Collaborative Data Access and Sharing in Mobile Distributed Systems

by

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I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

The multifaceted utilization of mobile computing devices, including smart phones, PDAs, tablet computers with increasing functionalities and the advances in wireless technologies, has fueled the utilization of collaborative computing (peer-to-peer) technique in mobile environment. Mobile collaborative computing, known as mobile peer-to-peer (MP2P), can provide an economic way of data access among users of diversified applications in our daily life (exchanging traffic condition in a busy high way, sharing price-sensitive financial information, getting the most-recent news), in national security (exchanging information and collaborating to uproot a terror network, communicating in a hostile battle field) and in natural catastrophe (seamless rescue operation in a collapsed and disaster torn area). Nonetheless, data/content dissemination among the mobile devices is the fundamental building block for all the applications in this paradigm. The objective of this research is to propose a data dissemination scheme for mobile distributed systems using an MP2P technique, which maximizes the number of required objects distributed among users and minimizes to object acquisition time. In specific, we introduce a new paradigm of information dissemination in MP2P networks. To accommodate mobility and bandwidth constraints, objects are segmented into smaller pieces for efficient information exchange. Since it is difficult for a node to know the content of every other node in the network, we propose a novel Spatial-Popularity based Information Diffusion (SPID) scheme that determines urgency of contents based on the spatial demand of mobile users and disseminates content accordingly. The segmentation policy and the dissemination scheme can reduce content acquisition time for each node. Further, to facilitate efficient scheduling of information transmission from every node in the wireless mobile networks, we modify and apply the distributed maximal independent set (MIS) algorithm. We also consider neighbor overlap for closely located mobile stations to reduce duplicate transmission to common neighbors.

Different parameters in the system such as node density, scheduling among neighboring nodes, mobility pattern, and node speed have a tremendous impact on data diffusion in an MP2P environment. We have developed analytical models for our proposed scheme for object diffusion time/delay in a wireless mobile network to apprehend the interrelationship among these different parameters. In specific, we present the analytical model of object propagation in mobile networks as a function of node densities, radio range, and node speed. In the analysis, we calculate the probabilities of transmitting a single object from one node to multiple nodes using the epidemic model of spread of disease. We also incorporate the impact of node mobility, radio range, and node density in the networks into the analysis. Utilizing these transition probabilities, we construct an analytical model based on the Markov process to estimate the expected delay for diffusing an object to the entire network both for single object and multiple object scenarios. We then calculate the transmission probabilities of multiple objects among the nodes in wireless mobile networks considering

network dynamics. Through extensive simulations, we demonstrate that the proposed scheme is efficient for data diffusion in mobile networks.

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Dedication

For my parents,
Mohammad Rafiqul Islam and Monowara Begum
and brothers,
Mohammad Asadul Islam and Mohammad Kamrul Islam

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Nomenclature

MANET	:	Mobile Ad Hoc Network
P2P	:	Peer-to-Peer
MP2P	:	Mobile Peer-to-Peer
RWP	:	Random Way Point
RDM	:	Random Directional Model
WLAN	:	Wireless Local Area Network
SPID	:	Spatial-Popularity based Information Diffusion
WiMAX	:	Worldwide Interoperability for Microwave Access
7DS	:	Seven Degrees of Separation
FSP	:	Flooding with Self-Pruning
RBB	:	Rank Based Broadcast
MIS	:	Maximal Independent Set
ASM	:	Available Segment Matrix
ASV	:	Available Segment Vector
PM	:	popularity matrix
ODE	:	Ordinary Differential Equation
CTMC	:	Continuous Time Markov Chain

Chapter 1

Introduction

The rapid growth in the number of mobile computing devices (including smart phones and personal digital assistants with increasing functionality) and the advances in wireless technologies have shifted the paradigm of use of these devices. Initially, mobile devices mostly provided voice communication, but are now capable of producing and storing content for future use. In addition, users of these devices can share personal content. Typically, users are interested in exchanging data from their locality or want to be notified about local events. The type of information exchanged among mobile users can be categorized as temporal, spatial or spatio-temporal. For example, information about stock prices or sports scores is temporal information. Spatial information refers to a specific area, such as an engineering students' bonanza or math olympiad at a university. Available space in a parking lot and traffic conditions on a busy highway are considered spatio-temporal information. Using a data dissemination technique, vehicles can exchange maps of an area, people can share personal information and content (throughout the dissertation, the terms content and object are used interchangeably) and entertainment files.

Mobile devices use wireless communication networks to exchange information. Currently, these networks are dominated by centralized architecture. When a mobile device is turned on, it searches for a base station or an access point to get onto a network. However, this centralized architecture restrains the enormous flexibility of mobile devices. Consider a scenario between two students in a classroom who want to exchange course material. With traditional mobile networks, both have to communicate to a base station and exchange data through that station. Due to the large volume of requests, users are often constrained by slow speeds for their data exchange. However, the users in a classroom can exchange the required information quickly using Bluetooth or Wireless LAN without going through the base station or a server. Now consider another scenario. Two mobile device users want to exchange critical information about stock prices. However, one or both of them do not have any access to a base station or a server. With traditional wireless net-

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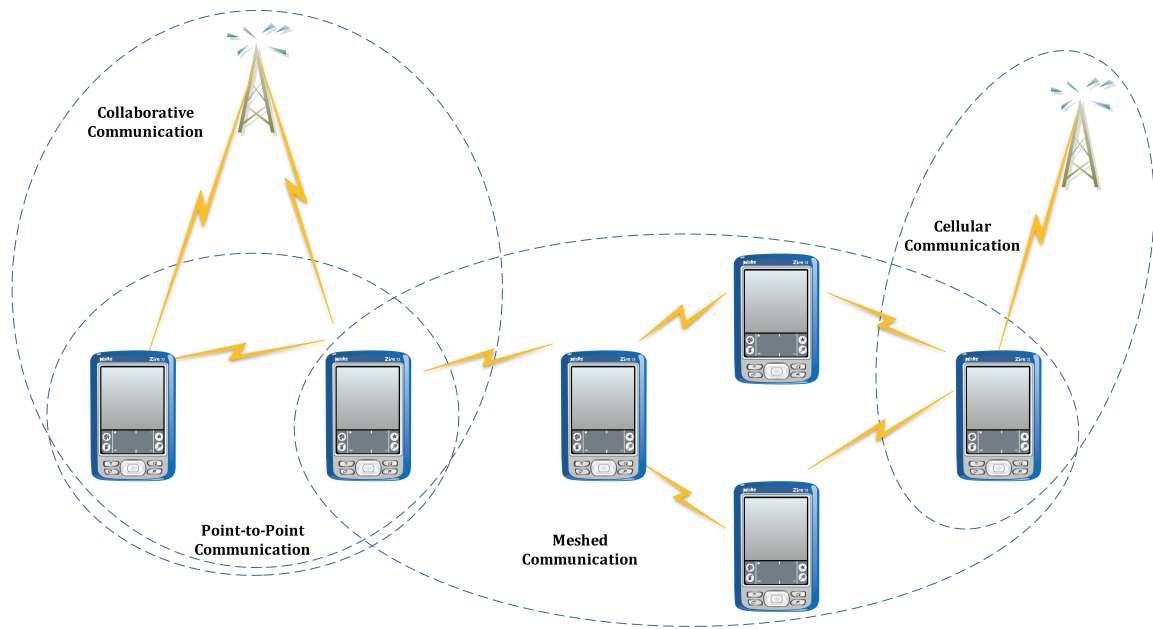
Figure 1.1: Mobile Peer-to-Peer Architecture

works, they are unable to exchange information. Direct collaboration among the devices via short-range wireless networks may provide an excellent solution to the problem of information exchange in infrastructureless mobile environments [7, 49]. Besides non-critical data, mobile data dissemination is of utmost importance in a number of critical situations such as rescue missions and military operations. Infrastructure often does not exist on a battlefield or in an area after a catastrophe, which is why research on collaborative computing in mobile environments has been focused on its application in digital battlefields and rescue missions in natural disasters. However, this type of network is expected to soon arise on university campuses, in urban areas, and large office premises as described in the aforementioned scenarios. These networks are characterized by the owners' willingness to exchange information, which is at the foundation of Peer-to-Peer (P2P) networks.

P2P networks have already replaced centralized client-server technologies. P2P networks are used for various purposes, including content sharing, distributed data storage, and collaborative computing on the Internet. P2P is a notion of computer networking that relies on the computing power and resources of each participant in the network; each participant acts as both a server and a client. P2P networks are characterized by self-managing capability, fault-tolerance, scalability, and low-cost of deployment.

The great success of P2P networks in wired environments has inspired the evolution of Mobile Peer-to-Peer (MP2P) which has been proposed as a mean of sharing network resources among peers in a mobile network [22, 82]. In MP2P networks, a set of moving

peers (throughout the dissertation, the term peer, mobile device and mobile user are used interchangeably) collaborate with each other to exchange information without using any central coordination or fixed infrastructure in a mobile environment [13, 25, 56]. In this paradigm, peer devices that are in transmission range directly connect with each other on a pairwise basis. To communicate with peers that are outside of the transmission range of a node, messages are propagated through multiple hops. MP2P can be implemented in many kinds of network connectivity and mobility conditions. Fig. 1.1 shows the typical architecture of a mobile P2P network which consists of cellular communication, meshed communication, as well as point-to-point communication.

There has been relentless effort to migrate architectures and applications of P2P approaches in wired networks directly to mobile networks [43]. Several studies have been conducted to apply P2P content sharing methodologies on MANET [17, 20, 42]. Nonetheless, due to the specific characteristics of mobile networks such as unreliable wireless links, limited radio ranges, and limited mobility of nodes, multihop forwarding operations hinder the success of those efforts. In MP2P, special attention is given to mobility of peers, temporal disconnections, and frequent churn of nodes, which are all absent in traditional wired P2P topology [16, 58].

Despite the challenge of MP2P networks, we envision that the ubiquity of wireless computing devices could form a large scale wireless network. However, due to the size of the network, the centralized architecture is unsuitable for information distribution among the devices. The communication medium for this large scale wireless network should have certain characteristics: robustness, scalability and spatiality. Unreliable wireless connections and the sudden departure of a node can change the topology of the network. The goal is to have the network continue its work in the midst of these disruptions, which means the network cannot depend on any single node to carry out a task. Since the number of nodes varies throughout the lifetime of a network, the essential property of this network is that it should be scalable to the number of nodes available. Exploiting spatially or locally available information is a key factor in the success of these networks. Each node is connected and exchanges information with its physical neighbor(s). This locality helps to build a scalable and robust network. Since, MP2P networks exhibit these characteristics, we chose the MP2P as a network model for our dissertation.

Mobile ad hoc network (MANET) shares similarities with MP2P networks since nodes in both networks are equally equipped and self-organize their topology to find and share information. Nevertheless, there are also differences between MANET and MP2P networks. MP2P refers to the application layer in the protocol stack, while MANET focuses on the network and lower layers. In addition, MP2P mainly addresses the content-centric applications and their deployment while MANET focuses on routing and related issues on the network layer.

1.1　Research Contribution

In this dissertation, we particularly focus on efficient data dissemination in wireless mobile networks. Data dissemination is a basic service for wireless mobile networks, which acts as a building block for all other applications in this paradigm. We engineer three interrelated contributions to this basic service of wireless mobile networks.

- First, we propose a localized demand based data dissemination/diffusion scheme (Spatial-Popularity based Information Diffusion (SPID)) among the nodes in a network. We then simulate the scheme on a synthesized network model. To see how it deals with a real-life environment, we also test our scheme on the data of existent traffic in a big city. In both cases, our scheme outperforms the existing techniques of data diffusion.

- Second, we design an analytical model with the Markov process for single object diffusion, which represents the methodology of our data diffusion scheme SPID. In this analytical model, we also consider scheduling in wireless networks, mobility patterns, and node speed in a mobile network. This analytical model captures the formal analysis of our SPID scheme for single object diffusion.

- Finally, we delve into a probabilistic analysis of the interaction among the nodes which are involved in exchanging multiple objects. We devise the expression for a node to receive an expected number of objects in the current network condition. Eventually, we estimated the expected time/delay to achieve a particular number of objects for a node given different network scenarios that involve varying number of nodes, scheduling probabilities, and mobility patterns with node speed.

Our scheme and associated analytical models are useful when integrated with data dissemination/diffusion applications such as emergency message propagation in the vehicular ad-hoc network and multimedia content sharing in the mobile ad-hoc network.

1.2　Thesis Outline

The following list presents the brief description of the upcoming chapters.

Chapter 2:　This chapter discusses the preliminary literature review, which serves as a stepping stone for this research. In addition, there is a comprehensive description of the existing research efforts to solve similar problems.

Chapter 3: Chapter 3 describes the architecture of the system in detail. This includes the system model, the communication system, and the comprehensive description of the internal components of the proposed system.

Chapter 4: This chapter presents the proposed method SPID for data dissemination in wireless mobile networks using MP2P. This chapter also examines the distributed algorithm's capacity for finding the maximal independent set algorithm for radio networks. At the end of the chapter, there is a comparison of the proposed method with existing methods in the literature.

chapter 5: An analytical model that represents the SPID for single object diffusion is discussed in this chapter. The analytical model for single object dissemination based on the Markov process is elaborated here. The chapter concludes by showing how the analytical model and simulation results measure up.

chapter 6: The diffusion of multiple objects using broadcast techniques similar to the SPID scheme is discussed in this chapter. The analytical model presents the estimated delay for multiple object diffusion in a wireless mobile network given the dynamics of the network.

Chapter 7 Chapter 7 draws the conclusions of the research and includes a discussion of the challenges we faced during this research. Following the discussion, the dissertation also sheds light on the possible future research directions of this paradigm.

Chapter 2

Literature Reviews

Data dissemination methods for mobile networks, especially for mobile ad hoc networks, have been actively investigated recently [46,50,54,71,88]. As a result, a handful amount of data dissemination schemes have been proposed in the literature [35,90]. In this chapter, we discuss the most relevant research works that are the stepping stones for our research on data dissemination for wireless mobile networks.

2.1 Tree and Mesh Based Data Distribution

In the recent years, two approaches, namely tree and mesh based solutions have become popular for data dissemination in overlay networks. However, in a conventional tree-based model, downlink bandwidth of a child is constrained by the uplink bandwidth of the parent. SplitStream [15] is a high-bandwidth content distribution system designed to overcome the problem of conventional tree based approach. The main idea is to stripe the content, and distribute the stripes using separate multicast trees with disjoint interior nodes. However, constructing such multicast trees in ever changing mobile networks is impractical.

Dejan et al. have proposed a mesh based scheme to disseminate mission-critical data [45]. The source node split data into smaller segments. They utilize a mechanism for making data deliberately disjoint and distribute among the neighbors in such a way that increases the probability of finding peers with missing data equal for all nodes. In addition, they provide a technique known as RanSub [44] to locate missing data from peers in an efficient manner. Using simulation, they have shown that mesh-based approach achieves twice throughput compare to equivalent tree based approach for data dissemination.

