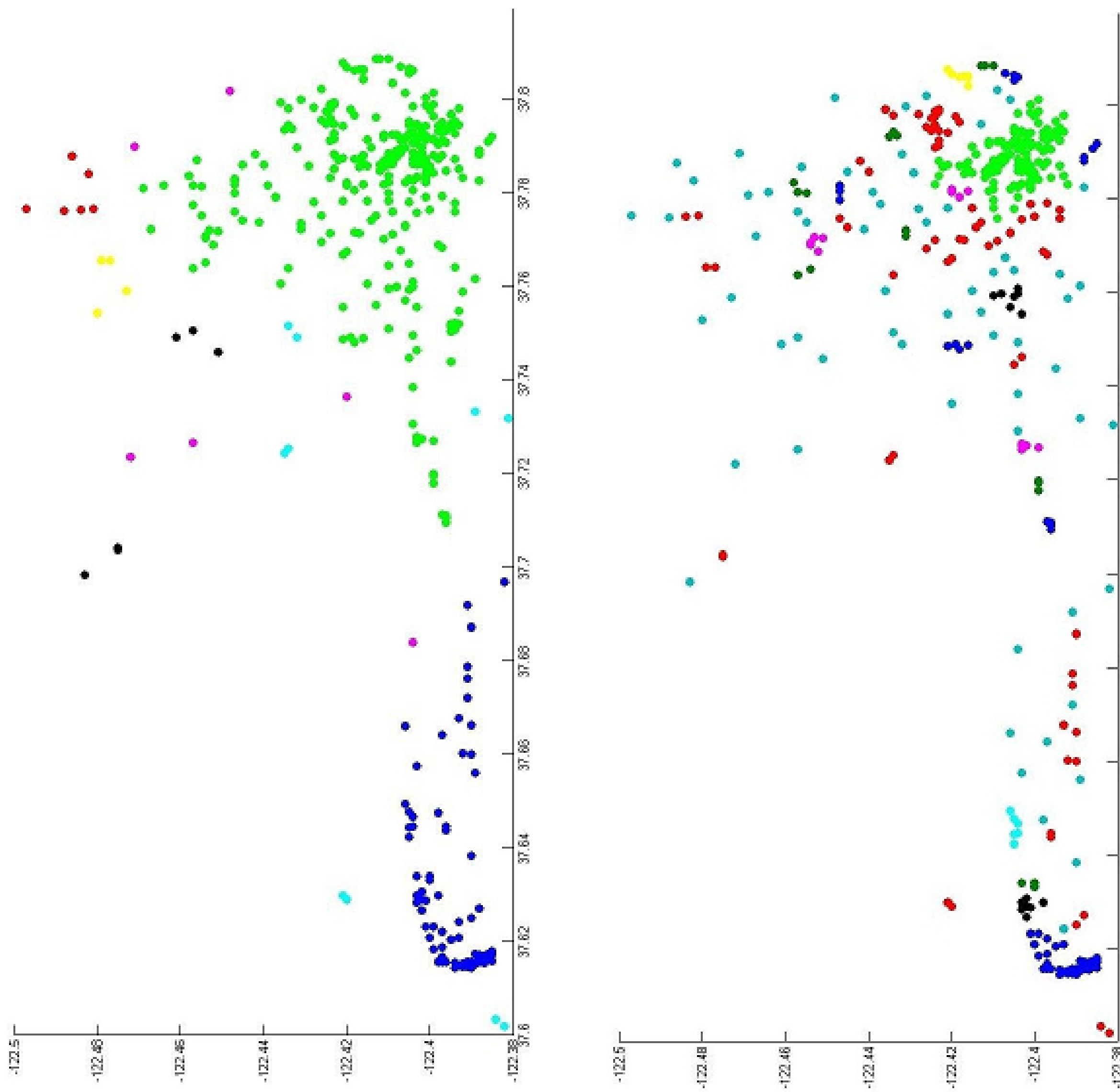

Figure 3.22: Change of Network Partitions with respect to transmission range. The left figure corresponds to a TX range of 1000m and the right corresponds to 300m.

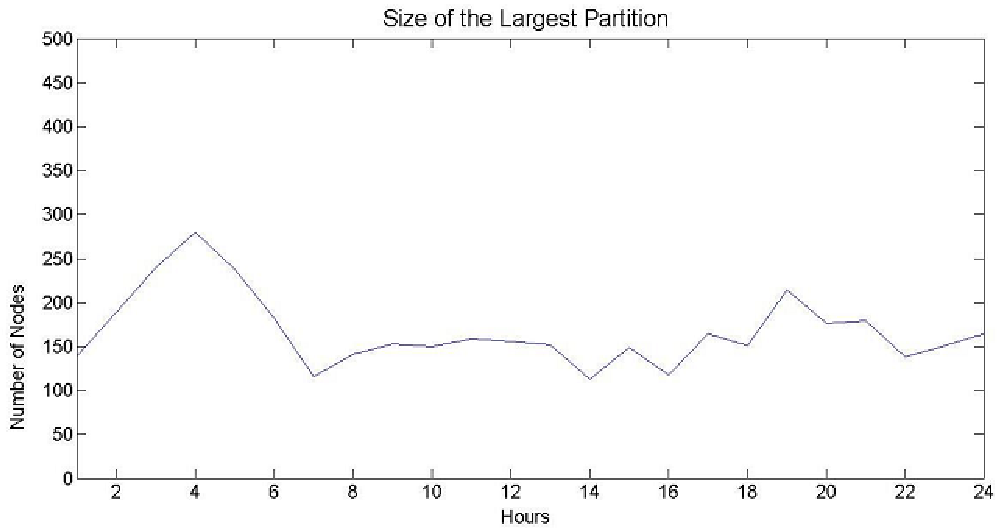

Figure 3.23: Sizeof the largest partition for 300m transmission range.

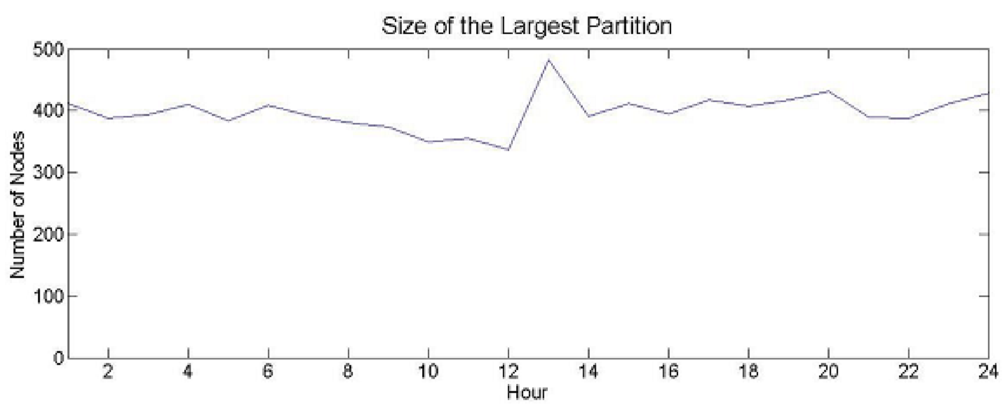

Figure 3.24: Sizeof the largest partition for 1000m transmission range

Table 3.4: Number of Partitions for Different Transmission Ranges

Partition Size	Number of Partitions			
	300m	500m	750m	1000m
1	110	69	46	31
2	16	11	10	10
3	9	7	3	1
4	1	1	2	1
5	3	0	0	1
6 to 10	1	1	3	3
11 to 20	1	0	0	1
21 to 30	1	1	1	1
31 to 50	1	1	1	1
51 to 100	0	0	0	0
101 to 150	1	0	0	0
151 to 350	1	0	0	0
350+	0	1	1	1
Total	145	92	67	51

3.7 Conclusion

The chapter presents a spatio-temporal analysis of multi-hop V2V connectivity and network partitioning along with the investigation of urban taxi mobility pattern with velocity profile, spatial distribution of hotspots and other characteristics like trip duration, empty cruise interval etc. Our results show that, on an average more than 70% vehicles can be communicated using multihop vehicular commmunication with reasonable transmission range in an urban environment . The analytical data presented in this chapter revealed many new and useful features that can be helpful for wireless researchers, government organizations, taxi companies and even for the drivers or passengers. Our future work will explore the clustering feature of mobility for V2V communications and for DSRC infrastructure configurations.

Chapter 4

Taxi Hailing System Using V2X Communication

4.1 Introduction

Taxis play an invaluable role in urban transportation. According to the NYC Taxi cab fact book [104], on an average 470,000 trips are made by thirteen thousand yellow cabs per day in New York City, carrying nearly 241 million passengers annually. This numerical figure is even exceeded in some other major metropolitan cities across the globe. In Singapore city, the total number of taxi cabs, by the end of 2010, was 26,073 [105] making around 600,000 trips per day. These statistics prove the invaluable role of taxi cabs in urban life. In many cases, people can prefer a taxi than cheaper options like public transit. However, it is also well-perceived that finding a taxi sometimes can be cumbersome, mostly during the busy hours, or unpopular places. In those cases, the passengers often get delayed by long waiting period in searching for a taxi.