2.2   Flooding - Based Method

Among existing data dissemination methods, flooding based algorithms are the simplest [37, 52, 65]. *Flooding with Self-Pruning* (FSP) [31], with its simplicity and low message overhead, demonstrates excellent performance among neighbor knowledge-based broadcast methods. In FSP, each node records their one-hop neighbors information received through *hello* messages, which are broadcasted by every node in a network at a regular interval. Each node includes information about all of its one-hop neighbors into a message which is used to transmit an object. Upon receiving an object transmitted from a neighbor, a node compares its own neighbor list with the neighbors of the sender, and determines the uncovered neighbors from the sender's transmission. If there exists no uncovered neighbor, the receiver does not re-broadcast the message. Otherwise, it retransmits the object to make it available to more nodes. This flooding method enables reliable data dissemination, because every connected node receives a data object at least once. In a network, where two nodes remain very close to each other and have all their neighbors in common, using FSP would require only one transmission from each node and would suppress the subsequent transmissions of same object. In other situations, FSP does not save significant bandwidth compared to blind flooding. In addition, flooding schemes suffer from the inherent problems of overlap, implosion and resource blindness. Therefore, flooding schemes are not effective and efficient means of data dissemination in mobile environment.

2.3   Seven Degrees of Separation

Maria et al., proposed Seven Degrees of Separation (7DS) system for information exchange between mobile and stationary nodes in P2P fashion [68]. This system exploits the host mobility and spatial locality of information. In 7DS, a peer periodically broadcasts its query to all its neighbors. Upon receiving queries, a peer searches its own cache for the specific object and broadcast that object if it is found. After receiving an object, a node caches the received object for later use. Due to the broadcast nature, 7DS is regarded as epidemic data dissemination scheme. 7DS does not consider priority of specific objects in a network. It does not keep the history of last broadcast data from a peer. Thus, there are redundant transmission in a network which eventually waste significant bandwidth. In 7DS, each peer keeps object for future relay. However, 7DS does not address the storage management of a peer. Thus, a peer may carry objects which will not be required by any other peer in the network. On the other hand, a peer may discard object due to space limitation which may have heavy demand in the network.

2.4 Dissemination via Social Networking

Recently enormous researches has been conducted to disseminate information in mobile networks using the concept of social networking [8, 12, 24]. In social networking people with common interest gather together and exchange their information. In this section, we are going to discuss two of these approaches.

2.4.1 PeopleNet

PeopleNet [61] mimics the the way people seek and exchange information via social networking. A group of peers with common interest form a specific network known as bazaars. The geographic location of bazaars are predetermined. PeopleNet submit specific queries to a specific bazaar and this bazaar is responsible to answer the query. For example, peers interested in financial information in a certain geographic location form a financial bazaar. Therefore, any specific query related to financial information of this geographic area is directed to this bazaar. The queries are further propagated to the nodes inside the bazaar via P2P approach until a match is found. In PeopleNet, peers exchange limited information about their buffer contents for improving query matching. Peers exchange buffer content using a greedy algorithm. To accommodate a new content in a limited storage space, a peer randomly purges content from its storage. Thus, a peer may carry unnecessary object instead of popular object. PeopleNet tries to maximize the matching query for a specific group of users. However, it does not pay any attention to bandwidth conservation while disseminating information for maximizing query matching.

2.4.2 Content Updates over Mobile Social Network

Stratis et al., has proposed a dynamic content distribution service over a mobile network [34]. They have exploited social interactive nature of human being in their proposed scheme. Peers subscribe to specific services and get updated information from the service provider. However, due to mobility and bandwidth constraints, a peer cannot get most recent updates continuously. Instead, when peers encounter each other during "social interaction", they exchange their information. After receiving an object, a peer compares the freshness of that object with the same object that it kept earlier and purges the oldest one. In this way, the most recent information prevails in each peer. The proposed scheme emphasizes on bandwidth preservation of the servers. In this scheme, a server does not allocate equal bandwidth to all its subscribers. Instead, bandwidth of a server is allocated in proportion to the actively social peers among the subscribers. Stratis et al. analytically show that peers in their scheme always get "fresh" information compared to that of equal bandwidth allocation scheme. However, this scheme suffers from serious drawbacks.

First, the scheme that assumes each of the mobile peer does have any bandwidth limitation which is not true in real wireless network. Secondly, the scheme does not consider size of an object. Thus, there is no space limitation for any number of objects. A peer in their system can carry infinite number of objects. However, this assumption has a serious flaw for data distribution in mobile network since mobile devices which has limited storage space, capable of storing a few objects.

2.5 Content Driven Data Dissemination

Thomas et al. have introduced an adaptive content driven routing algorithm, and a data dissemination scheme for mobile peer-to-peer networks [74]. According to their scheme, each node must maintain a content summary of local data, as well as data at remote peers. The content synopses is used to route the query for a data to a node that is most probable to serve the query. Each node uses Bloom Filter [6] to maintain the content synopses local data as well as remote data. The author discusses three method for content summary dissemination.

2.5.1 Immediate Local

In this technique, each peer broadcasts it local content summary to its immediate neighboring peers. Although this method is simple, but it does facilitate the efficient routing towards data. There is only limited information available to make the routing decision for a specific data. As a result, this method chooses random peer to forward queries and generates lots of unnecessary traffic.

2.5.2 Adaptive Local

According to this method, a node transmit local content synopses to selective peers which may or may not be the immediate neighbors. A node select peers for content synopses dissemination whose queries have been successfully answered in the past.

2.5.3 Adaptive Local Remote

A node hosts the content synopses about its content and the content of the remote peer. In adaptive local remote (ALR) strategy, a node broadcasts both the local content synopses and the remote peerścontent synopses to other peers. The major drawback of this scheme

is that it generates lots of traffic during the content summary broadcast where a large amount of traffic is duplicate in the network.

Thomas et al. have showed that their results are promising compared to the conventional flooding schemes in terms of reliability. However, maintaining a consistent content summary for all the peers in a large network incurs excessive overhead. Thus, this approach is not suitable for data dissemination where high volume data dissemination is the prime concern. The author also suggest different data dissemination techniques for static and dynamic peers. Nevertheless, it is difficult to distinguish dynamic peers from the static peers. Specifically, in ALR, which distribute synopses of the remote peer, a false prediction of node mobility can degrade the performance.

2.6 Collaborative Spatial Data Sharing

Compared to client server wireless channel, P2P channels have considerably higher bandwidth. Motivated by this observation, Huang et al. have proposed a spatial data sharing framework among mobile devices [32]. In their framework, a data object in a server is partitioned and mapped into a grid-based structure. Each mobile device in a virtual grid host a portion of data object. The server periodically broadcast the index information of actual data and their corresponding grid location. Like *Content Driven Data Dissemination* as discussed in previous section, each node also broadcasts locally about its contents to its neighbors. Each node builds a routing table regarding data according that index information from the neighboring peers and the server. To retrieve data, each peer first check its own storage. Failure to find data in local storage triggers a peer to access its routing to find the appropriate peer for the data. If none of the available peer has this specific data, the server provides the specific data to the requesting peer. They emphasize on location based queries, and provide a probability-based predictive cost model for cache replacement and routing table maintenance.

There are couple of drawbacks in their assumptions. In their method, a peer should be synchronized with a server all the time. However, this assumption is impractical in MP2P system and snatch the benefit MP2P systems. Secondly, a node stores index of data that resides in remote peer and query for this to data to a peer according to the information in its routing table. However, due to the mobility, the entries in a routing table of a peer may be stale. They did not consider this specific scenario.

2.7 Mobile Discovery of Local Resources

A group of researchers from University of Illinois, Chicago pioneered a rank based broadcast technique in MP2P network. They emphasized on *distance* and *age* of data from the point

and time of the data origination. Here, we provide a summary of works conducted by them in this regard.

2.7.1 Opportunistic Data Dissemination

Sistla et el. first represented an *Opportunistic Report Dissemination (ORD)* technique mobile peers exchange their report or data during their interaction or when they come close each others radio range. Each report is associated with a timestamp at the time of its creation. It is also assumed that each report is also associated with a geographic location at the point of its generation. During report propagation from one peer to another peer, report generation time and location are also propagated. Upon receiving a report, a peer is able to measure the age and distance of this report from the originating point. Due to the spatio-temporal nature of information, a report with smaller age and shorter distance is assigned higher ranking value than the others. Due to the limited storage capacity, a peer keeps only the top ranked reports. In addition, while in exchange, a peer only transmits the high ranking reports to other peers. Sistla et el. compared their work with client/server model and showed the superiority of the work. However, the ranking mechanisms used by these algorithms are very critical, and is not suitable for highly dynamic systems.

2.7.2 Rank Based Broadcast

In continuation of previous researches on efficient data dissemination in MP2P, Wolfson et al. have proposed Rank Based Broadcast (RBB) which is also based on the idea of sptio-temporal property of data [86]. In RBB, a node ranks its segments according the number of queries received from different nodes. A node broadcast the top ranked segments when the *freshness* of the segments surpass a predefined threshold value (g). To calculate the freshness of a segment, a node measures the distance (d) between the location of last broadcast of the segment and the current location. The node also calculates the difference between the list of segments from the last (S_0) and the current (S) broadcasts. Finally, the freshness of the segment is computed as $\frac{d}{2r} + \frac{|S-S_0|}{|S|}$, where r is the radio range of a node. It is well understood that the performance of RBB heavily depends on the choice of the threshold value. Nonetheless, it is critical and quite often impossible to predefine the optimum threshold value for a network. In addition, accumulated ranking for segments without concerning the local demand is not a good metrics for data dissemination. In section 4.2, we show that these metrics for prioritizing contents provide an inferior performance compared to the metrics used in our scheme.

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2.7.3 RANDI

In RANk-Based DIssemination (RANDI), Wolfson et al. [85] considered three constraints - bandwidth, energy and storage for data dissemination in mobile network. They intuitively provide a optimal transmission size for a node based on the energy remaining of that node and the amount of bandwidth available for this node. They assume that each node assigns a fraction of remaining energy for data dissemination application. First, a peer calculate the optimal transmission size according to its bandwidth. Secondly, the node calculates the maximum transmission size according to energy assigned for data dissemination using the equation 2.1.The node chooses the minimum value among the two transmission sizes.

$$M_{max} = \frac{c.(\frac{\Omega_{avail}}{T_{last}} - g)}{f} \tag{2.1}$$

where Ω_{avail} is the amount of energy available for data dissemination application, T_{last} is the length of time period from the end of last broadcast to a designated time, c is the number of seconds since the completion of the last broadcast to the state of current broadcast, g and f are two linear coefficient of WLAN [21].

A node ranks each *report* or data unit in two different ways; consumer rank or broker-rank. When a node encounters another node, they exchange index and query information. According to the query, a node ranks the report which known as consumer-rank. Since, this node consider the query from only one node, the rank is either 1 or 0 for each of the report. A report is ranked 1 if it is in the query list from the requesting node, otherwise this report is ranked to 0. To utilize the bandwidth efficiently, RANDI algorithm chooses smaller reports whose rank are 1 constrains to the transmission size. If there is still available space transmission bucket after filling with all the reports with rank 1, RANDI considers the reports with rank 0. The reports with rank 0 are evaluated for broker-rank. Although the reports with rank 0 are not requested by the requesting node, the sender node transmits those reports to requesting node considering it as a broker node for these reports. A broker node store reports for future transmission. For broker-rank, each report is assigned a value of a ratio of total query for this report in the past and the size of the report. Then the reports are sorted descending order according their broker rank. The topmost report are considered for transmission. RANDI also uses the same policy whenever a node broadcasts its reports to all its neighboring nodes considering them as broker of the reports.

There are couple of drawbacks in RANDI algorithm. Firstly, they did not consider the amount of energy consumed during the index and query exchange period. Secondly, a node unicast index to a particular node and also unicast the required data to that node. However, consider a scenario where more than one neighbors of the sender node require exactly same report. The sender node in RANDI repeat the entire operation for each neighboring node. Thus, RANDI wastes both bandwidth and energy of the system. Thirdly, RANDI does not

consider the local demand for broker-rank. A report may be popular in the past, but it may not popular in the present and future due the spatio-temporal nature of the information. Therefore, a report may be broadcasted to the neighboring nodes continuously for its past popularity without contributing any benefit to the network.

Chapter 3

Preliminary Work

In the beginning of this chapter, we discuss the system model for our proposed scheme. Following the system model, there is a details discussion of the application framework of the whole system. At the end of the chapter, we give brief description of the attributes of each object that to be disseminated throughout the system.

3.1 System Model

In this research, our system model consists of nodes which can move and are equipped with wireless communication capability. These nodes are interested in exchanging information. Let these nodes form a network on-the-fly using an ad-hoc networking technology to establish communication among them. Though searching for hardware technologies to engineer ad-hoc networks is still an active area of research, several of them have already been implemented in WLAN [33] and are intended to be implemented in future cellular networks [48, 53, 55]. In our model, each node participates in forming a P2P network. Let the network be equipped with a low level (lower than application level) single hop broadcast service. All nodes are synchronized and are capable of communicating in, at least, half-duplex mode. While a node is live in the network, it can discover all other nodes within its radio range and exchange information with them. In the remainder of the thesis, we focus on reliable communication at application level, without considering lower level details. Fig. 3.1 shows the considered network model. These mobile nodes receive information or data as objects from either public or private networks, and from user inputs. We consider that each mobile node is equipped with (primary or secondary or both kinds of) memory, as large as to store all the data objects. In the following subsections, we discuss the details of our proposed dissemination scheme.
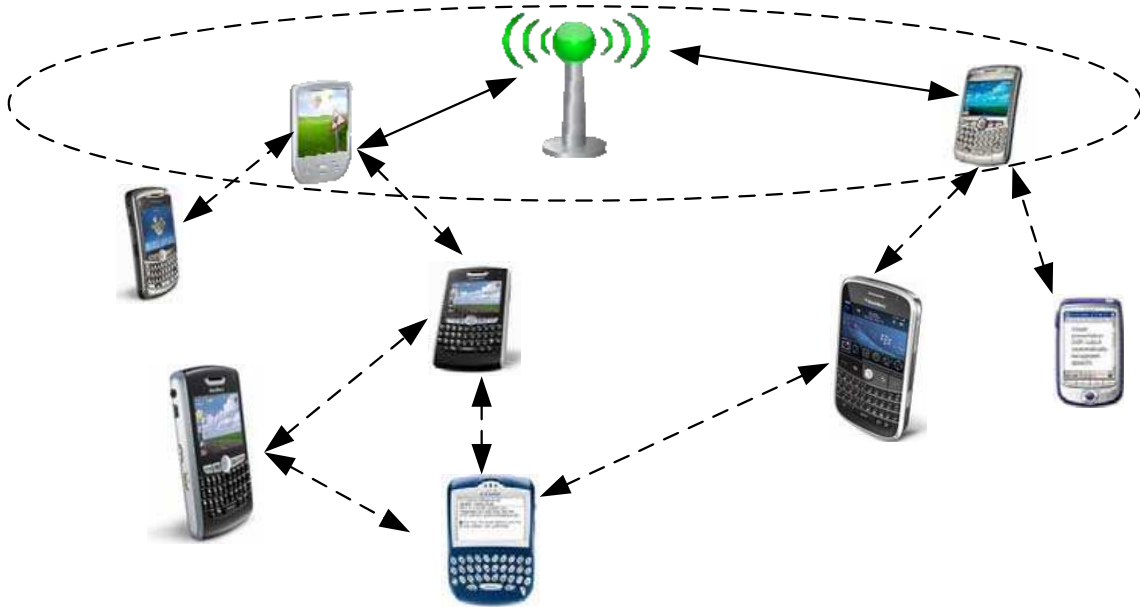
Figure 3.1: Schematic diagram of the network model

3.2 Application Framework

From the protocol layer perspective, the MP2P data distribution system resides in application layer. Fig. 3.2 shows a framework of our proposed data dissemination system for mobile network. Applications that requires data dissemination among mobile peers communicate with the system through a application interface. The *Buffer* represents a symbolic place to hold information for exchange. We are going to provide detail description of each module.