Street hailing was the only option for reserving a taxi until the early eighties of the last century before the introduction of radio paging system in the taxi industry. With the advancement of wireless communication technology, the taxi reservation system has evolved to provide flexibility and ease of booking to the customers as well as optimizing the dispatching procedure with the aid of automated systems. Today, frequent urban travelers need not bother standing beside the road under the hot sun or in rainy weather trying to hail a cab or wait for long periods during rush hour. Having a taxi at the doorstep could be now a matter of few clicks or just a call away. The computer aided dispatching systems in the industry

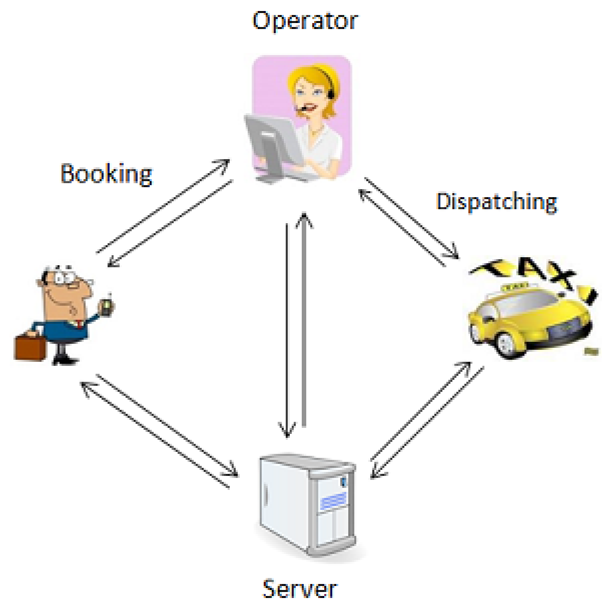

Figure 4.1: Typical Taxi Reservation Procedure

have revolutionized mobility in an urban setting.

In general, a complete taxi reservation procedure includes two sub-processes: the booking process and the dispatching process (see Figure 4.1).

Booking refers to the sequence of communication that occurs between the customer and the intermediate entity. This intermediate entity can be either an operator or a server machine that interacts with the customer electronically. There are a number of possible ways that a customer can communicate with the intermediate entity. Dispatching refers to the act of assigning the appropriate taxi cab to the requested job. The operator or the automated server, upon receiving the service request, selects an available taxi cab out of many possible options and then notifies the driver about the job assignment. This selection procedure can involve many criteria, such as geographical location, empty cruise time, distance from the pickup point, etc. Taxi companies currently use a number of selection strategies for dispatching the best taxi cab for maximum customer satisfaction as well as minimum cost overhead.

This chapter summarizes the existing computer aided taxi booking and dispatching systems that are currently implemented in the industry as well as proposed in literature. Our goal is to point to new opportunities emerging from recent advances in wireless technologies. Such opportunities include using DSRC technology, a technology that is highly promoted by US Department of Transportation (DOT) and technically supported by IEEE and FCC. The survey classifies the existing systems in terms of their underlying communication technologies and also discusses from the perspective of different implementation issues associated with booking and dispatching processes. Especially we believe booking and dispatching methods influence greatly on the performance of a system when measured by the users. We dedicate Section 4.4 for comparative analysis on the advantages and disadvantages of some of the existing booking methods and dispatching strategies. The analysis also motivates the use of the DSRC technology for the advantages it will bring to the taxi applications. In this regard, we propose a novel taxi hailing application using DSRC technology. Based on the primary results obtained from real world GPS traces, it can be predicted that, our proposed system can significantly increase the availability of taxi cabs while reducing the wait time for the passenger. At the same time, from the perspective of a taxi driver, it can reduce the cruising time and increase daily trip count and eventually help increase the revenue of the taxi company. This system can make a revolutionary change in the day today urban life, particularly for the crowded metropolitan cities around the world where people spend several exhaustive hours in transportation to and from work places. Our system can reduce the transportation overhead for city people and help them spare more time and efforts in productivity.

The rest of the chapter is organized as follows. Section 4.2 describes the evolution of wireless technologies in taxi dispatching. Section 4.3 gives an overview of the selected existing taxi reservation systems. At the end of section 4.3, we compare some of the technical features of these automated systems. Features that impact the performances of automated taxi reservation systems are described in section 4.4. Starting from section 4.5 we describe our innovative solution of DSRC based Taxi Hailing System and all the technical details about the underlying proposed communication protocol.

4.2 Evolution of Wireless Technologies in Taxi Dispatching

4.2.1 Radio- paging System

By incorporating radio technology, taxi companies were able to manage their vehicles more efficiently and provide better service than street hailing. During the eighties, the concept of phone reservation for taxi services started to develop within the frequently traveling people [125]. People could hail a taxi by phone, and the central operator notified a driver over the radio. Drivers installed a radio receiver and intercom in the car, and they could contact everyone in the network. This equipment was inexpensive and could be easily set up, and as a result, it is still used by many taxi companies. However, the radio paging system had many problems that brought the necessity of better communication technology to handle the dispatching operation. For example, the job allocation was done on the basis of "first come first serve." The earliest bidder got the job even though the pick-up location was far away from the taxi's current location. Also, the central operator was not aware of the exact location of the taxi due to not having GPS facility which led to inaccurate estimation of arrival time

4.2.2 Cellular Network

This is the most widely used technology in the existing taxi industry. Many of the current booking and dispatching systems use the cellular network for communication between customer, central server and taxi driver. Cellular technologies of different generations are utilized in the industry particularly for the dispatching process. In the Southeast Asian countries like Singapore, Taiwan, Korea the mobile terminal inside the taxi cab communicates using CDMA or GPRS technology whereas some of the European companies use 3G supported devices. These in-vehicle mobile terminals are integrated with GPS technology. As of today, all the systems are centralized. These systems can be subcategorized into two different categories based on the level of human intervention: operator controlled or fully automated. Below we describe these categories:

Operator Controlled

In this case, the booking and dispatching processes are controlled by a human operator. The taxi company may employ their own staff for this operation or may hire a 24/7 call center. In either case, the customer makes a phone call and provides the pickup and dropoff location as well as the time of pickup. The operator searches for the best available taxi cabs depending on the dispatching strategies described in section IV. After selecting the taxi, the operator notifies the driver and customer about the job assignment and booking confirmation, respectively.

Fully Automated

In a fully aotuomated system, the customer interacts either by phone call to an automated answering machine or communicates through SMS or the internet. The system automatically chooses the best dispatching option and assigns the job.

4.2.3 Wireless LAN and Multihop Ad Hoc Networks

Currently the automotive industry is investing in offering factory built Wi-Fi transceivers inside vehicles. Some luxury vehicles already provide in-built 3G connectivity or a mobile broadband connection while some others are focusing on WiFi radio to provide connectivity through multi-hop mobile ad hoc networks (MANETs). In near future, it is quite conceivable that almost every new vehicle would be equipped with a Wi-Fi transceiver. With this vision, some researchers have proposed to implement a distributed taxi dispatching system over MANET. One example of this type of application is EZCab [107] which is described in section 2. One of the key advantages of this kind of distributed dispatching scheme is that the system does not require any central server and hence it reduces the overhead cost of a human operator or server infrastructure or maintenance. On the other hand, some drawbacks of this system are that there is no guarantee that the customer will be able to communicate with an available taxi a through multi-hop routing scenario and that the customer is required to have a smartphone with GPS receiver.

4.2.4 Dedicated Short-Range Communications (DSRC)

Dedicated Short-Range Communications (DSRC) [119] is a recent technology specifically designed for automotive use in order to provide a platform for wireless access in vehicular environments (WAVE). This state-of-the-art technology, also known as IEEE 802.11p, incorporates both vehicle to vehicle (V2V) and vehicle to infrastructure (V2I) communications. The technology is envisioned to contribute greatly to Intelligent Transportation System (ITS). In October 1999, the United States Federal Communications Commission (FCC) provided license for 7 channels spanning a total of 75 MHz spectrum in the 5.9 GHz band for DSRC. Also, the European Telecommunications Standards Institute (ETSI) has allocated 30 MHz of spectrum in the 5.9 GHz band in Europe. By now, the technical standards of IEEE 802.11p are available. Electronics companies are concentrating on manufacturing the aftermarket On-Board Equipment (OBE) hardware for DSRC while vehicle manufacturers like General Motors (GM) are investing in DSRC by designing cars with factory built OBE. During the last couple of years, ITS applications have rapidly evolved towards the DSRC platform. Recent initiatives from the US Department of Transportation (DOT), such as the "Connected Vehicle Technology Challenge" [126] hosted by the ITS program office have highly stimulated the convergence towards DSRC. We envision that DSRC can provide a direct communications between a taxi driver and a customer and offer a much quicker and higher quality service to the city transportation system.

4.3 Existing Automated Taxi Booking and Dispatching Systems

In this section, we describe four different automated taxi booking and dispatching systems along with their respective advantages and disadvantages. At the end of this section we tabulate the comparative technical specifications and environmental requirements for each of these systems.

4.3.1 EZCab

EZCab [107] is based on MANET which does not require any centralized application server. Currently, this is the only decentralized application for automated taxi dispatching. The system consists of two types of entities: client stations and driver stations.