3.2.1 Storage Management Module

This module is responsible for managing the storage and cache of mobile device. This module keeps the detail information of complete objects and segments of objects as well as the index of the objects. This module is also responsible for decision on cache replacement.

3.2.2 Data Segmentation/Reconstruction Module

Data segmentation module collects information of the bandwidth capability of a system from link layer. This information helps this module decide the optimum segment size of an object. Each node transmits as much data as possible in a single transmission. If the segments are pretty small, then there are enormous control overhead. On the other hand,

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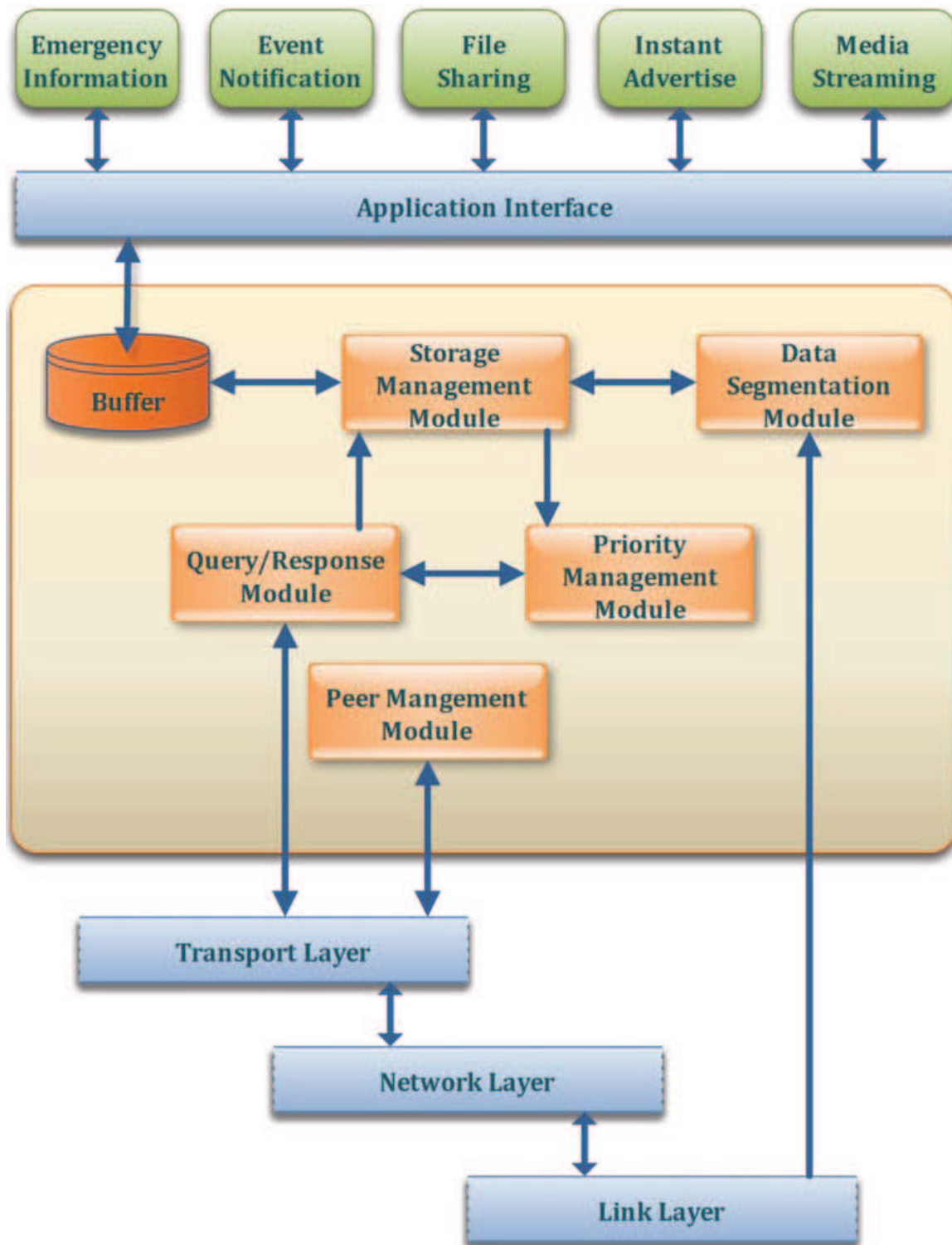
Figure 3.2: A framework for mobile data dissemination system

if a segment size is too large to transmit in a single transmission, there is a wastage of potential bandwidth for unsuccessful transmission of this object. In addition, a retransmission of large segment consumes a significant amount of bandwidth. Therefore, determine an optimum segment size is an important performance metric for data dissemination application. This module maintains coordination with the storage management module. The reconstruction module rebuild an object upon receiving all the segments of that object.

3.2.3 Query/Response Module

Each mobile node generates query for its required object or object segment. This query is transmitted to other mobile nodes. If a node has requested object or segment, it responds back to the requested node. The query/response module takes care of this entire operation.

3.2.4 Priority Assignment Module

A mobile node may not be able to transmit all requested object or object segment due to bandwidth constraints. This module prioritize the segments for transmission according to the system parameter. This module calculated priority of segments based on the number of request for each segment of objects, priority level of objects and the size of objects. This module may also assign priority of query emergency information.

3.3 Object Attribute

Each object is regarded as a report R. Thus each report is associated with a set of attributes. There is an attribute time stamp, st, which contains the time of the data generation. In addition, there is an expiry time, et, for each object. If the time of an object expires, all the data segments of this object are purged from the system. There is another important attribute is the location, loc. The location attribute contains the location of the data from where it is generated. This attribute helps to broadcast the location specific information among the nodes in the overlay network. The size of the content is also important to deliver the small critical data in emergency basis. Thus a report also contains an attribute for its size, s.

It is common that two different source may generate two different objects in the same overlay network. In this case, it is possible to apply the first come first serve basis to distribute the data. However, this may potentially degrade the system applicability if one data is more important than the other one. For example, one node intends to broadcast an object that contains the information about a nearby accident and the closure of the road.

On the other hand, another node wishes to share large a music file among the nodes in the same network. In that situation, the priority of the object is an important criterion. Therefore, each object is associated with a priority p which is also a system parameter.

Chapter 4

Spatial-Popularity based Information Diffusion

In this chapter, we address the key issues of data dissemination in mobile networks and propose an efficient data dissemination scheme among mobile devices using a P2P technique. In particular, we make three major contributions. First, we introduce segmentation for efficient data dissemination among mobile nodes. With segmentation, we can reduce transmission failures and increase bandwidth utilization. Second, we propose a novel data ranking scheme based on the local demand. We have theoretically proven that the proposed spatial ranking provides maximum broadcast utility and ensures complete data dissemination even in an intermittently connected network. Finally, we further improve the ranking strategy with a heuristic based on overlapped neighboring peers. Additonally, we propose a modified distributed maximal independent set (MIS) algorithm for efficient broadcast scheduling among nodes in a chaotic mobile network. With rigorous experiments, we show that our scheme achieves significant performance improvement over the existing methods in terms of both bandwidth utilization and distribution latency.

The remainder of the chapter is organized as follows. In Section 4.1, we describe our system model and propose methods for data dissemination, respectively. Extensive simulation is performed to verify the performance of our proposed data dissemination scheme in Section 4.2. We conclude this chapter with future research direction in Section 4.3.

4.1   Methodology

Consider the number of peers in the P2P network is N, and the peers are designated as p_1, p_2, ..., p_N. The network hosts M distinct objects, denoted as O_1, O_2, ..., O_M. To facilitate transmission of a large object in a limited transmission time window, each object

is divided into equal size segments. Let the segment size be s and the largest object in possession be of K segments, i.e.,

$$K = \max_{1 \leq i \leq M} \left\lceil \frac{|O_i|}{s} \right\rceil \tag{4.1}$$

where $|O_i|$ denotes the size of the object O_i. The i-th object is defined as,

$$O_i = \{os_{i1}, os_{i2}, \ldots, os_{iK}\} \tag{4.2}$$

where, os_{ij} is the j-th segment of object i and $os_{ij} = \emptyset$ i.e., $|os_{ij}| = 0$ for $\lceil O_i/s \rceil < j \leqslant K$.

In SPID, peers use an extended distributed maximal independent set (MIS) algorithm [60] to find non-interfering nodes in a network. The detail discussion of the extended MIS algorithm will be given in Subsection 4.1.3. Members of an independent set can transmit simultaneously without network interference. Note that MIS of a mobile wireless network changes due to mobility of nodes. Let L be the number of maximum independent sets during a cycle t, $S_i(t)$ be the i-th independent set. Then, the following equality holds,

$$N = \sum_{1 \leqslant i \leqslant L} |S_i(t)| \tag{4.3}$$

A distribution cycle is divided into the L number of slots, i.e., the total number of slots in a cycle is equivalent to the number of maximal independent sets. A peer $p \in S_i(t)$ transmits only during the i-th slot. A distribution cycle is further divided into two phases – *index distribution cycle* and *information distribution cycle*. In the first phase of a cycle, peers determine the object segments in demand; and in the second phase, segments with maximum demands are shared with the neighbors.

4.1.1 Determining the Demand

At cycle t, let the content of a peer p be $\mathbb{C}^p(t) = \{O_1^p(t), O_2^p(t), \ldots, O_M^p(t)\}$. Here, $O_i^p(t) \subseteq \{os_{ij} | 1 \leqslant j \leqslant K\}$, i.e., $O_i^p(t)$ represents a subset of segments of object O_i. Assume that when $O_i^p(t) = \{os_{ij} | 1 \leqslant j \leqslant K\}$, i.e., when all the segments of an object become available, peer p can reconstruct O_i from $O_i^p(t)$.

In SPID, each peer maintains an *Available Segment Matrix* (ASM). The ASM matrix is formed by combining *Available Segment Vectors* (ASVs). ASM at peer p is defined as,

$$ASM^p(t) = [ASV_1^p(t) \ ASV_2^p(t) \ \ldots \ ASV_M^p(t)]^T \tag{4.4}$$

where $ASV_i^p(t)$ is defined as,

$$ASV_i^p(t) = [a_{i1}^p(t) \ a_{i2}^p(t) \ \dots \ a_{iK}^p(t)] \tag{4.5}$$

In (4.5), $a_{ij}^p(t) \in \{TRUE, FALSE, NULL\}$ determines availability of os_{ij} at peer p. An $a_{ij}^p(t)$ gets a $NULL$ value when $os_{ij} = \emptyset$, i.e., the object segment os_{ij} does not exist. However, if the segment exists but not available at peer p, $a_{ij}^p(t)$ gets the value $FALSE$. Otherwise, it is assigned a $TRUE$ value. In summary,

$$a_{ij}^p(t) = \begin{cases} NULL & \text{if } os_{ij} = \emptyset, \\ FALSE & \text{if } os_{ij} \neq \emptyset \wedge os_{ij} \notin O_i^p(t), \\ TRUE & \text{if } os_{ij} \neq \emptyset \wedge os_{ij} \in O_i^p(t). \end{cases} \tag{4.6}$$

ASM, is used to determine the object segments available to a peer and is made available to the neighbors during an index distribution cycle. Note that a peer p choose to include only those $ASV_i^p(t)$ in the index broadcast[1] for which $O_i^p(t) \neq \emptyset$.

Due to the bandwidth constraint, a node may not transmit all its available segments to its neighbors in a single time slot. Therefore, a node has to choose a small set of segments, where the set size depends on the transmission ability of the node, particularly due to the length of the allowed time slot in a cycle. A node places those segments into its next information distribution cycle that maximizes the utility of information dissemination by this node.

To calculate utility of segments, each peer also maintains a popularity matrix (PM) similar to ASM, defined as,

$$PM^p(t) = \begin{bmatrix} sp_{11}^p(t) & sp_{12}^p(t) & \dots & sp_{1K}^p(t) \\ sp_{21}^p(t) & sp_{22}^p(t) & \dots & sp_{2K}^p(t) \\ \dots & \dots & \dots & \dots \\ sp_{M1}^p(t) & sp_{M2}^p(t) & \dots & sp_{MK}^p(t) \end{bmatrix} \tag{4.7}$$

where row i of the matrix is for object i, column j is for segment j, and sp_{ij}^p represents the popularity of os_{ij} at the neighborhood of p. At the beginning of an index broadcast cycle, the popularity matrix is initialized with 0. Formally, initialization process can be expressed as $sp_{ij}^p(t) \leftarrow 0$ where $1 \leqslant i \leqslant M \wedge 1 \leqslant j \leqslant K$. At the reception of an index broadcast from neighbor q, peer p updates it popularity matrix according to Algorithm 1. The algorithm increments the popularity of all those object segments which are available at p but not at q.

Complexity Analysis 1. *The worst case time complexity of Algorithm 1 is $O(M)$.*

---

[1]The term broadcast in our methodology refers to single hop broadcast.

Algorithm 1: Computation of popularity
---
1 **foreach** i, *such that* $O_i^p(t) \neq \emptyset$ **do**
2　　**foreach** j, *such that* $os_{ij} \in O_i^p(t)$ **do**
3　　　**if** a_{ij}^q *is FALSE* **then**
4　　　　$sp_{ij}^p(t) \leftarrow sp_{ij}^p(t) + 1$;

4.1.2　Selecting Segments to Broadcast

Let the broadcast of segments at cycle t from peer p include a set of segments denoted as $\mathbb{B}^p(t)$. $os_{ij} \in \mathbb{B}^p(t)$, if and only if $a_{ij}^p(t)$ is $TRUE$, $sp_{ij}^p(t) > 0$, and $sp_{ij}^p(t) \geqslant sp_{ik}^p(t)$, where $a_{ik}^p(t)$ is $TRUE$ but $sp_{ik}^p(t) \notin \mathbb{B}^p(t)$. When an index distribution cycle finishes, a node has the updated PM according to its neighbors' requirements. Then this node picks up the segments with maximum popularity value to create a list to be broadcasted to its neighbors during the next information distribution cycle. This process continues until information diffusion in the network completes. In SPID, we define the utility of a broadcast as follows.