Any sophisticated smartphone or PDA having a GPS receiver and a wireless LAN radio can act as a client. On the other hand, a driver station can be a system embedded in the taxi cab integrated with an IEEE 802.11 network interface. All driver stations within the transmission range can be used to form a mobile ad hoc network (MANET). The client station is required to join such an ad hoc network to make a request for an available cab. If there is an available cab located within the range of the client station, then it can communicate directly, otherwise, the occupied cabs in the network forward the request until an available cab is discovered.

The EZCab booking process begins when the client application sends out a cab request together with the trip information (e.g., pickup location, destination) and ends by validating the client's identity. Hence, the protocol includes two-phase communication: Cab Booking and Validation. Cab Booking is a three-way handshake protocol which ensures that a nearby available cab is booked and no more than one client books a cab simultaneously. However, the protocol does not provide a way to select the best cab in case multiple cabs respond to the request. When the booked cab arrives at the client location, the driver initiates the Validation phase to mutually authenticate with the client. The Validation protocol uses a challenge-response scheme based on public-key cryptography. This ensures that no one else had booked the cab.

One major advantage of this system is that, it does not need a high cost infrastructure to be installed and hence no central operator is needed. The system works autonomously to find an available cab and complete the booking, but it requires the passenger to possess a smart phone with an IEEE 802.11 transceiver and GPS receiver. In addition the EZCab client application has to be created for each specific type of smart phone and thus not every smart phone is supported. This can be a potential constraint for the wide range acceptance of the system. Perhaps even more importantly, routing of the request to an available cab is not guaranteed and may not be possible even in situations where an available cab is located relatively close to the client station. All of these problems have restricted this system from commercial deployment.

4.3.2 AVLDS

The satellite-based dispatch system known as Automatic Vehicle Location and Dispatch Systems (AVLDS) [119] consists of a GPS receiver in the taxi, wireless data communication link between the taxi and the dispatching server, and automated dispatching software. The wireless communication system is usually a cellular network, which can be either CDMA or GSM technology like 3G/Edge/GPRS. In Singapore, the largest taxi company, ComfortDelGro, having fleet size of over 15,000 vehicles uses the GPRS technology of Sing Tel cellular network. Examples of similar kind of systems are Digital Dispatch [108], Taxi-Central Dispatch Software [109], TranWare Enterprise Taxi Dispatch [110], Sigtec Computer Aided Dispatch [111] etc.

AVLDS is claimed to be the most advanced taxi booking system in the world [**?**]. The AVLDS offers great flexibility in advance reservations in that it provides a multiple-access platform enabling customers to reserve taxi services via various modes. For instance, Comfort CabLink-the dispatching system used by Comfort Transportation-consists of a variety of access features such as CabLink AutoCall, CabLink Dial-a-Cab, CabLink Fax-a-Cab, CabLink PCDial, CabLink Hot Button and CabLink TOT's. Of the estimated daily calls, approximately 30 percent were made through the AutoCall system, 65 percent through Dial-a-Cab, and the remaining 5 percent through other reservation modes. They also provided smart phone booking applications for several devices.

Each taxi vehicle is equipped with a mobile data terminal (MDT) to communicate to the control center via the stations that are set up at various locations. With a centralized taxi dispatch system, all customers' taxi booking requests are being queued on a first come first serve basis at the dispatch center. For each request, the system is able to detect the nearest taxi to the customer based on the latitude and longitude (provided by the GPS) and the taxi's current route. All taxis within a 10 kilometers radius to the customer are able to receive the job via wireless transmission. Upon the human driver accepting the job via the in-vehicle mobile data terminal (MDT), the taxi number and its estimated time to reach the customer will be conveyed through the means of booking. In case no drivers have accepted the job, the system continues to search for the next nearest taxis and the job is dispatched again, until a successful matching.

AVLDS can help users increase fleet utilization and reduce fuel, labor and capital costs. Using this system, the fleet management center can handle all its taxis. In addition, it also has the capability to record the tracking, driving behavior and traffic violations of taxis. Key benefits of AVLDS include improved dispatch fairness and timed transfers, more accessible passenger information, increased availability of data for transit management and planning, and improvements in efficiently carrying out services. Furthermore, due to supplemental technology such as automatic passenger counters, the user is better able to analyze transit service performance in real time and historically, to gather information needed for system planning, and to locate vehicles for emergency repairs. Hence it ultimately increases the total number of bookings as well as the revenue of the taxi company. With the aid of AVLDS, ComfortDelGro's annual booking soared to a new record of 24 million in 2010, where more than 1 million bookings were made through the iPhone apps in 2010.

4.3.3 GSM Positioning based Taxi Booking

The GSM Positioning Taxi Booking System [13] is comprised of three main tiers: the mobile application (used by the passengers), the taxi terminal and the server. Instead of making a call to the Call Centre Operators, customers can now "call" for a cab by using a mobile application that resides on a mobile phone. As soon as the mobile application is started, it will retrieve the ID of the cell that the mobile phone is connected to at that

particular point in time. Using the ID, the mobile application will query the server for the description and location of that particular cell. After which, the mobile application will know which of the map images (residing on the mobile device), should be displayed to the user. The initial map image shown will be the approximate location of the user. The user is then able to indicate where they want to be picked up, by selecting a point on the map image. Once they have decided, he can send his selection, together with his mobile phone number, to the server.
With all the selected pickup points being transmitted to the taxi terminal (through the server), the taxi drivers are able to view all of them on them the device terminal which resides in their taxi. Despite being able to see all the selected pickup points, a taxi driver is only allowed to select a passenger that is located within a certain radius from their current location as provided by the GPS. This is to prevent a passenger from having to wait for too long if the taxi is too far away from him.

After a pickup point has been chosen by the taxi driver, the phone number associated with that pickup is displayed on the console of the terminal. At the same time, the phone number and the taxi plate number will also be transmitted back to the server, indicating that the pickup point denoted by the phone number has been accepted by the driver of the taxi carrying that plate number. The server will then broadcast to all the taxi terminals that the job has been accepted and that the pickup point associated to the mobile phone number is no longer available and, therefore, is no longer displayed on other taxi's terminals. Simultaneously, the taxi plate number will be sent to the mobile application, to indicate that this particular taxi will be picking the user up at the indicated pickup point.

Even though this system requires a centralized application server as an interface between the customer and taxi cab, it does not require any human operator. Hence it removes the miscommunication issues between the passenger and the Call Centre Operators. In terms of booking time it is relatively fast compared to other systems. However, the system allows only predefined pickup points which may sometimes be located quite far away from the customer's current position. The customer is required to have a keen idea about the map of the geographical location. Often it might be very difficult to locate the pickup location when cell radius is over 1 km, especially for a visitor or a person who is not a local resident. Finally, similar to EZCab, this system also requires a somewhat sophisticated smart phone in order to be able to install the application. Therefore, this application is yet to be implemented in the taxi industry.

4.3.4 Taxi on Demand (TOD)

Taxi on Demand (ToD) [117, 118] is a large scale enterprise taxi management system that incorporates an automated booking, dispatching, and monitoring application with a number of distinctive features including: Location Based Ad-hoc Grouping and Dispatching (LBAG) [121], multi-lingual presentation (MP), tracking for customized mappings, route navigation with traffic hints, customized charging and billing (CAB) and automated emergency voice calls over Terrestrial Trunked Radio or TETRA [120], formerly known as Trans-European Trunked Radio. The overall system architecture is complex and hence it requires significant installation and maintenance cost. The booking and dispatching operations are almost the same as a typical centralized system. The dispatching functionality can operate in two modes: one is the global broadcast mode and another is selective local broadcast mode based on proximity to pick-up location. The latter mode is enabled by LBAG mechanism. The system additionally supports the integration of in-car video surveillance along with a centralized monitoring option.

4.3.5 Summary

Each of the above systems demonstrates representative and distinguishable features. We summarize them in Table 4.3.5 through comparisons using various metrics. These metrics quantify system features and performance impact as measured by user experiences.

4.4 Factors Impacting Taxi Reservation Systems

4.4.1 Booking Strategies

Most advanced taxi companies provide the flexibility of several booking options in order to minimize the communication hassle for making a reservation during rush hours. The time taken in different methods of reservation varies a lot. Hence, the efficiency of the taxi reservation system often depends on the nature of the communication technology used for booking. Below we listed most of the options currently available in the industry:

Phone Call

Perhaps this is the most widely used option due to its simplicity. Customers can use a conventional telephone or wireless mobile phone to call operators directly for taxi reservation. The phone calls can also be made from public telephones that have a preset hot button for the cab company without requiring the customer to know the phone number. Unfortunately, there are several problems associated with phone based reservation like:

- Takes significant amount of time for the operator to fill up the booking details in the central system by listening to the verbal communication from the customer.
- Customers need a good geographical knowledge of the area in order to pin point the pickup location to the operator. This is sometimes difficult for customers who are not local to that area.

- Customers are very often unable to get through the phone line during rush hours [116]
- Taxi drivers may not be able to locate the passenger due to miscommunication about pickup address
- Requires maintaining a call centre with high operational cost

Fax

Some companies also receive booking request over fax. For example: in Singapore, CabLink's Fax-A-Cab service is also used by customers who have the facility handy. However, most customers do not prefer this option due to the extra effort required for this.

SMS

Another alternative to voice call is the SMS which takes less time than verbal communication. In the Cablink SMS-A-Cab system, customers simply enter the street address and get confirmation of booking through reply SMS that contains the taxi number and arrival time. The total process takes about a minute on the average which is significantly faster than the phone call which takes over 5 minutes to get the confirmation of booking.

AutoCall

Taxi reservation can be more flexible and hassle-free process to a registered customer. An account number and an individual PIN is given to ensure confidentiality and security. The system enables the customer to preset regular pickup and destination locations, for example, home and office, in the cab company's database. Customers can instantly select their regular pickup locations by pressing a particular button. In Singapore, Comfort's registered customers can book using CabLink AutoCall by calling a dedicated hotline. An automated voice verifies the identity of the customer through the PIN and asks for entering pick-up location and destination. The system then locates the nearest available taxi and the customer is provided with the taxi number and the approximate arrival time

Online

Most companies also have the flexibility of online booking which can be done using smartphones, PDA or PC with internet connection.

Taxi Order Terminal(TOT)

This is is an automatic taxi-calling machine facility similar to ATM machines. Singapore's CabLink TOT is installed at major shopping centers, hotels, and other commercial buildings with substantial taxi demand.

Smartphone Apps

Most taxi companies have smartphone applications for booking developed by third party software companies. Of these applications, the most common are iPhone and Android apps. In Singapore, more than a million bookings are made annually using the iPhone application. One of the major advantages of these applications is that the customer need not specify the pickup location. The GPS reciever of the smart phone automatically forwards the exact pickup location accurate to 10 meter distance. Some other applications [116] use the cell ID of the mobile network to approximately locate the customer .

In summary, we compare these booking methods in Table 4.4.1 for their pros and cons.

4.4.2 Dispatching Strategies

Another factor that directly impacts the efficiency of a taxi reservation system is the dispatching strategy which decides the best available candidate for job assignment among all the available empty taxi cabs. Most advanced taxi companies use a central monitor that displays the current location of all taxis using GPS signal. Many of the companies select the taxi cab based on the proximity of the pickup location, while some others choose the earliest bidder. Below we describe some of the strategies currently under practice in the industry.

Earliest Bidder

This is the most comon and widely used strategy. Here a central operator broadcasts the job request to all the taxi cabs and whoever bids first gets the job. In Singapore, Comfort and CityCabs dispatch taxi based on the earliest bidding for any advance booking. Advance booking is when the pickup time is at least half an hour later. Hence even a taxi driver is on a trip, he can still bid if he knows he can pickup the new passenger within half an hour. Some other companies select a taxi based on several other criteria apart from this one.

Closest Availability

This selection is mostly based on GPS location. The central operator monitors the current location of all available taxi cabs near the customer and selects the closest one. In case of fully automated systems, the automated dispatching agent selects by calculating the point to point geographical distance from the taxi and customer.

Fastest Arrival Time

This is a modification of the previous scheme where the selection is based on the fastest arrival time which may or may not be same as the geographically closest taxicab. Because the driving route to the pickup location may be longer than the next closest available taxi. Both these strategies are used mostly for current bookings where the customer requests immediate pickup.

Longest Cruise time

This criterion is also used by many dispatching systems (eg. ToD). The intuition is to balance the workload between the taxi drivers by favoring the drivers who are cruising empty searching for passengers for longer period of time. Several variations of this condition can be possible like accumulating the total empty cruise time over the whole day and selecting the one with maximum idle time.

PDPTW

Wang et. al. [122] proposed a strategy called Pickup and Delivery Problem with Time Window (PDPTW) which is only applicable for advanced booking. The core algorithm of this strategy is a variation of a well known NP-Hard problem named Vehicle Routing Problem with Time Window (VRPTW). The problem can be stated as an optimization problem that minimizes the total distance travelled with the minimum number of cabs to fulfil a given number of advanced booking requests. A potential problem for this strategy can be the overhead of computational complexity for global optimization.

Multi-agent Dispatching

Seow et al [123, 124] proposed a multi-agent dispatching model named as NTUCab. In this system, the total geographical area of road network is partitioned into a number of zones and each taxi is registered into one of the zones. The dispatching job of each zone is handled by a dedicated agent, hence if there are N zones than there will be n agents for dispatching. The centralized server recieves booking requests and classifies the booking based on the pickup zone and hands over to the appropriate zone dispatching agent. The dispatching agents act independantly with their own queue of booking requests in a distributed fashion. Therefore, the dispatching system locally optimizes the goals for both customer and driver satisfaction.

In summary, all the above strategies have their own applicability scenario. For example, PDPTW cannot be used for current bookings. On the other hand, considering only the longest empty cruise time may satisfy the driver but lead to dissatisfaction for customer for potential delay in service. A good dispatching strategy should incorporate several criteria with less computational cost requirement.

4.4.3 Positioning Techniques for identifying pickup location

Another potential issue that controls the efficiency of booking method is the positioning technique for identifying pickup location in case the customer is using a smart phone application for booking. There are three different positioning methods available so far. These three techniques are: (i) WLAN Positioning (ii) GPS positioning and (iii) Cellular positioning.

WLAN Positioning

This is the most economical solution among the three techniques. Now-a-days, WLAN hotspots can be found in many areas of a city. To get the location of a device, the signal distribution of access points is collected to train a position-determination model. The propagation delays of the signals are being monitored to triangulate and calculate relative position. Despite of being the cheapest option, as of today, no automated dispatching system uses this positioning method because WLAN access points are still unreachable from most part of the city.

GPS Positioning

This is the most widely used and accurate positioning method. The accuracy of the position determined by GPS can be around 10 meter or less, whereas a differential GPS

(DGPS) can provide accuracy close to 1 meter. However, GPS is typically inefficient for indoor use or in urban areas where high buildings shield the satellite signals. AVLDS, ToD, EZCab and many other existing systems use the GPS based positioning technique.

Cellular Positioning

Voon et. al [116] proposed a new cellular based positioning technique called GSM positioning. The problem for this positioning technique is that its accuracy can be as low as 100 - 1000 meters, depending on size of the cell. The size of the cell is determined by the signal strength of the base station. While using this method, the system needs additional information from the customer to pin point the pickup location. For example, the customer might be prompted with a predefined set of landmarks within the cell area to choose his preferred pickup location. One problem for this might be in the rural or sub-urban areas where the radius of the coverage area for base station is more than 10-15 km. In such cases, the closest landmark might be located more than 1 km away from the current position of the customer. Such scenario would impose a challenge for the system to provide suitable pickup location to the customer.

4.5 Proposed Taxi Hailing System

The proposed DSRC based taxi hailing system consists of Roadside DSRC equipment (RSE), hailing interface, vehicle response device (VRD) and a signaling protocol that enables both direct communication and multi-hop half-duplex communication between the hailing and response units. In section 4.6, we describe the protocol in details.

4.5.1 Roadside DSRC equipment (RSE)

The RSE comprises of a processor, memory, storage device, operating system, I/O ports and DSRC wireless transceiver that can communicate using 5.9 GHz frequency band. Apart

Figure 4.2: Roadside equipment (RSE) deployed by US DOT

from that, it also supports Wi-Fi and Bluetooth communication. The state of the art DSRC infrastructure deployed by US Department of Transportation includes all these features at present. Hence our system will utilize the existing DSRC infrastructure for hosting the proposed taxi hailing application and protocol. Figure 4.2 shows a typical RSU deployed the US Department of Transportation.

4.5.2 Hailing Interface

The hailing interface can be any software application or a hardware interface that is used by the potential passenger for making a request for taxi hailing. Here we present two different possible ways to implement the hailing interface- Cell phone application and Road-side Hailing Device (RHD).

Cell Phone Application

Now days, most cell phones have in-built Wi-Fi and Bluetooth chips which allows them to easily communicate with the RSE from a reasonable distance. The client application for cell phones will provide an easy way to make a taxi hailing request through the nearest RSE. It can also provide the flexibility to specify the current location as the pickup location if the

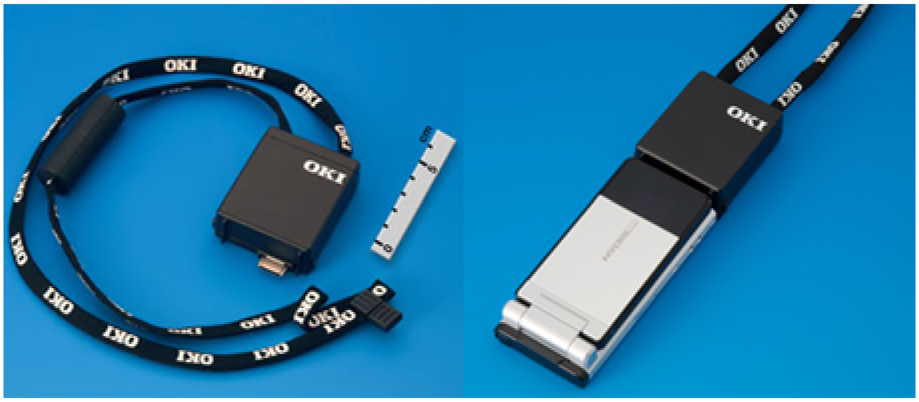

Figure 4.3: External DSRC plug-in radio for cell phones

cell phone has a built-in GPS receiver. Otherwise, the pickup location, by default, would be the RSE location. Currently, some companies are manufacturing DSRC add-on device for cell phones (figure 4.3) which allows it to communicate on 5.9 GHz frequency band from a distance of maximum of 1 km. It is envisioned that, in future, cell phones will be equipped with factory built DSRC radio to interact with different ITS applications.