Definition 1. *Utility of a segment in a broadcast during an information distribution cycle is defined as the numbers of neighboring peers those find the segment useful, i.e., the number of peers those did not host the segment before the broadcast. Utility of a broadcast is the summation of utilities of all the segments included in the broadcast.*

With the definition, the utility of a segment os_{ij} at peer p during a cycle t is represented as $U^p(os_{ij}, t) = sp_{ij}^p(t)$, and utility of a broadcast as,

$$
\begin{aligned}
U^p(\mathbb{B}^p(t)) &= \sum_{\forall i,j \mid os_{ij} \in \mathbb{B}^p(t)} U^p(os_{ij}, t) \\
&= \sum_{\forall i,j \mid os_{ij} \in \mathbb{B}^p(t)} sp_{ij}^p(t)
\end{aligned}
\tag{4.8}
$$

Therefore, we have the following theorems

Theorem 1. *In SPID, there exists no other broadcast segment set that further increases the utility of the broadcast.*

Proof. The theorem is proved by contradiction. Let $\overline{\mathbb{B}^p(t)}$ be another segment set for a information distribution cycle t, where $U^p(\overline{\mathbb{B}^p(t)}) > U^p(\mathbb{B}^p(t))$. We consider the following cases:

Case 1, For $\overline{\mathbb{B}^p(t)} = \mathbb{B}^p(t)\backslash\{os_{ij}\}$, where $os_{ij} \in \mathbb{B}^p(t)$: we have,

$$
\begin{aligned}
U^p(\mathbb{B}^p(t)) &= \sum_{\forall u,v|os_{uv}\in\mathbb{B}^p(t)} sp^p_{uv}(t) \\
&= \sum_{\forall u,v|os_{uv}\in\mathbb{B}^p(t)\backslash\{os_{ij}\}} sp^p_{uv}(t) + sp^p_{ij}(t) \\
&= U^p(\overline{\mathbb{B}^p(t)}) + sp^p_{ij}(t)
\end{aligned}
\tag{4.9}
$$

Since, $sp^p_{ij}(t)$ must have a non-negative value. Thus, $U^p(\mathbb{B}^p(t)) > U^p(\overline{\mathbb{B}^p(t)})$, which contradicts initial assumption $U^p(\overline{\mathbb{B}^p(t)}) > U^p(\mathbb{B}^p(t))$;

Case 2, For $\overline{\mathbb{B}^p(t)} = \mathbb{B}^p(t) \cup \{os_{ij}\}$, where $os_{ij} \notin \mathbb{B}^p(t)$, if $U^p(os_{ij}, t) > 0$, os_{ij} would have to be included in $\mathbb{B}^p(t)$ by the proposed scheme, unless the size of $\mathbb{B}^p(t)$ becomes larger than the allowable size in an information dissemination cycle. Otherwise, $U^p(os_{ij}, t)$ is 0 and $U^p(\overline{\mathbb{B}^p(t)}) = U^p(\mathbb{B}^p(t))$ which contradicts the initial assumption;

Case 3, For $\overline{\mathbb{B}^p(t)} = \mathbb{B}^p(t) \cup \{os_{xy}\}\backslash\{os_{ij}\}$, where $os^p_{ij}(t) \in \mathbb{B}^p(t) \wedge os_{xy} \notin \mathbb{B}^p(t)$, we have,

$$
\begin{aligned}
U^p(\mathbb{B}^p(t)) &= \sum_{\forall u,v|os_{uv}\in\mathbb{B}^p(t)} sp^p_{uv}(t) \\
&= \sum_{\forall u,v|os_{uv}\in\overline{\mathbb{B}^p(t)}} sp^p_{uv}(t) + sp^p_{ij}(t) - sp^p_{xy}(t)
\end{aligned}
\tag{4.10}
$$

According to the definition of $\mathbb{B}^p(t)$, $sp^p_{ij}(t) \geqslant sp^p_{xy}(t)$ and thus, $U^p(\mathbb{B}^p(t)) \geqslant U^p(\overline{\mathbb{B}^p(t)})$, which contradicts the initial assumption.

All other situations are the combinations of the above three cases. ◻

Lemma 1. *Given any two connected peers, eventually object segments propagate from one to other and both peers host same segments.*

Proof. Let p_1 and p_k be two peers who are connected by the path consisting of the peers $p_1, p_2, \ldots, p_{k-1}, p_k$. Without loss of generality, we assume that p_1 hosts an object segment o_{ij} that no other peer hosts. As p_2 is a neighbor of p_1 and o_{ij} is in demand from p_2, i.e., $sp^{p1}_{ij} > 0$, o_{ij} will be broadcasted over to p_2. Similarly, o_{ij} is propagated to $p_3, p_4, \ldots p_{k-1}$ and finally, to p_k.

In this way, all $o_{ij} \in \mathbb{C}^p(t)\backslash\mathbb{C}^q(t)$ are propagated from p_1 to p_k and vice-versa, resulting in both peers hosting same object segments. ◻

Theorem 2. *Given two peers are connected through an intermittent path, eventually object segments propagate from one to other and both peers host same object segments.*

Proof. Let p_1 and p_k be two peers. Without loss of generality, assume that the path $p_1, p_2, \ldots p_h$ and $p_{h+1}, \ldots, p_{k-1}, p_k$ are stable, and peers p_h and p_{h+1} are connected through intermittent peers $p_{k+1}, p_{k+2}, \ldots, p_N$. Let o_{ij} be a segment that is hosted by only p_1. According to Lemma 1, segment o_{ij} is propagated to p_h. Due to the intermittent neighborhood relation between p_h and $q \in \{p_{k+1}, p_{k+2}, \ldots, p_N\}$, in worst case o_{ij} is propagated to all possible q. Similarly as q has intermittent neighborhood relation with p_{h+1}, o_{ij} is eventually forwarded to p_{h+1} and finally, to p_k.

Similarly, it can be shown that all $o_{ij} \in \mathbb{C}^p(t) \backslash \mathbb{C}^q(t)$ eventually propagate from p_1 to p_k with any finite number of intermediate intermittent peers. $\square$

4.1.3 Distributed MIS algorithm

Algorithm 2: Initialization

---
5 $step = count = 0$;
6 $state = \mathbb{W}$;
7 $p_v = \frac{2^{-\alpha-1}}{n}$;

Moscibroda et.al. proposed a distributed MIS algorithm for unstructured radio networks [60]. They have proved that the proposed algorithm requires $O(\log^2 n)$ time to find the MIS for a given network with n nodes. We proposed a modified distributed maximal independent set algorithm preserving the time bound of $O(\log^2 n)$. We propose to assign a *status* to each node, where *status* gets the value of either COMPETING or WORKING. Besides, each node is in any of the four different states – WAITING ($\mathbb{W}$), ACTIVE ($\mathbb{A}$), CANDIDATE ($\mathbb{C}$) and MISNODE ($\mathbb{M}$). A node with COMPETING status actively participates and exchanges message with neighbors to become a MISNODE. While in a WORKING status, a node makes progress in a passive mode and does not participate in any message exchange.

Upon entering into the network, a node executes the initialization steps, as shown in Algorithm 2, and starts with a $\mathbb{W}$ state. Each node participates in MIS selection process, i.e., Algorithm 3, whenever it has data to send. Thus, each node executes its own MIS algorithm prior to each index and data distribution cycle. However, context (i.e., values of different variables) is preserved between execution of the algorithm. During the MIS selection process, each node also triggers different responses based on different kinds of message reception, as shown in Algorithm 4.

Algorithm 3: Modified Distributed MIS Algorithm
---

8 $status = COMPETING$;

9   **for** $i=1$ **to** *MIS TimeSlot* **do**

10   **switch** *state* **do**   `/* For different state of a node */`

11   **case** $\mathbb{W}$

12   **if** $step \geq 4\mu\delta\log^2 n$ **then**

13 $state = \mathbb{A}$;

14 $step = 0$;

15   **case** $\mathbb{A}$

16   **if** $step \geq \lambda\log n$ **then**

17 $p_v = 2p_v$;

18 $step = 0$;

19   **else if** $status = COMPETING$ **then**

20   **if** `WithProbability`(p_v) **then**

21   restore p_v;

22   send(m_A);

23 $state = \mathbb{C}$;

24   **case** $\mathbb{C}$

25   **if** $status = COMPETING$ **then**

26   **if** $step \geq \lambda\log^2 n$ **then**

27 $state = \mathbb{M}$;

28 $step = 0$;

29   **else if** `WithProbability`$(\frac{\tau}{2^\alpha\log n})$ **then**

30   send($m_C, step$);

31   **else**

32 $step = 0$;

33   **case** $\mathbb{M}$

34   send m_M with probability $q_M = 2^{-\alpha}$;

35   **if** $step = 1$ **then**

36 $state = \mathbb{W}$;

37 $step = 0$;

38   Exit Loop and capture the next cycle;

39 $step = step + 1$;

Algorithm 4: Receive Trigger (Only when not sending)

40 switch $receiveMessage$ **do**

    41 case m_A

        42   **if** $state = \mathbb{A}$ **then**

        43 $state = \mathbb{W}$;

        44 $step = 0$;

        45 $status = WORKING$;

    46 case m_C

        47   **if** $state = \mathbb{C}$ **then**

        48 $\Delta c = |step' - step|$;

        49   **if** $\Delta c \leq \lambda \log n$ **then**

        50 $step = 0$;

    51 case m_M

        52   **if** $state = \mathbb{M}$ **then**

        53 $state = \mathbb{C}$;

        54   **if** $state = \mathbb{C}$ **then**

        55 $state = \mathbb{A}$;

        56   **if** $state = \mathbb{A}$ **then**

        57 $state = \mathbb{W}$;

        58 $step = 0$;

        59 $status = WORKING$;

Algorithm 5: WithProbability

60 input: probability p

61 $s = \begin{cases} true \text{ with probability } p \\ false \text{ with probability } 1 - p \end{cases}$;

62 return s;

Each node sets its status to COMPETING at the beginning of an MIS selection process (line 8) and iterates through different stages for *MISTimeSlot* times which is $O(\log^2 n)$. A node moves from $\mathbb{W}$ to $\mathbb{A}$ state after $4\mu\delta\log^2 n$ iterations. In $\mathbb{A}$ state, after waiting for $\lambda \log n$ iterations (line 16), the node makes attempts to promote itself to state $\mathbb{C}$ probabilistically (line $20 - 23$). To reduce the number of competitors, willing to be in CANDIDATE ($\mathbb{C}$) state, an $\mathbb{A}$ node notifies other competing nodes about its state change to $\mathbb{C}$ (line 22). While a node is in $\mathbb{A}$ state and receives this message, the node steps down to $\mathbb{W}$ state (line 43) and leaves the competition by setting its status as WORKING (line 45). In WORKING state, the node is allowed to elevate to $\mathbb{A}$ state and thus, unlike the original MIS algorithm, reduces waiting time in the next MIS selection process.

To reduce the number of CANDIDATE nodes further, a COMPETING node may broadcast *step* value to its neighbors (line 30). Neighbors having *step*, counting close to the broadcasted value, resets *step* (line $45 - 48$). When a COMPETING node stays in CANDIDATE state for long enough, the node is promoted to MISNODE ($\mathbb{M}$) state (line $26 - 28$). A node with $\mathbb{M}$ state broadcasts its status through m_M message to its neighbors with a probability $q_M = 2^{-\alpha}$ (line 34). All receiving nodes of the message rollback to the beginning of one backward state (line $52 - 59$). The MISNODE node, not receiving any m_M message, captures the wireless channel for data transmission. It is proved in [60] that due to the iterations through different states, the likelihood of more than one node capturing the wireless channel is negligible.

In the original algorithm, all rollbacks (due to messages m_A and m_M) result in execution of MIS process from the very beginning. Whereas, in our algorithm, a rollback simply backs off one step. Moreover, by introducing WORKING status and preserving context in between MIS process executions, nodes are allowed to make progress without hindering the node, capturing the wireless channel. Interested readers may refer to [60] for detail analysis of the algorithm.

4.1.4   Considering Neighbor Overlap

When two peers are very close to each other, their transmission ranges overlap and may have some common neighbors. In such a setup, it is possible that more than one peers are distributing same segments. However, the later distribution may result in small to no utility and would simply waste the available bandwidth of the mobile networks. To avoid this wastage, Each peer q appends its current neighbor list at the end of its data distribution cycle, i.e., the data distribution broadcast at cycle t from peer q contains $\mathbb{B}^q(t) \cup N^q(t)$, where $N^q(t)$ is the list of neighbors of q. After receiving a data distribution broadcast from q, a receiving peer p adjusts the popularity of each segment that it has in common according to Algorithm 6.

We take an heuristical approach, where the popularity of a common item is reduced by

Algorithm 6: Adjusting the popularity

---

63 **foreach** i, *such that* $O_i^p(t) \neq \emptyset$ **do**

64   **foreach** j, *such that* $os_{ij} \in O_i^p(t)$ **do**

65   **if** $os_{ij} \in \mathbb{B}^q(t)$ **then**

66 $sp_{ij}^p(t) \leftarrow sp_{ij}^p(t) * \left(1 - \frac{|N^p(t) \cap N^q(t)|}{|N^p(t)|} \right)$;

---

the proportion of common neighbors (line 66 of Algorithm 6). However, with this approach, following lemma holds.

Lemma 2. *Given that two peers share exactly same neighboring nodes, no object segment is duplicately broadcasted in a single data distribution cycle.*

Proof. Define two such peers to be p and q. There are two possible scenarios : 1) a segment is hosted by only one peer – either by p or q. In this case, the segment cannot be duplicately broadcasted; and 2) both the peers host a segment. Let o_{ij} be a segment hosted by both p and q. Without loss of generality, assume that p captures the wireless channel before q and broadcasts o_{ij} due to its demand. As $N^p(t)$ and $N^q(t)$ are the same, sp_{ij}^q yields 0 (line 66 of Algorithm 6), irrespective of the initial value and hence is not included in data distribution cycle broadcast from q. □

4.2 Performance Evaluation

We have performed extensive simulations to evaluate the performance of SPID. In this section, we present results obtained from our simulations. We compare the performance of SPID with other data dissemination schemes such as RBB [86], and Flooding with Self Pruning (FSP) scheme [31]. Both RBB and FSP schemes are discussed briefly in chapter 2. In original RBB and FSP algorithms, there is no concept of segmentation. To make a fare comparison with SPID, we have modified system models of these algorithms. Nodes in RBB send queries for individual segment instead of an entire object. Therefore, the rank is calculated and assigned according to the queries received for each segment. Each node in RBB exchanges segments of objects during their interaction. Similarly, let the nodes in FSP retransmit segments of objects received from the neighbors. Each node maintains a list of received segments and retransmits segments from the list FIFO basis. For both RBB and FSP, there is no node monopolizing the wireless channel.

In our simulations, a varying number of mobile nodes, ranging from 50 to 600, roam around within a square area of size 450 meters by 450 meters. Initially, these nodes are

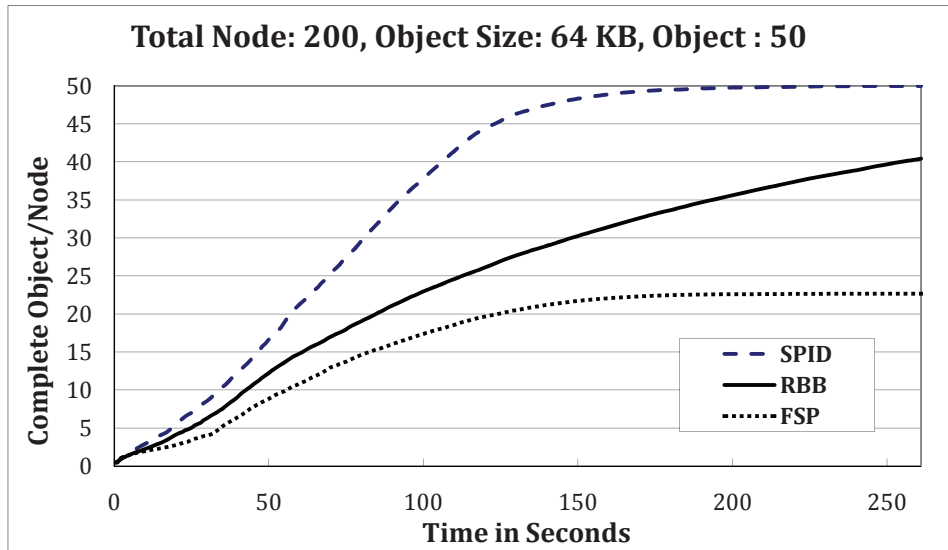**Total Node: 200, Object Size: 64 KB, Object : 50**

Figure 4.1: Experimental results on object diffusion time

randomly distributed throughout the simulation area. Let the mobility pattern of nodes follows the *random way point* mobility model with a mean speed of 30 Km/hr and a mean pause time before changing direction of movement of 10 seconds. In our simulations, our application uses at most 1 Mbps bandwidth of the wireless channel and rest are available for other applications. Let a data transmission range of 50 meters for any mobile node. Considering WLAN technology, these assumptions are very pessimistic and practical. Our simulated networks host 20 to 100 distinct contents in different experiments. Size of the objects varies from 32 KB to 256 KB. Each object is divided into equal size segments of 1 KB. Initially 50% of the total nodes are injected with a randomly selected complete object.