Roadside Hailing Device (RHD)

The Roadside Hailing Device (RHD) is proposed as a human interface to make a request for taxi from the street. The device may comprise of the following components:

- a switch or push button used for calling or requesting a taxi cab;
- a collection of Light Emitting Diodes (LED) for displaying the status of the request;
- a digital counter to handle concurrent multiple hailing requests;
- a digital display unit to show the Taxi number responding the call and approximate arrival time

Figure 4.4 shows a sample model of the RHD where the circular switch resembles the push button for calling taxi cab. Above the push button, a collection of colorful LEDs

Figure 4.4: Roadside Hailing Device for taxi calling

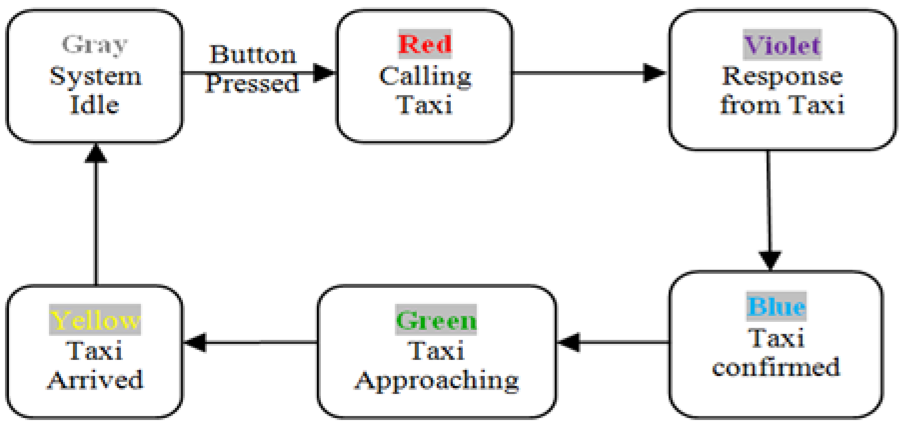

Figure 4.5: Hailing procedure

indicate the current state of the operation cycle. It must be noted that, the digital display unit is not shown in this model.

Taxi Calling Operation Cycle

The entire hailing procedure can be described as a finite state machine with six states as shown in figure 4.5.

When the system is idle, which means there is no pending requests, the gray LED is on. Once the pushbutton is pressed by any passenger, the system initiates a new hailing request and the state is changed to red which indicates that the system is broadcasting the request to all taxis located within the transmission range of the RHD. Once the call for service is broadcasted, available taxi drivers within the range gets the pickup location of the passenger and if the taxi driver is willing to serve the call, he will be able to respond using the driver's interface of the vehicle mounted DSRC device. After getting response from any available taxi driver, the RHD changes the state to violet which indicates that a taxi has been found. In case multiple taxi drivers respond to the request, only the first responder will be welcomed. On the other hand, if there is no taxi available, this request will be forwarded by all other hailing units to respective zones. This multi-hop forwarding is described in a section VI. Blue state indicates the taxi is currently approaching towards the pickup location after confirmation, At this time, the passenger is informed about the taxi number and approximate arrival time through the digital display. While the taxi parks near the passenger, the state turns to green and finally when the taxi is hired the state becomes yellow which completes the cycle. In case, the taxi driver refuses to go to the destination, the system again changes back to red when other taxis are called once again.//

Figure 4.6 displays an example scenario where the central brown spot indicates the call originating RHD and the circle describes the broadcast range of this RHD. The black spots near the circumference of the circle are other nearby RHDs. These RHDs can further relay the hailing request to respective zones in case none of the four taxis in the circle respond with acceptance.

Broadcast Range

Typically the transmission range for a DSRC signal is from 300m to 1000m depending on the environment. In a downtown area, transmission range can be limited to less than 300 meter due to the builds and other obstacles. While in sub-urban residential areas or rural areas the transmission range can be as large as 1000 meter which is the maximum allowable range for DSRC. This wireless transmission reality is contrast to the signal coverage demand

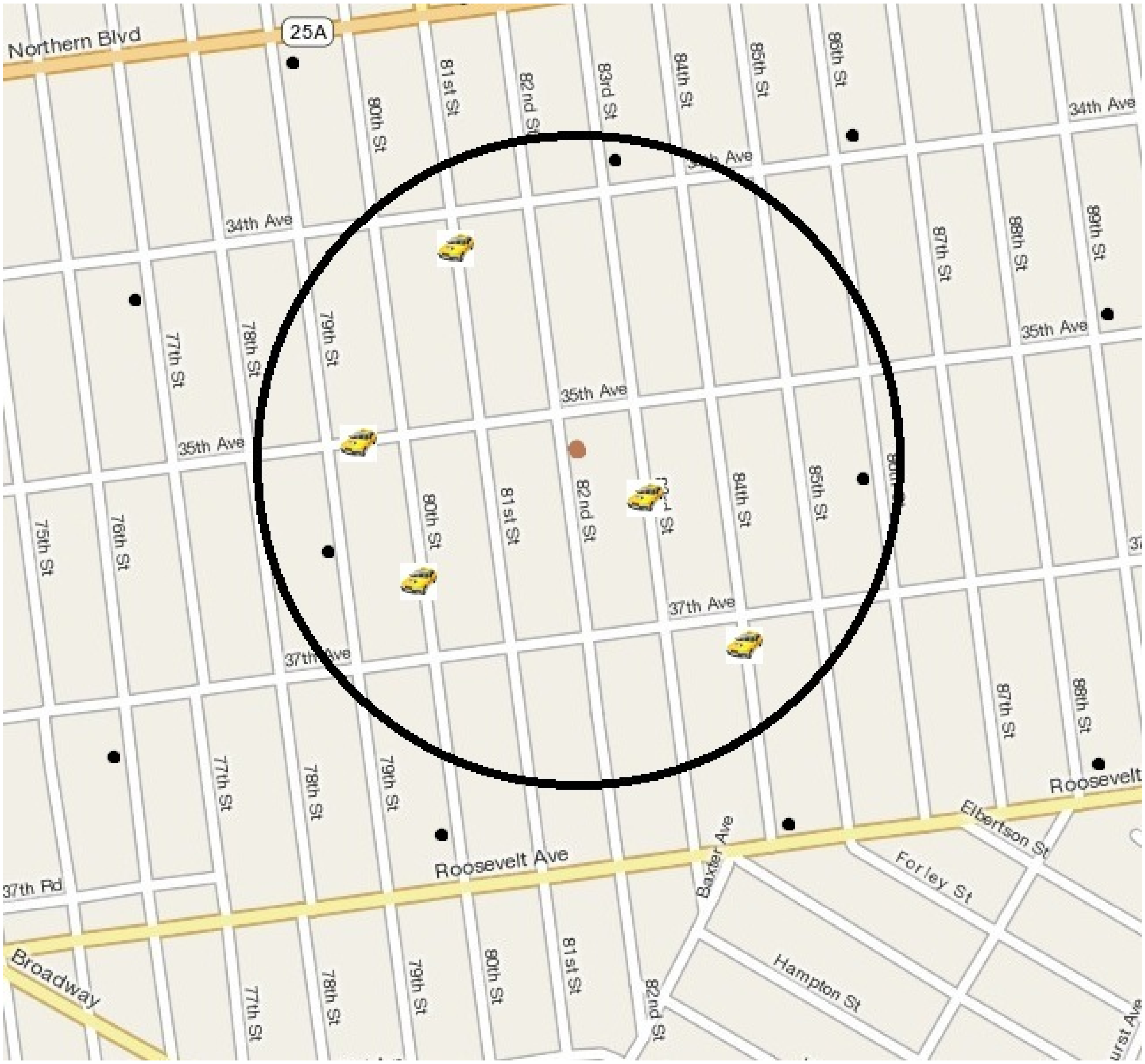

Figure 4.6: Example scenario for Taxi Calling Operation

of the taxi hailing application, for example, the system would perform better if it can reach more available taxis in downtown, which can be achieved directly by longer transmission range.

Many issues can be addressed for the coverage issue for the performance of the hailing system. Existing solutions can be using multiple-hop vehicle ad hoc networks, larger transmission powers, etc. However, we develop a new technique that will be introduced in a later section. Moreover, factors like, taxi availability, taxi demand, and road system traffic, should be considered. We will elaborate the influence of these factors in simulation section.

Handling Multiple Concurrent Requests

It is very natural that at certain times there will be several passengers in queue standing near the RHD, particularly during the rush hours. In order to handle such cases, the system uses a digital counter to process multiple hailing requests concurrently instead of having to serve each passenger one by one. This functionality provides the facility to hail several taxis back to back and in parallel. Each time a person presses the push button, a new hailing request is issued with new request ID (req_ID) and its operation is processed by a new instance of the finite state machine. All the communications from RHD involve the req_ID which identifies the particular request out of several concurrent hailing requests.