To compare performance among SPID, RBB and FSP, we compute the average number of complete objects received by the nodes in a network at a given point of time. Fig. 4.1 shows this object diffusion pattern. Here, the size of each object is fixed to 64 KB, and the total number of nodes in the network is 200. It can be seen that by using SPID, all nodes obtain all the objects, i.e., 100% object diffusion is achieved by 220 seconds. On the other hand, RBB scheme achieves approximately 70% of information diffusion in the network within the same amount of time. Whereas, FSP reaches only 45% diffusion in the same amount of time. These results indicate that SPID attains significant performance gain compared to RBB and FSP. The performance gain can be explained as follow. In SPID, a node prioritizes segments according to the *localized* popularity or demand in the neighborhood. Once a node distributes segments among its neighbors in a cycle, it is unlikely that the node will get a complete new set of neighbors in the next cycle. As a result, a diverse combination of segments becomes popular from cycle to cycle, and gets distributed.
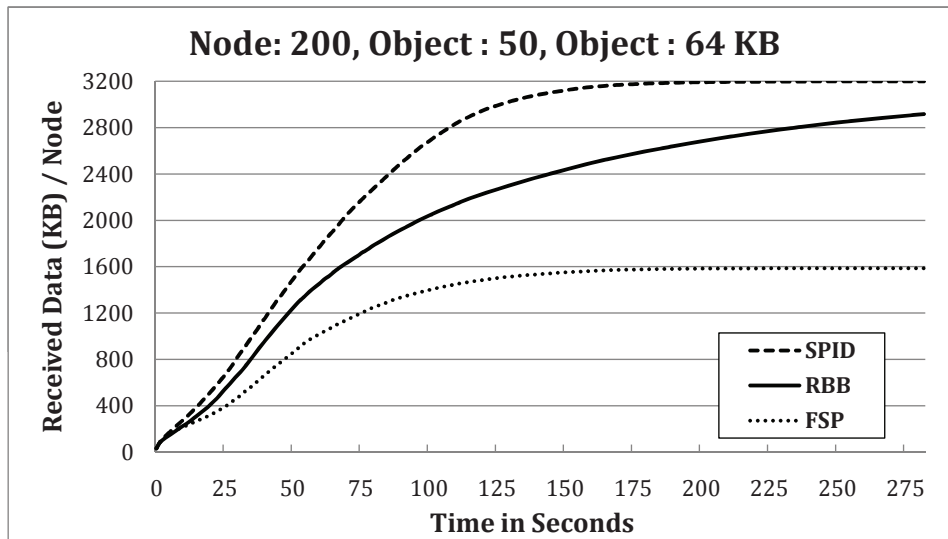
29

Figure 4.2: Experimental results on data distribution over time

Contrary in RBB, a node ranks segments based on queries from different nodes along its path. It does not provide any special consideration to the local demand. In addition, the scheme also considerers the distance from the last transmission point to rank segments. As a result, relative ranks of segments change at a slow pace. Segments, ranking higher, continue to maintain higher ranks with high probability, without considering the actual demand in a neighborhood where the segments are transmitted. Thus, RBB generates a good number of duplicate segments which rarely contribute in increasing distinct objects per peer, yielding poor performance. Similarly, in FSP, a node retransmits a segment irrespective of the demand from the neighboring nodes. Thus, the performance of FSP is worse than SPID and even poorer than RBB (see also the findings in [86]).

Besides complete objects, each node also holds segments of incomplete objects. To make a fair comparison in terms of long run performance among SPID, RBB and FSP, we compute average number distinct segments received per peer over time. Fig. 4.2 shows the gathered value for this metric as the simulation runs from 0 to 280 second. Clearly, SPID acheives superiority to RBB and FSP with a very large margin.

Fig. 4.3 shows the performance comparison of SPID with RBB and FSP for a bounded response time of 200 seconds with variable number of unique objects. In this figure, the delivery rate denotes the ratio of actual number of complete objects diffused with the total expected number of complete objects to be diffused in the network. Using SPID, every node gets a large number of unique objects within 200 seconds for all possible cases. In contrast, while using RBB, the delivery rate is good with small number of unique objects. Increasing the number of unique objects also increases the number of distinct data segments in the
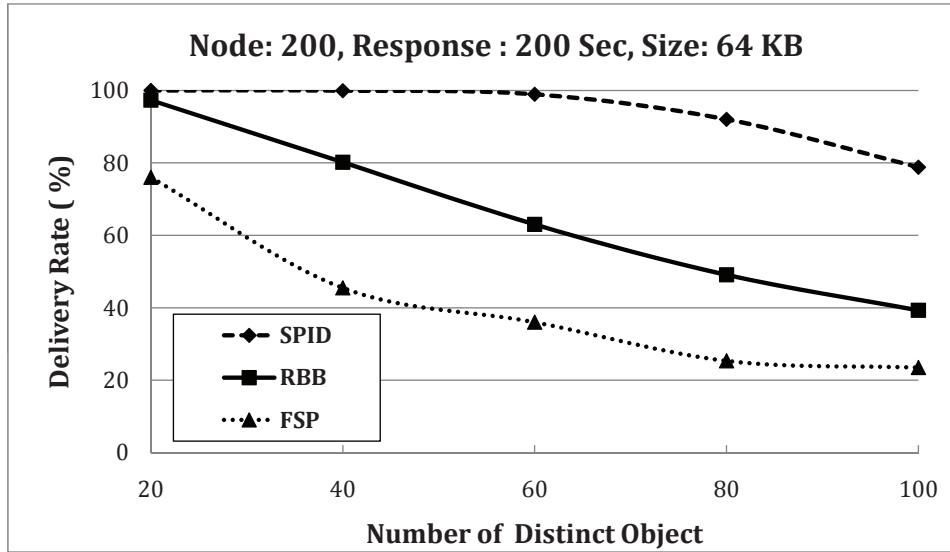
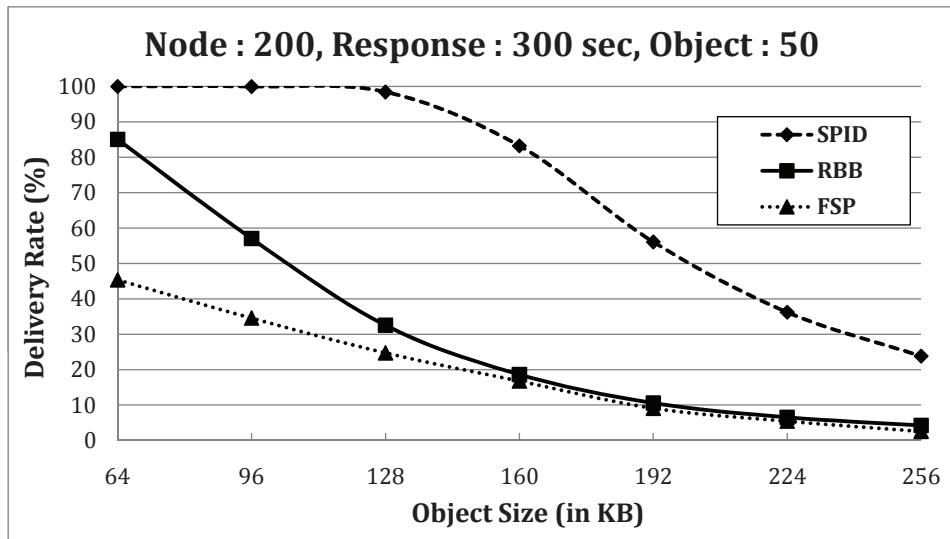Figure 4.3: Delivery rate in a bounded time with distinct objects

Figure 4.4: Delivery rate in a bounded time for different object sizes

network. As RBB continues to transmit segments which does not contributed increasing segments available per peer, with a bounded time, performance degrades drastically. With SPID, when the number of unique objects varies from 20 to 60, 100% diffusion takes place within 200 seconds. However, when number of unique objects increases to the range from 80 and 100, it takes more than 200 seconds to achieve 100% diffusion. Observation shows that initially objects diffuse to the network exponentially. At later stages, it takes much
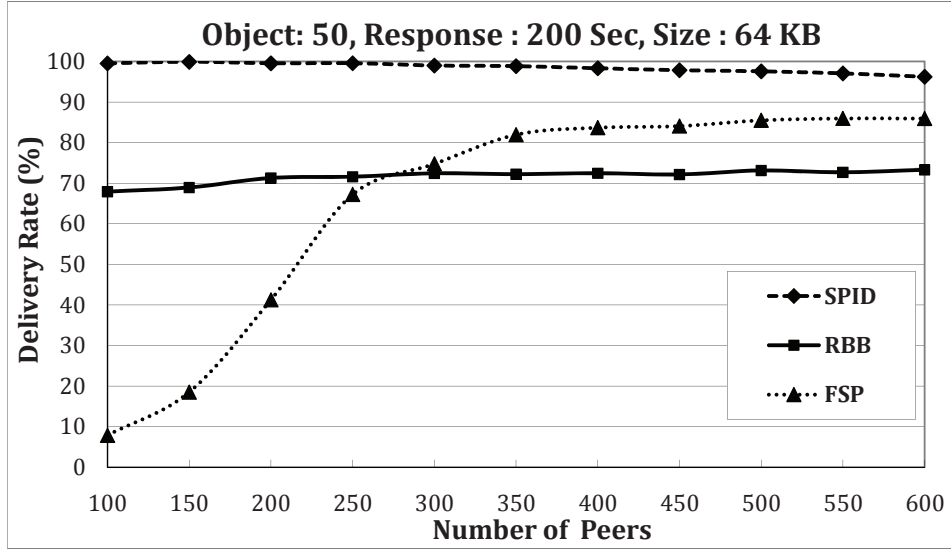
Figure 4.5: Delivery rate in a bounded time for a variable number of peers

longer for each node to obtain remaining few segments. Therefore, although it takes longer time to achieve 100% diffusion for a larger number of unique objects, almost all nodes get more than 90% and 80% of the objects for the cases of 80 and 100 unique objects, respectively. The declined rate of delivery for higher number of unique objects in SPID is much less than that of RBB. In FSP, each node retransmits a packet at most once, and only if the packet reaches any uncovered neighbors. Thus, FSP demonstrates its overall performance is much worse than RBB.

It is interesting to compare the performance of SPID, RBB and FSP with different object sizes in term of delivery rate. In our simulations, we vary the size of object from 64 KB to 256 KB while keeping the number of unique objects to 50. Fig. 4.4 shows that SPID excels RBB and FSP in the similar fashion of Fig. 4.3 where SPID demonstrate it superiority with varying number of distinct objects.

The number of peers in an area affects delivery rate of a network. With 50 unique objects, where each object is of 64 KB size, we vary the number of peers in the network from 100 to 600. From Fig. 4.5, it can be seen that the delivery rate is almost 100% in SPID for each case. The increasing number of peers also generates larger number of sources for data delivery in SPID. Therefore, SPID maintains the same delivery rate for large number of nodes. On the other hand, RBB shows a lower delivery rate in all cases with this bounded response time of 200 seconds. As compared to SPID, useful data dissemination rate is low in RBB (refer to Fig. 4.2), the delivery rate also suffers. In contrary, FSP shows promising results for increasing number of peers where the delivery rate increases exponentially till 350 peers. Then the delivery rate remains steady below 90%. When there
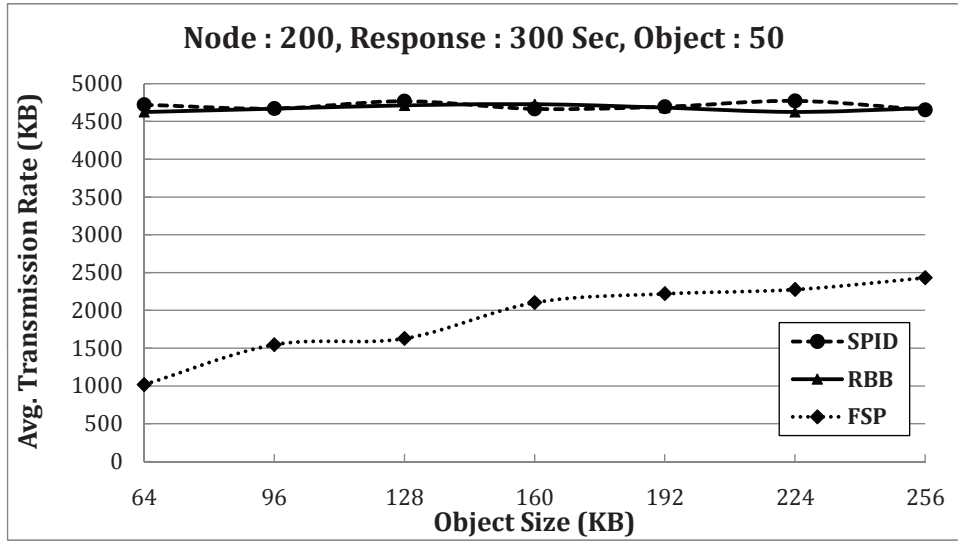
Figure 4.6: Average data transmission in a unit time
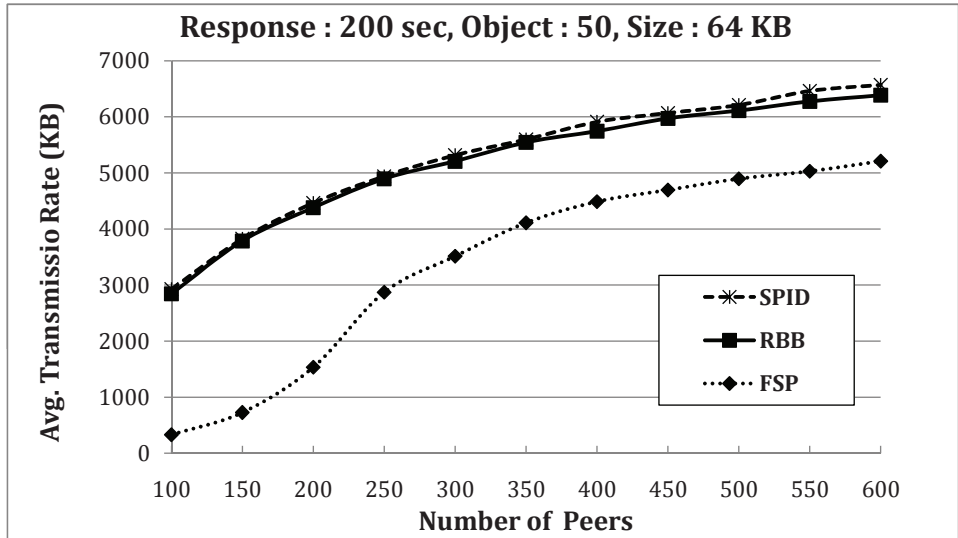
Figure 4.7: Average data transmission in a unit time

is a small number of peers, sparsely distributed in an area, all the nodes are not always connected. As an FSP node retransmits a data segment only once, in a sparse network, nodes are deprived of getting data segments from other nodes. When the concentration of nodes increases, the network becomes connected and FSP demonstrates steady delivery rates.

We have also investigated amount of data transmission by all the three schemes. We

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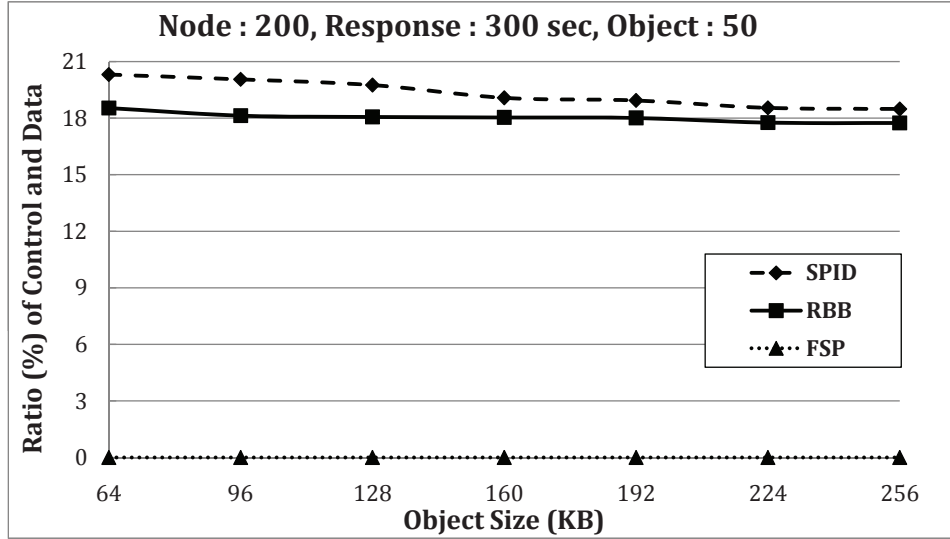Figure 4.8: Control overhead for different object sizes

evaluate the schemes for different object sizes, varied from 64 KB to 256 KB with a total 50 unique objects in a network of 200 nodes. Fig. 4.6 shows the comparison of average data transmission rate in the entire network. The results reveal that a network with SPID scheme transmits on average slightly more data than that with RBB. In RBB, a node transmits a segment only if the rank passes over a threshold value. FSP incurs much less transmission rate. There are two reasons for this: firstly, unlike SPID and RBB, nodes in FSP, do not transmit any index; Secondly, as a segment in FSP is retransmitted at most once, a node can not even utilize the available bandwidth. It should be emphasized that neither RBB nor FSP exploits the utility of a transmission. A handful of the segments, transmitted by these two schemes, are simply useless or provide very low utility to the receivers, resulting in bandwidth wastage. Thus, though RBB and SPID consumes similar network bandwidth, actual data dissemination rate of SPID is significantly superior. Fig. 4.7 shows message overhead for the network when the number of nodes varies from 100 to 600. The figure reveals similar characteristics, we have discussed earlier.

Fig 4.8 shows the average ratio of the amount of control or index data over the total amount of data transmitted in the entire network. An FSP node does not transmit any control data[2]. Therefore, FSP does not have any control overhead. SPID has more overhead compared to RBB. This is because for both SPID and RBB, the total transmission which includes both the index and useful data is almost the same (refer to Fig. 4.7 and 4.8). As a node in SPID acquires (partial) objects more quickly, each node broadcasts more index

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[2]We assume that *hello* messages are part of the underlying network architecture and are not overheads introduced by the flooding scheme.
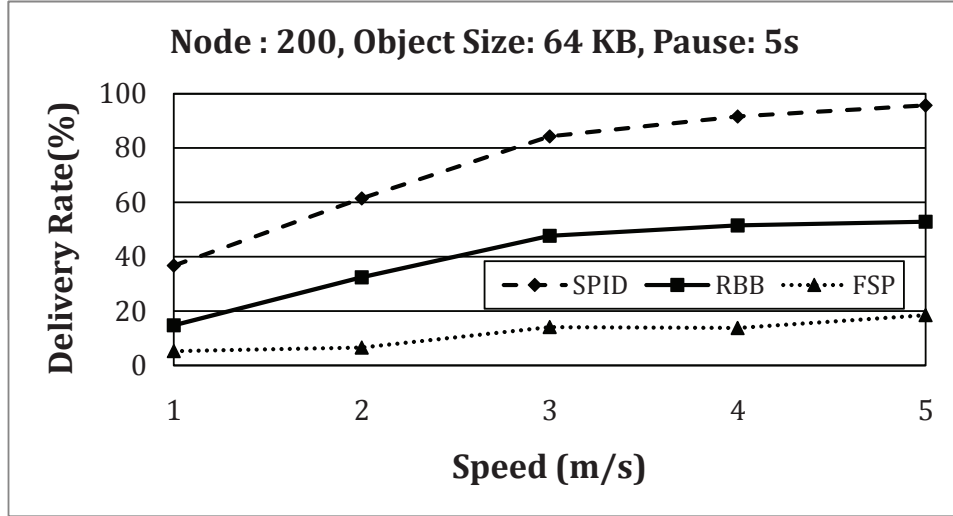
Figure 4.9: Data delivery rate for different speed

information compared to a node in RBB. Again, unlike RBB, in SPID, a node transmits a segment if and only if the transmission gives positive utility. Thus SPID transmits fewer data segments but more control overhead than RBB. Therefore, the ratio of control overhead with actual data is slightly higher for SPID.

User or node movement is a key performance factor on data dissemination in the mobile network. The nodes exchange data with neighbors while on the move. Node's mobility has two nearly opposite impacts on the performance on data delivery. When a node moves from its stationary condition, it meets newer nodes and exchanges required object/segments. On the other hand, when a node moves at a higher speed, it may remain connected to a node for a very short duration depending on the wireless transmission range of the nodes. A node may require a certain amount of time to transmit a segment to another node(s) constraint to its upload and its neighbors' download bandwidth capacity. The connection period may be so small that a node cannot transmit complete segments to its short term neighbors. In a summary, the performance study of the second aspects of mobility, which is out of scope of this dissertation, depends on the speed of a node, its transmission range and bandwidth capability.

We have conducted preliminary investigation on the first aspect of the mobility on data dissemination and validated our intuition through simulation. In this experiment, the total number of nodes in the system is 200, the total number of unique objects is 50 which are initially distributed to the 50% of the nodes randomly. The size of each object is 64 KB. In this simulation, the speed of nodes varies from 1 m/s to 5 m/s which captures nomadic to slow moving vehicles in an urban area. Let a node can exchange at least one chunk of data (32KB) with its neighbors during an interaction while moving with the maximum speed of
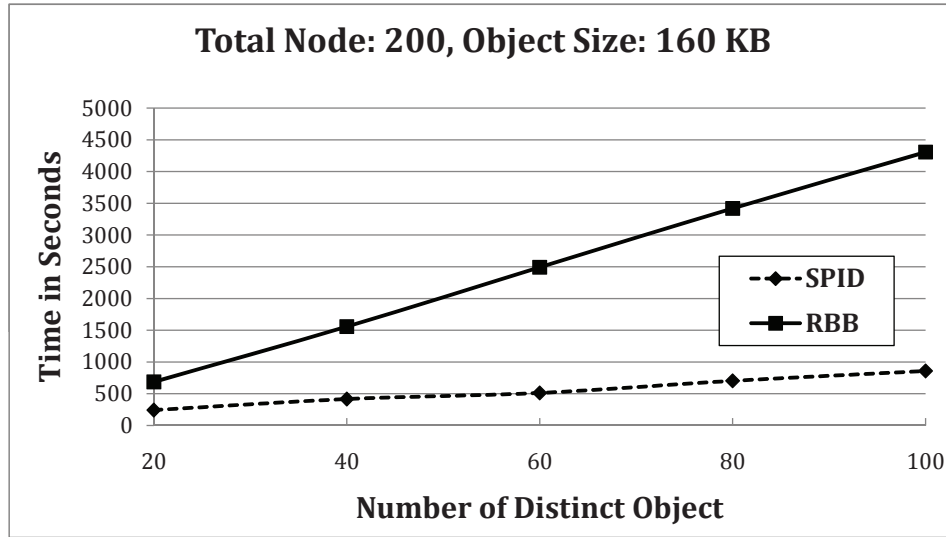
35

Total Node: 200, Object Size: 160 KB

Figure 4.10: Complete data diffusion time for different number of unique objects

5 m/s. The response time is bounded to 200 seconds. Fig 4.9 shows the delivery rates of objects for different mobility speeds. In SPID and RBB, the data delivery rate increases with increases mobility. Nodes encounter new neighbors much faster with increased speed. The result also reveals that object delivery rate in SPID is almost twice than that in RBB. The higher delivery rate for SPID with increasing speed is obvious. When nodes move slowly, their neighbor sets also change slowly. A node exchanges segments with its neighbors only during the first few cycles of their interaction. Later, the nodes do not have any thing to exchange since all the nodes in the neighborhood hosting the same segments. With higher speed, a node meets newer neighbors much frequently and exchanges different sets of data. Therefore, different objects are distributed throughout the network much faster. This phenomena eventually helps escalating the data delivery rate in a bounded time. In contrary, nodes in RBB broadcast data based on the *freshness* of data. The time elapsed from the last broadcast is a key parameter for freshness estimation along with traveled distance. When a node in RBB moves longer distance at higher speed, the freshness of data does not change equally faster since the age of an object does not change with the speed of the nodes. In addition, RBB does not consider local demand which diminishes the benefit of meeting new neighbors more frequently. Therefore, data delivery rate in RBB is much lower than that of SPID in different mobility condition. In FSP, data delivery rate does not increase significantly with the increase of speed. This is because a node broadcasts segments to its neighbors blindly and broadcasts a unique segment only once. Therefore, encountering new neighbors in FSP does not have much impact on data delivery rate and shows significantly poor performance than SPID and RBB.

Since we are interested in diffusing data quickly in a network, it is important to compare
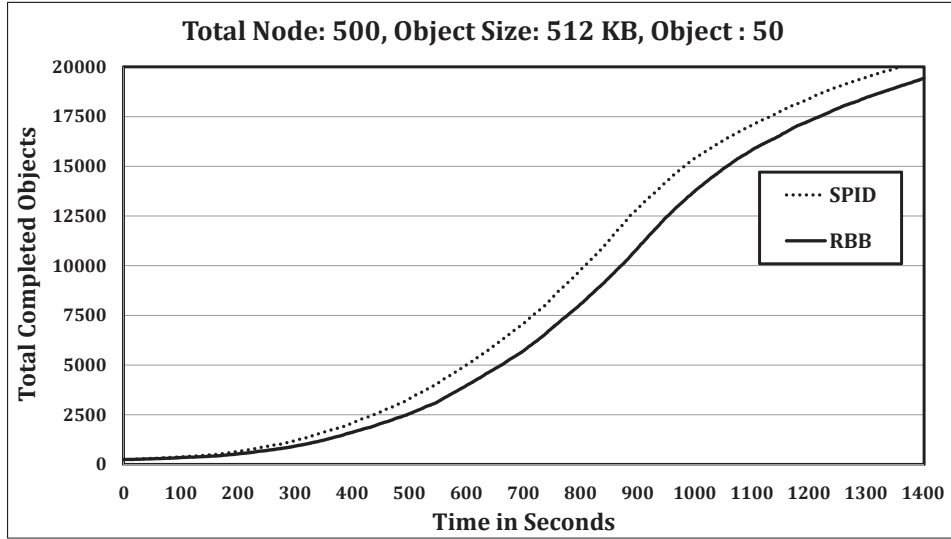
36

Figure 4.11: Objects diffusion time for real life vehicles

the time required for complete data diffusion i.e. all the node gets all the unique objects in the network. Complete data diffusion time for SPID is significantly less than that of RBB as shown in Fig. 4.10. The figure also reveals that the rate of increase in time for RBB with respect to the increase of unique objects is significantly higher than that for SPID. FSP does not converge for any number of distinct objects and hence omitted.

We thrive to see the application of our scheme in real life moving nodes besides synthetic generation of data. Therefore, we have experimented with our scheme on the data collected from vehicles of Shanghai city [84]. More than 4000 taxis in Shanghai, which were equipped with GPS devices and reported their location in real time (see the appendix). We have obtained these data from Wireless and Sensor networks Lab (WSN) in Shanghai Jiao Tong University, China. We have utilized 500 vehicles traces to experiment with our scheme.