4.5.3 Vehicle Response Device (VRD)

As for the responding entity, the vehicles used as taxi cabs need to be equipped with a DSRC driver's interface which we term as Vehicle Response Device (VRD). Each VRD is equipped with a DSRC transceiver, GPS receiver, a processor for running the application and communication protocol, a small touch screen monitor which is also used for the driver's interface for operating the device and for showing the city map. Currently, many electronic

Figure 4.7: Sample Vehicle Response Device

companies are manufacturing smart integrated devices that can be used for DSRC communication while mounted in the vehicle. One example of such device is the Vehicle Intellidrive Module manufactured by DGE Inc. shown in figure 8 below. These aftermarket devices can be implemented with any custom built application and communication protocol based on DSRC.

4.5.4 VRD Operation

Once a hailing request sent from RHD is received by the VRD, the device pops up the message along with pickup location (which is the location of the RHD). Upon receiving the message, the device also prompts for two options: Accept or Reject. If the driver is not willing to serve the on-call pickup request, he can simply ignore it by pressing the reject button displayed in the touch screen interface. A default will be set to reject after a period of silence. The user interface should be designed in such a way that it requires minimal input from the driver's end so that it does not distract the driver's concentration from the road environment. If the taxi driver accepts the request, the GPS module integrated with the VRD calculates the approximate arrival time and the VRD replies back to the RHD acknowledging the acceptance of hailing request along with approximate arrival time to the pickup location. At the same time the VRD also sends the taxi number to the RHD so that the passenger can identify the vehicle that responded to the call after arriving at the pickup location. This information is displayed to the passenger at the RHD using the digital display unit. After arriving at the pickup location, when the driver agrees to go to the destination, the trip is started and this concludes the operating cycle of the RHD. Even though many taxi regulatory commissions do not allow denial of service to passengers, but there are incidents when the taxi driver refuses to go to a certain destination due to extreme traffic conditions or shift changing periods. In such cases, once the driver refuses the passenger about the destination, the RHD changes its state back to Red when other vehicles are called. An option of additional auxiliary device can be a microphone and a speak to allow the drive to operate hand-free.

4.6 Hailing-Response Protocol(HRP)

We propose a novel communication protocol that handles the signaling and messaging between RHD and VRD. We name this protocol as Hailing-Response Protocol (HRP). It must be noted that, all the messages in the protocol are transmitted according to the standards of IEEE 802.11p or WAVE. Our protocol uses six different types of messages: Beacon, Hailing Request, Response, Service Offer, Acknowledgement and Dispatch Order. Of these messages, Beacon is already existing in IEEE 802.11p standard communication architecture. We extend the existing Beacon format to add a little more information that can be used for the hailing cycle. Below we mention the details of each message:

- *Beacon: <Latitude, Longitude, Occupancy Status, Timestamp>*
- *Request: <Req_ID,Comm_Mode,RSU_ID,Pickup Location,Max Range,Timestamp>*
- *Response: <Req_ID,Comm_Mode,Accept/Reject,VRD_ID,Taxi Number,Arrival Time>*
- *Offer: <Req_ID,Comm_Mode,RSU_ID,VRD_ID,Pickup Location,Max Range>*

- *Acknowledgement: <Req_ID,Comm_Mode,Confirm,VRD_ID,Arrival Time>*

- *Dispatch: <Req_ID,Comm_Mode,Confirm,VRD_ID>*

4.6.1 Beacon

This is an extended version of the "Here I am" message defined by the SAE J2735 standard for DSRC message set dictionary according to IEEE 802.11p [25]. Beacons are sometimes referred as Heartbeats of vehicle and are generally broadcasted on a periodic basis to inform all other DSRC enabled vehicles as well as road side devices about the current location of the vehicle. Figure 10 shows how DSRC enabled vehicles produce their Beacons.

In addition to the global positioning information at a particular time, the proposed Beacon message also informs about the occupancy status of the taxi. In short, the Beacon comprises of the following information:

- GPS Location: Two floating point values indicating Latitude and Longitude of geographical location.

- Occupancy Status: Binary value (0 or 1) indicating whether the taxi is currently occupied or not.

- Timestamp: Unix timestamp of sending the Beacon message.

4.6.2 Hailing Request

The Hailing Request message is broadcasted from the RSU upon the activity of making a taxi request by a potential passenger either through cell phone application or directly interacting with the Road-side Hailing Device. The various fields of a Hailing Request message, are described below:

- Req_ID identifies each individual hailing request. It helps to avoid duplicate messages for the same request as well as to avoid broadcast storm.

- A single bit field Comm_Mode specifies whether the communication mode is based on V2V and/or V2I. A value of 1 in this field indicates both V2V and V2I, whereas, 0 specifies only V2I based communication.

- RSU_ID identifies the request originating RSU which also specifies the pickup location. In case the hailing request is relayed by neighboring RSUs, this field always remains unchanged as it denotes the original requestor.

- Pickup_Location comprises of latitude and longitude of the requested pickup location. This is based on either cell phone GPS receiver of the position of the RSU, whichever is specified by the customer.

- Max_Range specifies the maximum geographical distance to be propagated from the source RSU while forwarding and broadcasting the current request.

- Timestamp: is generated by the original RHD when the pushbutton is pressed.

4.6.3 Response

The Response message is sent from the VRD upon the activity of acceptance or rejection by a taxi driver. The various fields of a Response message are described below:

- Req_ID identifies the original hailing request for which this response corresponds to.

- A single bit field Comm_Mode as described earlier. Normally this field follows the specification of the corresponding field in Hailing Request.

- A single bit field Accept/Reject specifies whether the request is accepted or not, where 1 indicates acceptance and 0 means rejection.

- VRD_ID identifies the responding VRD which has a unique identifier.
- Taxi number is a alphanumeric field which is included when the request is accepted by the driver.
- Arrival Time is calculated by the GPS of the VRD and sent to the RSU.

4.6.4 Service Offer

After getting the responses from the interested vacant taxis, the application sends the offer of service to one of those taxis selected based on proximity and arrival time. This is very much similar to the hailing request, except for an intended recipient specified through VRD_ID which corresponds to the offered taxi.

4.6.5 Acknowledgement

Upon receiving the service offer, the selected taxi confirms his willingness to accept the job and pick up the passenger(s) from specified pickup location.

4.6.6 Dispatch Order

This message is to finalize the completion of the corresponding hailing request and to notify all the interested taxis (including the dispatched taxi) about the dispatch order for the service. Upon receiving the dispatch order, other taxis delete the pending hailing request from respective queues.

Figure 4.8 describes the step by step operations of HRP communications

4.7 Multi-Hop Communication Using HRP

In order to increase the availability of taxi cabs in rural or sub-urban areas, or even in urban area where the vacant ratio is low, the proposed system is capable to extend the