Interestingly, the experiment on real life data shows the similar result as well as our synthetic data. In Fig 4.11, the SPID outperforms the RBB in terms of the total number of objects successfully delivered to the vehicles/nodes. The object diffusion pattern in real vehicles traces conform to the result of Fig 4.1. We have measured the delivery rate of different numbers of distinct objects that have been diffused in the vehicular network. Both SPID and RBB schemes have been executed separately for 10 minutes to distribute 256 KB size of objects. In fig 4.12, it shows that SPID always performs better than RBB. This result inclines with our earlier claims in theory and experiment on synthetic data. A similar result follows when SPID and RBB schemes have diffused data in the real life vehicle traces with different object sizes. Fig 4.13 shows the results for two schemes where the total number of objects is 50 and the response time is 10 minutes.
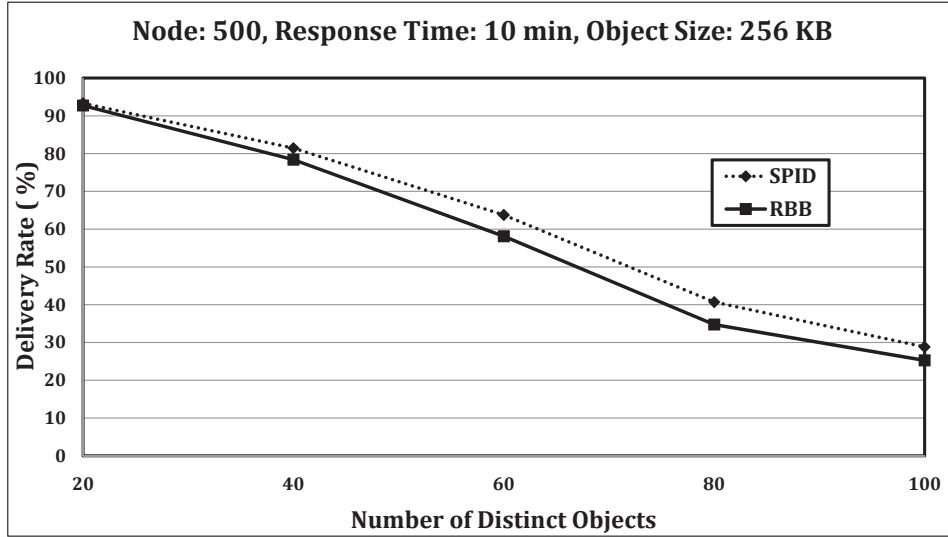
Figure 4.12: Delivery rate of object diffusion for different number of unique objects
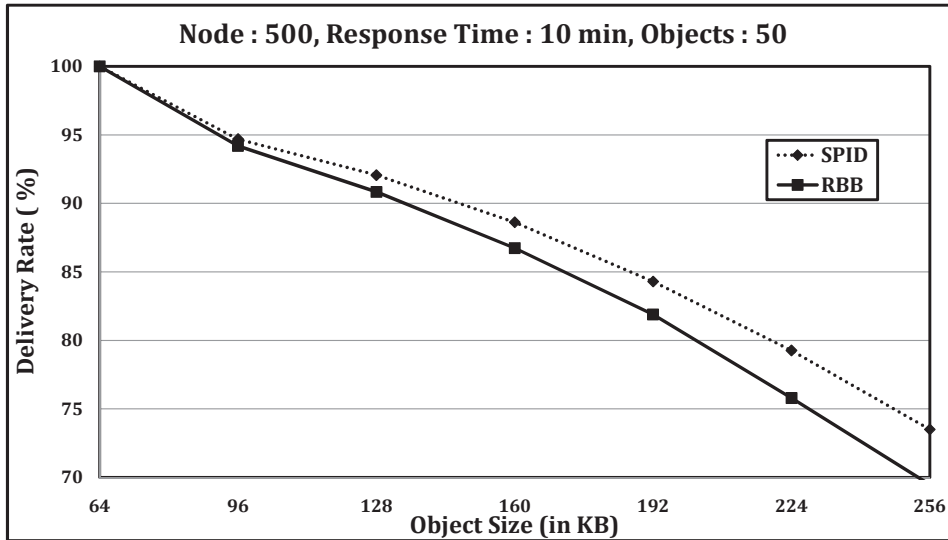
Figure 4.13: Delivery rate of object diffusion for different object sizes

4.3 Conclusion

We have proposed SPID, a novel data dissemination scheme for mobile networks. For efficient data dissemination, we split data objects into segments and rank segments based on spatial demands in a neighborhood. A segment with greater local demands gets higher priority while distributed among neighbors. We have proven that the scheme ensures the

maximum utility. In addition, to accomplish efficient broadcast scheduling among mobile nodes, we have proposed a modified distributed maximal independent set algorithm. We have also considered neighbor overlap for information dissemination, which substantially reduces message overhead into the network. Our extensive simulations demonstrate that SPID gives an immense performance gain over previously proposed ranking, and flooding based schemes.

Chapter 5

Analytical Model for Single Object Diffusion

In the previous chapter, through extensive simulation results, we have shown the basic properties of SPID for data dissemination in wireless mobile networks. In addition, the simulation results also reveal that SPID gains better performance in data dissemination compared to the existing techniques. Although executing the large-scale simulation sheds the light of the emergent behavior of the system, the impact of different system parameters on the performance of the proposed scheme is understood from the very high level.

Due to inexpensive devices and advances in wireless technology, a large- scale mobile distributed system often comprised of hundreds of nodes [28, 92]. It is sometimes infeasible to prepare a test-bed for hundreds of nodes to experiment on the behavior of this system. Therefore, large-scale simulation eventually replaces the urgency of the practical experiments on the test-bed for large system. This simulation gives the diagnostic of the system behaviors and shows the relationship of the different parameters on the performance of the total system. However, simulation can be time-consuming and the large combination of parameter setting for probabilistic system also extends the delay to get the view of the system through simulation. Moreover, sometimes it is difficult to make the strong relationship between the parameters and performance of the system. The design decision of the system relies on the fine-tuning of the different parameters of the system. Thus, developing an analytical model that gives fully or partial view of the system is considered as a necessary tool to measure the relationship of the system parameter with system performance. Nonetheless, the development of an analytical model for large-scale distributed system is a challenging task. In this chapter, we develop an analytical model for single-object dissemination in a large- scale wireless system using the epidemic disease spreading model.

We organize remainder of the chapter into following sections. In Section 5.1, we give a

brief description of existing research works for analytical modeling on data dissemination. In Section 5.2 and 5.3, we describe the system model of the analysis and then we describe our analytical model for data dissemination based on epidemiology, respectively. Extensive simulation has been performed to verify our scheme and is elaborated in Section 5.4. We finalize our discussion in Section 5.5.

5.1 Background and Related Work

Researchers have been actively investigating data dissemination method for mobile networks, especially mobile ad hoc networks [46, 50, 54, 71, 88]. As a result, a handful amount of data dissemination schemes has been proposed in the literature. Most of the model relies on the simulation results for the verification of their system. A few of the works provide the analytical model for the data dissemination.

Epidemic model for disease dissemination is an important research issue in bio-statistics and physiology. The spreading of epidemics is analogous to data diffusion process in many scenarios of communication network. The communication researcher has recently utilized the epidemic model of disease spreading in the field data dissemination for ad hoc network. The mathematical field of epidemic modeling has a long history where both the stochastic and deterministic models are used to study for infectious disease [18, 38].

Reed-Frost [3] model is the most common referenced work in the field of mathematical analysis of epidemiology. However, this model has a lack of generalization for generating function. Later Deitz et al. provided a modified model of En'ko, which eliminates the generalization problem of Reed-Frost model [38].

Maria et al., proposed Seven Degrees of Separation (7DS) system for information exchange between mobile and stationary nodes in P2P fashion [68]. This system exploits the host mobility and spatial locality of information. They used stochastic epidemic model to analytically determine the delay for data spreading to all devices in a network. Their model is a pure birth process which is simple continuous time Markov chain. The author considered for a small number of populations (five nodes) in the network. A similar work is presented by Helgason et al. [64]. They developed a Continuous Time Markov Chain (CTMC) for cooperative wireless content distribution. They categorize the cooperation in three basic types: no cooperation at all, cooperative sharing and generous sharing. In cooperative sharing node share only contents that they are interested while in generous sharing a node relays the content of other nodes. They also extended their model to capture the energy and storage limitation of mobile devices. They calculated the absorption state of CTMC numerically. Their numerical results showed that generous cooperation model diffuses data quicker than any other model. However, an analytical study of the Markov chain model is quite complex even for simple epidemic model of data diffusion.

Moreover, numerical solutions of such a model become impractical when the number of nodes is enormous. On the other hand, we are interested to model the data dissemination for large scale network.

Recently, Ordinary Differential Equation (ODE) based modeling for epidemic style data dissemination has been prominent in literature [27, 91]. The ODE models appear as fluid limits of Markovian models with appropriate scaling when the number of nodes under consideration is large. The major disadvantage of ODE models over the Markovian model is that they provide the moments of the various performance metrics of interest while a numerical solution of Markov chain models can provide complete information about coverage and replication of data.

Khelil et al. developed an epidemic based diffusion algorithm using their simulation results [41]. They observe the simulation result for the impact of node density on information diffusion. From, their observation, they laid out an ordinary differential equation to model the data diffusion pattern. However, their method is unable accumulate the randomness of MANETs.

In [63], Mundinger et al. present data dissemination solution for nodes with different download and upload capacity. They also provided the lower bound for data dissemination among nodes. However, the major drawback of their system is that they rely on their simulation results and provide analysis based on the simulation results.

Recently, Özkasap et al. presented the exact performance analysis of the data dissemination in P2P network using anti-entropy algorithm [66,67]. Their data distribution policy is almost similar to epidemic format of data distribution. Özkasap et al. described three different way of data distribution: *Push, Pull and hybrid.* In push approach, the sender proactive asks and delivers objects to the receiver. In pull method, the receiver queries the required object from the sender and acquired the object. The hybrid system is a simple combination of both push and pull approach. The paper claims the exact performance measure P2P epidemic information diffusion. However, the major drawback of their system is that they did not consider the churn out of peers which is a common phenomena in P2P network. Moreover, they consider only the static P2P network. Therefore, our study is more robust for mobile network, since we consider the mobility and uncertainty in mobile P2P network.

Gossip style data exchange is an important area of research for data dissemination in large scale data distribution [4, 36, 80]. Rena et al. presented a probabilistic analysis of push/pull approach of a gossip based protocol [5]. The difference between our model and the model presented in this paper is the basis of the analysis. Instead of utilizing epidemic diffusion, the authors developed their own analytical model using the transition probabilities of the whole system during data dissemination operation. The authors also investigated the replication and coverage of an object in a large scale distributed system. There was a closed form expression of approximate time and amount or replication of an
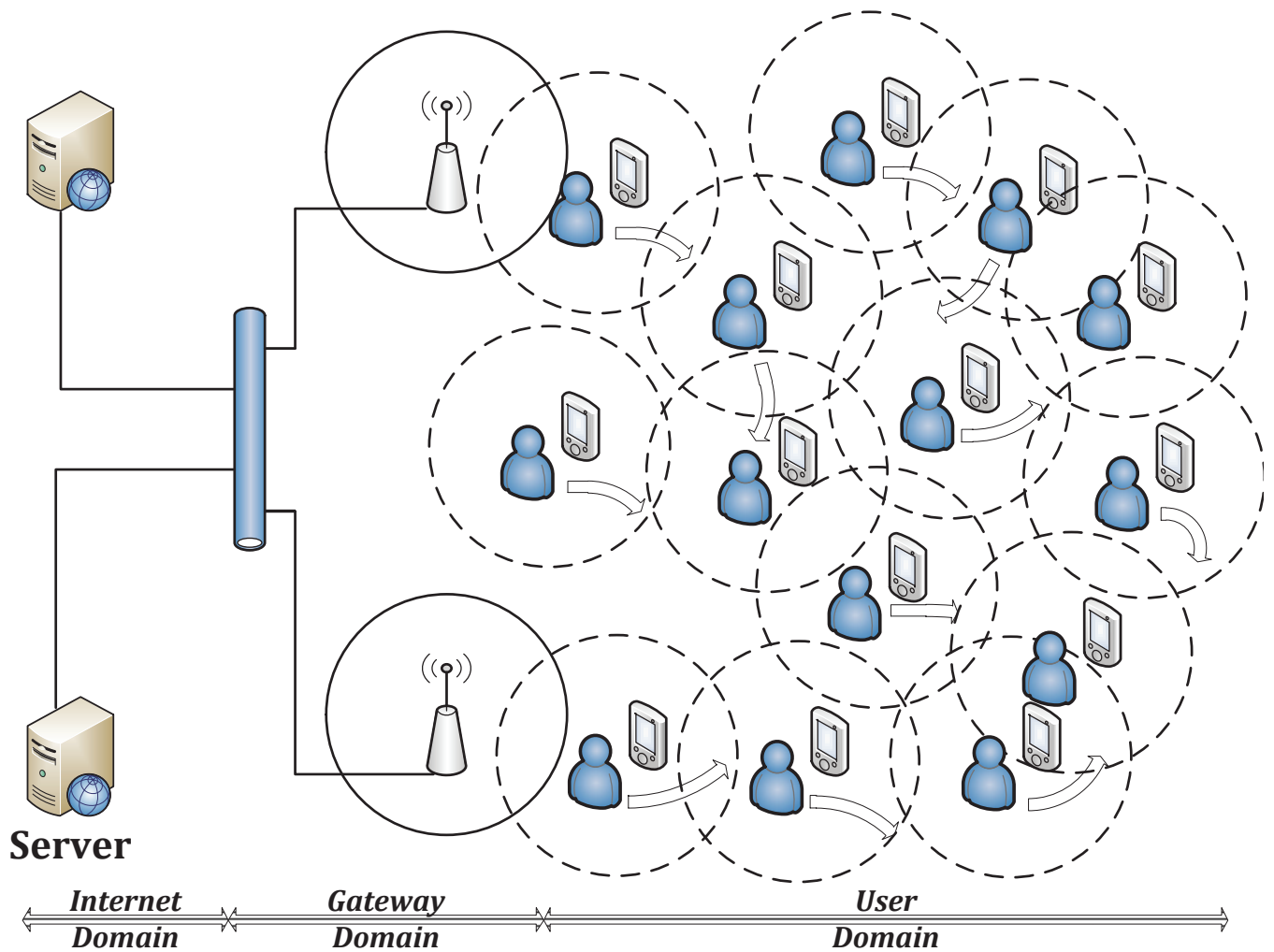
Figure 5.1: Schematic diagram of the network model

object in terms of the number of nodes in a system. The authors also presented the optimal buffer size for each node to maximize the performance of data dissemination in gossip style. However, their findings cannot be applicable in our problem domain. Because, Rena et al. considered static nodes where the nodes were fully connected inside the system. In practice, in large scale mobile network, this assumption is invalid.

5.2 System Model

We consider a network of mobile nodes, interested in exchanging information. We assume that these nodes can form a network on-the-fly using an ad-hoc networking technology

to establish communication between them. Though search for hardware technologies to engineer ad-hoc networks is still an active area of research, several of them have already been implemented in WLAN [33] and are intended to be implemented in future cellular networks [48, 53, 55]. In our model, each node participates in forming a P2P network. We assume that the network is equipped with a low level (lower than application level) single hop broadcast service. We consider that all nodes communicate in half-duplex mode. While a node is active in the network, it can discover all other nodes within its radio range and exchange information with them. In the rest of the chapter, we emphasize reliable communication at the application level, without considering lower level details. Fig. 5.1 shows an example of the considered network. In the figure, the circles outside the wireless gateway and the mobile devices show the radio range of the gateways and devices. The overlapping circles denotes the connection between the devices. The arrows in different direction attached with the users represent direction of movement of the users. These mobile nodes receive information or data as object from either public or private networks, and from user inputs. We consider that each mobile node is equipped with (primary or secondary or both kinds of) memory, as large as to store the object. We consider all objects to be diffused to the entire network. Each of the nodes can transmit the complete object with single transmission. This is also true for reception of data. The transmission and reception operation is considered as atomic and error free.

5.3 Analytical Model Descriptions

In this section, we identify and model analytically the data diffusion process in wireless mobile network using MP2P networks. We formulate the data diffusion process into the epidemic disease spread model and analyze delay for data diffusion in the MP2P networks. We consider a situation, where a single object needs to be distributed to all the interested nodes in wireless mobile network. We discuss the analytical models in the following section 5.3.1.

5.3.1 Preliminaries

Let the number of peers in the P2P network be N, and the peers be designated as n_1, n_2, ..., n_N. These nodes are moving in a closed area of size A with random direction mobility model [14]. The transmission range of each node is r. Let at any moment t, the total number of nodes infected with a specified content/object is C_t. There are $N - C_t$ susceptible nodes in the network and all of them are interested to get the particular object. Let S_t is the number of susceptible nodes in a tth period. Formally, the relation of the

infective, susceptible and total nodes can be expressed as

$$C_t + S_t = N, \qquad \forall t$$

Therefore, this system can be categorized as a demand-based system [35]. In epidemic modeling, a healthy person gets infected by the transportable disease when s/he meets an infected individual. Even multiple persons can be infected at the same time. To resemble the real life scenario of broadcast, we consider that an infected node can transmit data to multiple susceptible nodes in a single transmission.