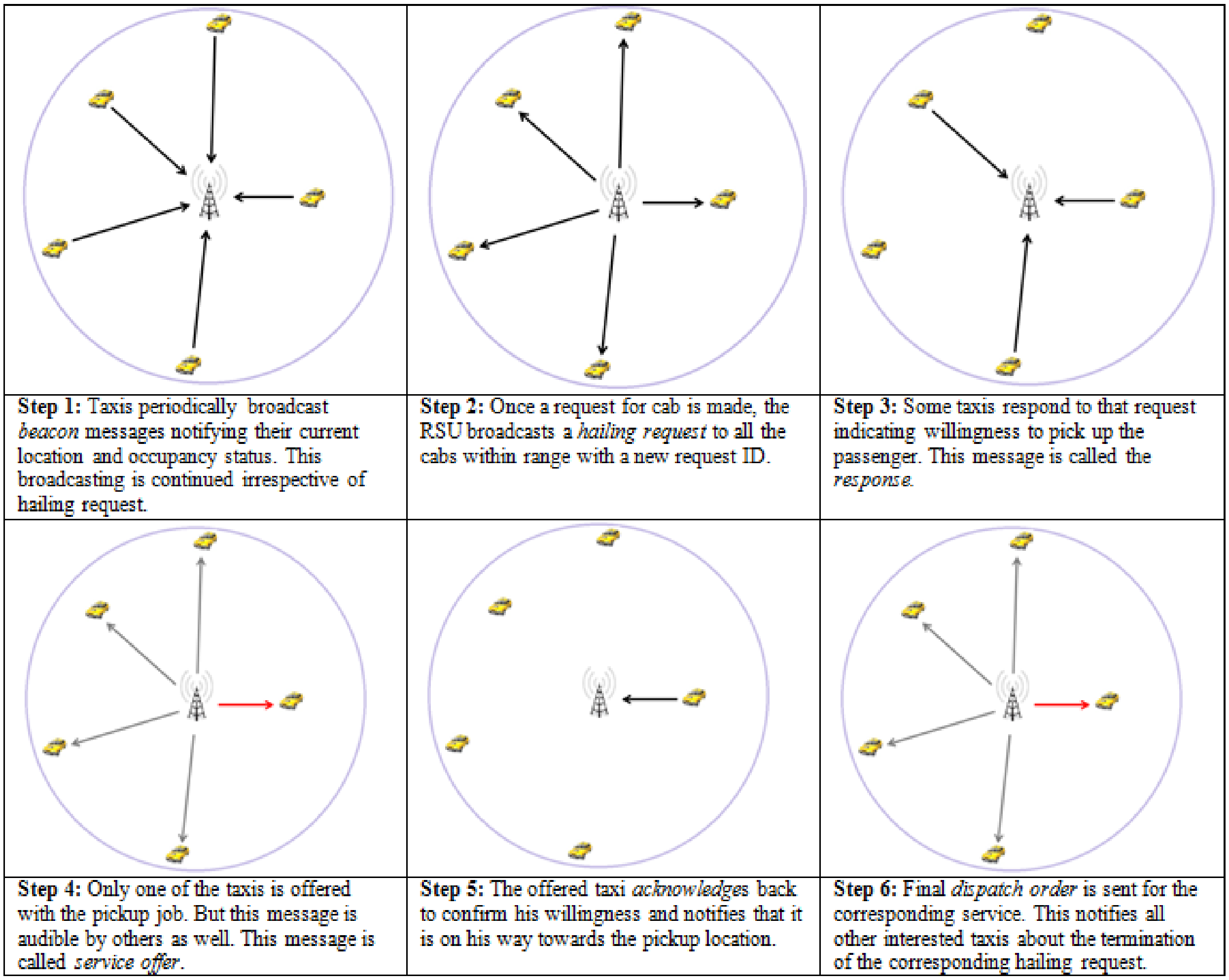

Figure 4.8: Steps of HRP protocol

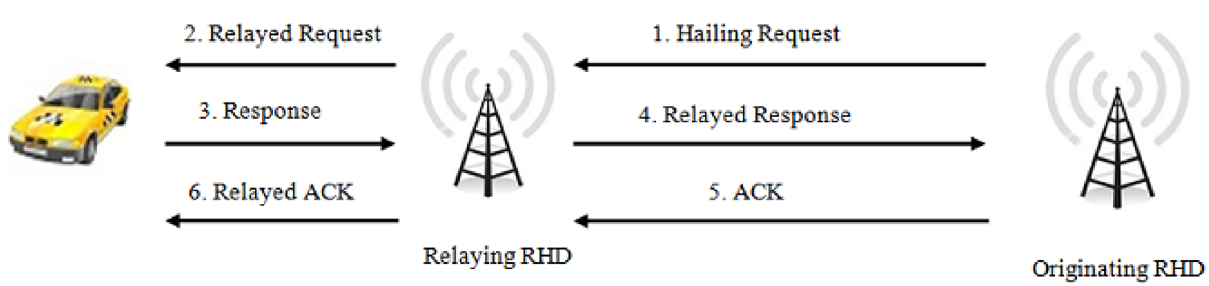

Figure 4.9: Multi-hop HRP protocol

HRP signaling over multiple hops. Even though there is no limitation on the maximum number of hops this communication can span, in practical implementation it is suggested that the multi-hop forwarding of the HRP communication should be limited to 5 hops which corresponds to a geographical distance of less than 5 km in rural areas. Practically, it does not make sense to request a taxi driver to pick up a passenger driving more than 5 km away from where is now. This kind of remote hailing request should be made through advanced reservation or booking.

Figure 4.9 shows a scenario of a 2 hop HRP communication. After pressing the push button, the request originating RHD initially transmits a hailing request with a new Req_ID and having the Relay_req set to 0. In case, there is no response heard back from any taxi cab within a certain short period, say, 10 seconds, after initial broadcast, the originating RHD re-broadcasts the request keeping the req_ID same but this time setting the Relay_req to 1 which indicates that this hailing request needs to be relayed. Upon receiving this relay request, the nearby RHDs rebroadcast this request (with standard treatments of handling wireless broadcast, such as, broadcast jitter, message suppression, etc.) to respective zones. If any available taxi within the range of the relaying RHD responses with an acceptance, this response is then sent back to the originating RHD through the relaying RHDs. If this is the first acceptance response received by the originating RHD, a positive ACK is sent confirming the job. This ACK will also have the Relay_req set to 1, which requests the relaying RHDs to forward this ACK to the responding taxi. If, by this time, the originating RHD has already confirmed the job to another taxi, then a denial ACK is sent in reply to this relayed response. When other participating RHDs receive a confirmation ACK, they terminate the relaying progress in their region.

Figure 4.10: Street view of test location

4.8 Evaluation of Proposed System

To evaluate the performance and effectiveness of our system, we simulated the system using real world mobility traces from San Francisco Yellow Cabs. To analyze the effectiveness of our system, we measured the increase of cab availability compared to the usual street hailing process of waving hands. We also calculated the hit ratio in both San Francisco downtown and nearby residential areas.

4.8.1 Increased Availability and Reduced Waiting Time

In order to see the effect of deploying the proposed DSRC based taxi hailing system, we chose an experimental time span of one hour in the afternoon (2 pm to 3 pm) on a random working day (Monday, June 2, 2008) near the heart of San Francisco downtown. It is obvious that there will be very less demand of taxis in the downtown on weekend holidays. Hence to perfectly measure the demand and availability we chose a working day. The GPS location of the experimental pickup spot is (37.788031,-122.406691) which is marked as 'A' in the map of figure 4.11. The street view of that location is shown in figure 4.10 where the position of the yellow cab exactly points the pickup spot. Now, let us assume that there is an RHD installed at the light post shown in figure 10. Considering a short transmission range of 300

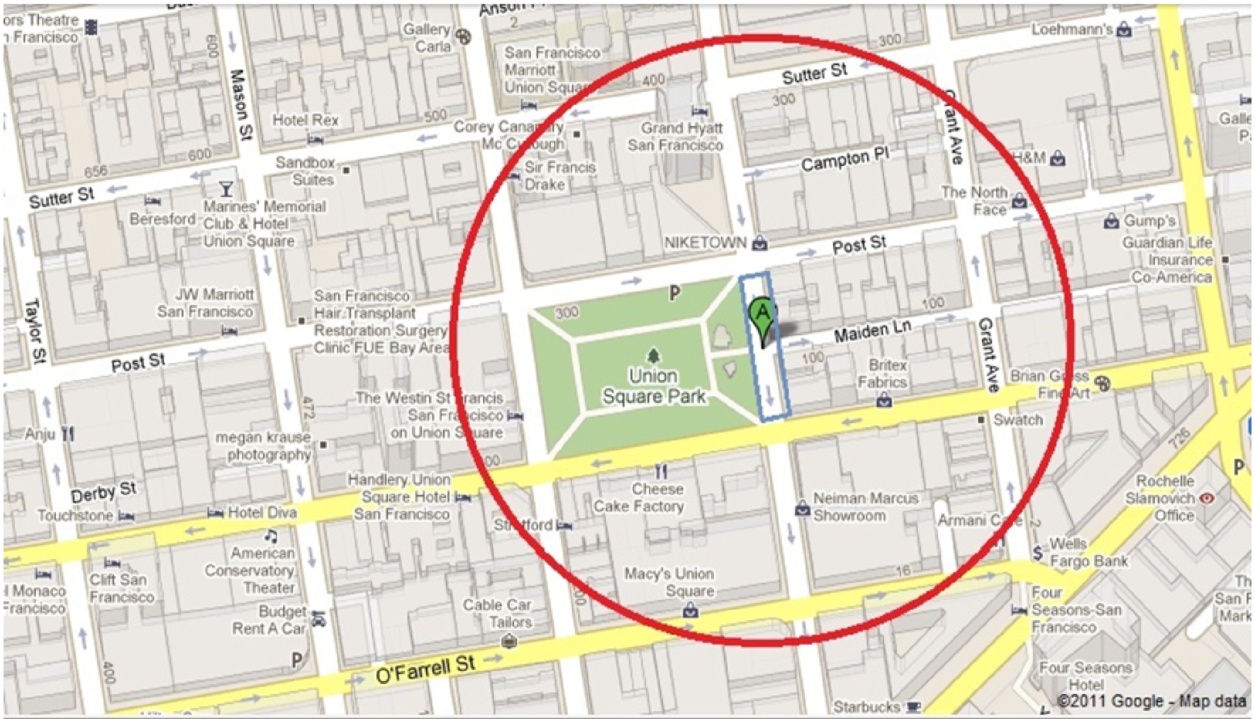

Figure 4.11: Map view of test location

meter for the downtown area, the red circle in the map defines the coverage area of the RHD where any free taxi can respond to a hailing request within this region. On other hand, without the RHD facility, a person can barely manage to secure the attention of a cab driver by waving hands within the road segment where he is standing at. This region is marked with the blue rectangle in the map.

Figure 4.12 shows the cab availability for both the regions within the time frame of 2pm to 3pm. The red bars indicate the number of free cabs available within the red circle and the blue bars denote the free cabs passing through that road segment marked with blue rectangle. The graph shows that a total of 150 cabs were available within that one hour duration if an RHD was deployed. On the other hand only 5 cabs that pass through this road would be available without an RHD facility. Moreover, a person looking for a cab at 2 pm would have to wait till 2:14 pm to see the first available cab passing in front of him.

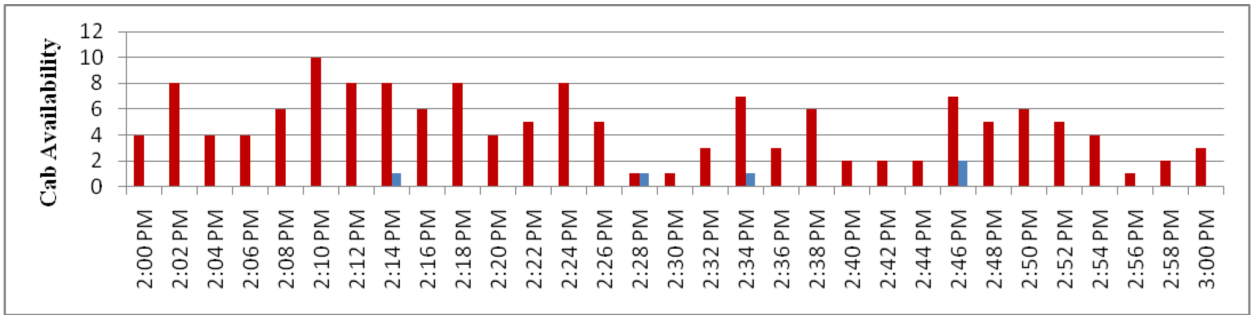

Figure 4.12: Increase of cab availability using proposed system

Whereas, if the RHD facility was deployed, the person would, in the worst case, require waiting for 1-2 minutes for any taxi to pick him up coming from less than 300 meters away. Hence, this shows that our system not only increases the availability of taxi cabs, but also reduces waiting time.

4.8.2 Average Hit Size

We define the hit size as the number of taxis available to respond to a request within a specified radius of communication. We evaluated the average hit size for both Downtown and suburban areas.

Downtown

Considering the average hit size over the whole month at the previously mentioned downtown location, our analysis showed that, at any particular moment between 6AM to midnight, the average number of available taxis to respond to a RHD call is 4.01. This means at least 4 passengers could be served every minute from a single RHD facility. This equals to a total serving capacity of 4330 trips from a single RHD unit within the specified 18 hour time frame. It must be noted that these statistics apply to the city of San Francisco where the total number of yellow cabs is 536. In a city like New York, where 13,000 yellow medallion cabs make an average of 470,000 daily trips, the average hit size would be much higher than that of San Francisco.

Suburban Residential Area

In case of suburbs the hit size is comparatively low as people mostly travel with their own cars. Nevertheless, our sample location (37.7573, -122.491363) near the San Francisco Bay area gives an average hit size of 0.18 per minute and 194 per day.

4.9 Conclusion

Based on the primary results obtained from real world GPS traces, it can be predicted that, our system can significantly increase the availability of taxi cabs while reducing the wait time for the passenger. At the same time, from the perspective of a taxi driver, it can reduce the cruising time and increase daily trip count and eventually help increase the revenue of the taxi company. This system can make a revolutionary change in the day today urban life, particularly for the crowded metropolitan cities around the world where people spend several exhaustive hours in transportation to and from work places. Our system can reduce the transportation overhead for city people and help them spare more time and efforts in productivity.

Table 4.1: Comparison between the existing systems

Criteria	ToD	GSM Positioning based	AVLDS	EZCab
Centralized/ Decentralized	Centralized	Centralized	Centralized	Decentralized
Booking mechanism	Online web form or client application	Client software application	Phone, Fax, Hotline, AutoCall, TOT, Online.	Client software application
Communication Technology	Cellular network (EDGE/GPRS/3G)	Cellular network	Cellular network, land phone etc.	IEEE 802.11a/b/g
Central Application Server	Required.	Required	Required.	Not required.
Human Operator	Required	Not Required.	Required.	Not required
Pickup location	Can be any street address	Only predefined pickup points allowed	Can be any street address	Can be any location
Passenger knowledge of pickup location	Required to know the pickup street location.	Requires significant knowledge of the map and location	Required to know the pickup street location.	No knowledge required
Booking Time	Less than a minute	45 seconds.	2 to 5 minutes on the average	Less than a minute
Average Wait time for pickup	Not estimated	More than 10 minutes.	30 minutes.	Not estimated
Broadcast Range	Depends on the size of the cell. Range can be up to 30 kilometers.	Depends on the size of the cell. Range can be up to 30 kilometers.	10 kilometers	Less than 100 meter
Positioning Method for locating pickup point	Street address	GSM Cell ID	GPS or street address	GPS address
Accuracy of pickup location	Within 100 meters	Within 100-30000 meters	Within 5-10 meters	Within 5-10 meters
Hailing Cost	Cost for data connectivity.	Cost for application and data connectivity.	Cost for phone call/SMS/Fax/ data connectivity.	Cost for application software and data connectivity.
Handshaking Mechanism	No handshaking	Customer phone number and taxi number	Customer name and taxi number	public key cryptography

Table 4.2: Summary of different Booking Methods

Process	Requirement	Advantage	Disadvantage
Phone Call	Cell phone or land phone	Convenient	1. Need to know phone number 2. Difficult to get through during rush hours
Preset button	Infrastructure	No need to know the phone number	Low availability
Auto-Call Hot-line	Account Registration	Fast booking with predefined pickup and drop off locations.	May also get busy during rush hours.
SMS	Cell phone	Easy to specify pickup location	1. SMS charge 2. need to type long message.
Fax	Fax machine	No particular advantage	Not possible without facility.
Online	Smart phone or PC with internet connection	Easy to book	1. Booking fees applicable 2. Not possible without internet
Taxi Order Terminal	Installed in large shopping malls.	No extra device needed	Low availability
Smartphone App	Sophisticated smartphone with GPS receiver	No need to specify the pickup address. Relatively fast booking.	Requires purchasing the software.

Chapter 5

CONCLUSION AND FUTURE DIRECTIONS

In conclusion, this research is focused on various aspects of Wireless Mesh Networks. Even though some of these issues are independant of each other, but still, all these works are correlated from the perspective of wireless networking. The proposed channel access algorithm, network partitioning algorithm, DSRC application can be regarded as some of mentionable accomplishments of this dissertation research. One of the objectives of this research included designing an efficient channel assignment scheme that utilizes partially overlapped channels together with an appropriate interference model that can increase the number of simultaneous transmissions in a multi-radio multi-channel wireless mesh network. We introduced the notion of I-Matrix as a new interference model which considers the effect of Self-Interference for multi-radio environment in addition to Adjacent Channel Interference(ACI) and Co-Channel Interference. Another main focus of this research lies in the area of vehicular communications and innovative applications of ITS. Using the presented V2V connectivity data analyses from real world GPS traces, wireless researchers can estimate the capabilities and constraints of vehicular communication from connectivity and mobility patterns as well as government can plan and work on issues related to implementing proper DSRC infrastructure for optimal data connectivity in urban area. Moreover, we proposed a novel application for taxi hailing using DSRC, which is the underlying technology that enables the state-of-the-art vehicular communication. In order to measure the impact on the mobility of the frequently travelling urban people, we also conducted a literature survey on existing automated taxi dispatching systems. We believe that, this can be a revolutionary application which might improve the mobility of urban people to a great extent.

5.1 Future Directions and Open Issues

Some of the new areas of channel assignment are still under investigation by wireless researchers. For example, the constraints and restrictions originating from self-interference problem within the domain of POCs, is yet to be explored. Also, some more dynamic and robust channel/spectrum allocation algorithms can be designed that would suite the requirements of cognitive radio environment. This can be another major area of interest for researchers of the wireless community. The wireless literature still lacks an efficient POC based dynamic and distributed algorithm, a algorithm that can handle channel switching for each node. Though some static schemes have been designed with POC [56, 60, 61, 62, 63, 64], more emphasis should be on dynamic versions. No existing simulator is capable of simulating such MRMC networks that involve interference calculated from POCs. Hence current popular simulators might be extended with features supporting POC channel model and network protocols designed for partially overlapped channels. As of this date, there is no joint routing and channel assignment algorithm designed with POCs. Polynomial time approximation schemes are often considered as feasible solution in this area where many critical factors, such as compound routing metrics with appropriate interference model are handled.

Despite significant amount of research, the network capacity of WMNs is still a challenging topic. Although many researchers [22, 43, 44] characterized network capacity in terms of number of channels and radios as well as switching delay, more conditions can be added such as heterogeneous radios, mobility of nodes. In addition, as of to-date, not too many MRMC protocols exploit the multi-rate capability of current 802.11 wireless cards. By considering only homogeneous links, the problem becomes much simpler. However, a channel assignment protocol with adaptive rates can achieve better performance.

The channel switching delay is another important concern for channel assignment schemes that switch the radio interfaces very frequently. Despite of significant improvement in wireless networking hardware, channel switching delay is still in the order of millisecond which is considered as an overhead for overall end-to-end delay. On the other hand, using a static channel assignment approach to avail the benefits of reduced overhead and stable topology will lack from the capacity improvement gained by MRMC environment. Therefore, a well estimated tradeoff is necessary to overcome the problem arising from switching overhead.

Several researchers have contributed with spatio-temporal analysis of urban taxi mobility particularly emphasizing on statistical trip patterns and hotspots. But very less amount of work has been done investigating the multi-hop connectivity and partitioning of vehicular network. Finally, this area needs to be studied well with the aid of real world GPS traces.

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