Consider the total number of new infected nodes in the $t+1$th time is C'_{t+1}. Therefore, the total infected nodes in the $t+1$ time is

$$C_{t+1} = C_t + C'_{t+1} \tag{5.1}$$

Consider an infected node has k neighbors. The probability that any of the neighbors is susceptible can be derived as

$$\alpha = \frac{S_t}{N-1} \tag{5.2}$$

We also need to consider two facts of wireless mobile network: mobility and transmission error due to contention. In a mobile network, the nodes are not stationary in a place. Instead, they are moving in a different direction. Therefore, we need to identify the probability of meeting between nodes in a network. Additionally, in the wireless network, multiple nodes are able to transmit concurrently. When a node gets data from multiple nodes simultaneously in a wireless environment, none of the data are correct due to reception error. Therefore, it is not guaranteed that the contact between an infected and susceptible generates a successful event of content transmission. Let β is the meeting probability of two nodes in a network and γ is the probability of successful exchange of data between interested peer in a wireless mobile network. Therefore, a susceptible will be converted to an infective with the probability,

$$p = \alpha \times \beta \times \gamma \tag{5.3}$$

The nodes in the mobile network infected with objects independently. The independence of the infection events motivates us to model the demand-based data diffusion in the wireless mobile network with chain-binomial model. In the chain-binomial model, the number of susceptible node that will be infected in the next time cycle follows the binomial distribution with parameter S_t, p. Thus, the one step transition probability of the entire
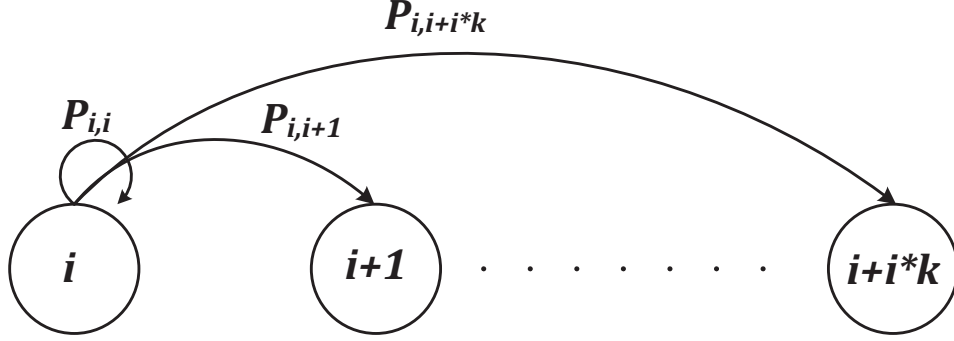
Figure 5.2: Transition probabilities from i^{th} state to next states for Markov Chain

system is,

$$
\begin{aligned}
P_{ij}[C_{t+1} = j + i | C_t = i] &= \binom{S_t}{j}(p)^j(1-p)^{S_t-j} \\
&= \binom{N-i}{j}(p)^j(1-p)^{N-i-j}
\end{aligned}
\tag{5.4}
$$

In the (5.4), the state i denotes the total number of infected node is i, and the state j denotes the total number new infected nodes is j. Since the state j completely dependent on the current state i, we can model the entire process as *Markov process*. Fig. 5.2 shows the transition probability graph for Markov process. Fig. 5.2 shows all possible transitions from state i to another state. Here, the state number inside the circle actually represents the total number of infected node in the current state.

Consider that an infected node has an average of k number of neighbors in a state i. Therefore, the maximum number of newly infected nodes in the next state is the minimum between the total susceptible nodes and the total number of susceptible neighbors of currently infected nodes. Formally,

$$
\max(j) = \min(S_t, \alpha \times i \times k)
\tag{5.5}
$$

Therefore, the expected number of new infected nodes in the next step is

$$
E[C_{t+1} = j + i | C_t = i] = \sum_{l=0}^{\max(j)} \binom{S_t}{l}(p)^l(1-p)^{S_t-l} \times l
\tag{5.6}
$$

There is a critical parameter k which is the average number of neighbors of an infected

node at each stage. In this analytical model, we assume that the nodes are uniformly distributed in the whole network area. Therefore, node's radio range plays an important role for identifying the number of neighboring nodes. A good approximation is to find the ratio of the covered region of the infected node to the total area of the entire region. This ratio can be used to estimate the number of neighbors of an infected node.

5.3.2 Area under the coverage

Finding the area under the coverage of the multiple infected nodes' radio range is a challenging task. Because, in a small area compared to the number of infected nodes and their radio range, there are multiple overlapping of the covered area. Therefore, simple addition of the geometric covered area would not give the actual area covered by multiple nodes. We assume that the wireless coverage of a node is represented by circle where the radius of the circle is equivalent to the radio range. We will use the term circle as the coverage area of nodes radio throughout the section.To get the good approximation, we analytically estimate the area under the coverage in the following.

Consider , there are n equal circles in a unit area where the radius of each circle is r. The area of ith circle is designated as a_i. We can find the actual area under coverage with n circles ϕ_n using the inclusion-exclusion principle:

$$
\begin{aligned}
\phi_n &= \left| \bigcup_{i=1}^{n} a_i \right| \\
&= \sum_{i=1}^{n} |a_i| - \sum_{1 \le i < j \le n} \left| a_i \bigcap a_j \right| \\
&\quad + \sum_{1 \le i < j < k \le n} \left| a_i \bigcap a_j \bigcap a_k \right| - \ldots + (-1)^{n-1} \left| a_i \bigcap \ldots \bigcap a_n \right| \\
&= n \left| a_1 \right| - \binom{n}{2} \left| a_1 \bigcap a_2 \right| + \binom{n}{3} \left| a_1 \bigcap a_2 \bigcap a_3 \right| \\
&\quad - \ldots + (-1)^{n-1} \left| a_i \bigcap \ldots \bigcap a_n \right|
\end{aligned}
\tag{5.7}
$$

In (5.7), the unknown terms to find the actual coverage area is the intersection area of multiple $(2, 3, \ldots, n)$ circles. The intersection areas are calculated in the following detailed description several cases.

Case 1: When there is only one infected node, the area under the radio range of the node is the coverage area of the infected node.
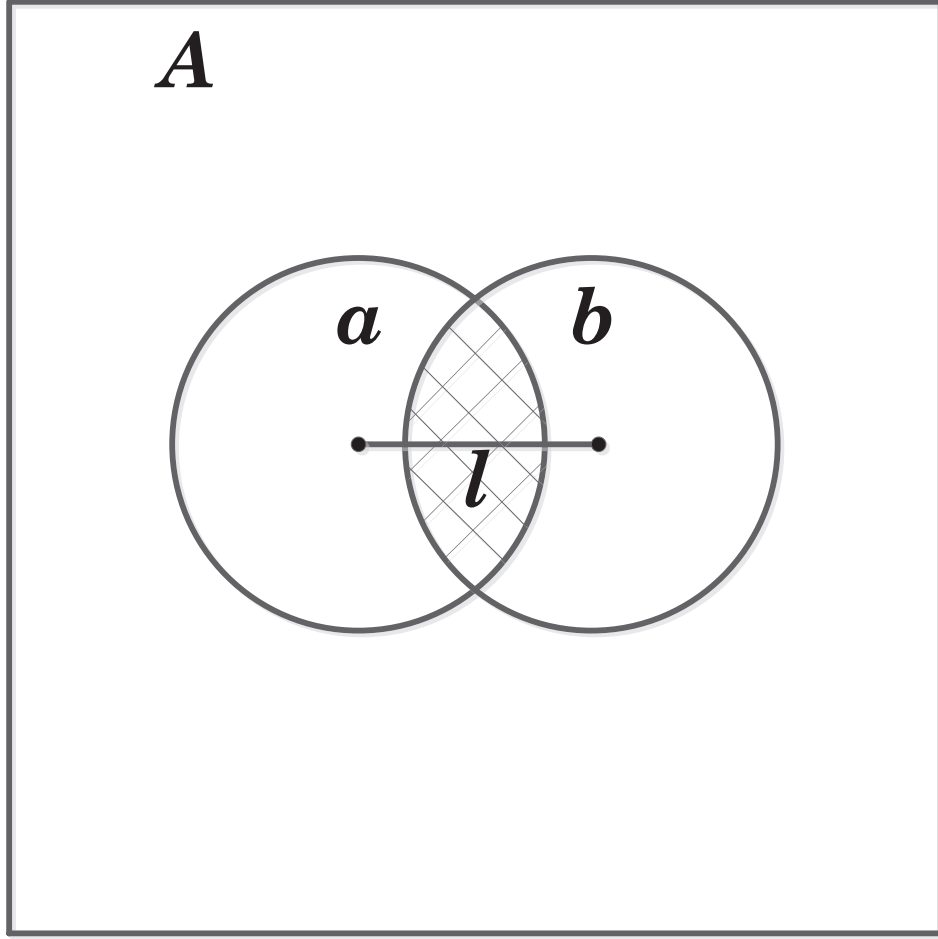
Figure 5.3: Intersection of two circles

Case 2: When there are two infected nodes in an area A, there is a probability that the coverage area of this two nodes will overlap. Figure 5.3 illustrates one of the possible scenarios. In this figure, the circle a and the circle b are intersected each other. The distance of their centers is ℓ. We can find the coverage area for both circle in a unit square A using the following theorem.

Theorem 3. *The expected area of intersection of two equal circles in a unit square is $\int_0^{2r} 2\ell(\ell^2 - 4\ell + \pi) \times \left(2r^2 \cos^{-1}(\frac{\ell}{2r}) - \frac{\ell}{2}\sqrt{4r^2 - \ell^2}\right) d\ell$ where r is the radius of each circle and ℓ is the distance between the centers of the circles and $0 \leq \ell \leq 2r$.*

Proof. Consider the radius of the circles is much smaller than each side of the unit square. Two circles intersect with each other if and only if $0 \leq \ell \leq 2r$. Therefore, the probability that two arbitrary circles in a unit square intersect is equivalent to

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the probability of the distance between the centers of the circles is less than $2r$. The probability $p(\ell)$ of the distance between the centers of the circles, ℓ is [83]

$$p(\ell) = 2\ell(\ell^2 - 4\ell + \pi) \tag{5.8}$$

The intersection area of two circles is dependent on the radius of each circle, r and the distance between the centers of the circle. The intersection area ϕ_2 is given by

$$\phi_2 = 2r^2 \cos^{-1}(\frac{\ell}{2r}) - \frac{\ell}{2}\sqrt{4r^2 - \ell^2} \tag{5.9}$$

In both the (5.8),(5.9), the only variable is ℓ. The value of ℓ can be varied from 0 to $2r$. Therefore, the expected intersection area $\phi_{2(exp)}$ between two arbitrary circle in a unit square is,

$$
\begin{aligned}
\phi_{2(exp)} &= \int_0^{2r} p(\ell) \times \phi_2 \, d\ell \\
&= \int_0^{2r} 2\ell(\ell^2 - 4\ell + \pi) \times \left(2r^2 \cos^{-1}(\frac{\ell}{2r}) - \frac{\ell}{2}\sqrt{4r^2 - \ell^2}\right) d\ell
\end{aligned} \tag{5.10}
$$

$\square$

Case 3: Three circles can intersect each other in 3 ways. Since, the (5.10) utilizes only the mutual intersection of three circles, we are interested about the common intersection area ϕ_3 of circles a, b, c in Fig. 5.4. The following theorem states the intersection area of three circles in a unit square.

Theorem 4. *Consider three arbitrary circles* a,b *and* c *with radius r in a unit square. The probability of mutual intersection of these three arbitrary circles in a unit square is $(2\ell(\ell^2 - 4\ell + \pi)) \times \left(4r^2 \cos^{-1}(\frac{\ell}{4r}) - \frac{\ell}{2}\sqrt{16r^2 - \ell^2}\right)$ where*

- *ℓ is the distance between the centers of any two circles* a *and* b *and $0 \le \ell \le 2r$,*

- *d is the maximum distance from the center of the circle* c *to the center of any circle* a,b *and also $0 \le d \le 2r$*

Proof. We will prove this theorem in two parts. From theorem 3, the probability of intersection between two circles in a unit square is $2\ell(\ell^2 - 4\ell + \pi)$ where the distance between the center of the circle is ℓ. Since, the probability states the intersection of two circle, for example the circle a,b, we need to find out the probability of the intersection of the another circle, c, to both the circles a,b. The condition of intersection of any circle with circle c is that the distance between the centers of the
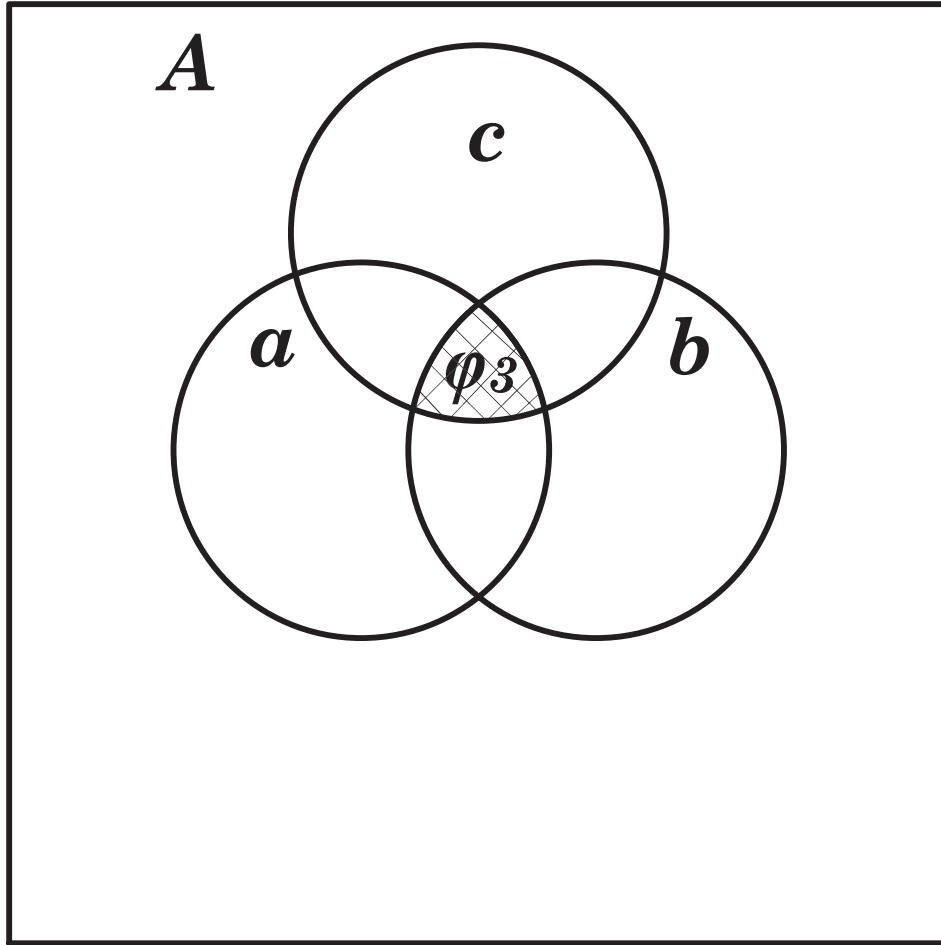
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Figure 5.4: Intersection of three circles

circle and circle $\texttt{c}$ must be less than $2r$. In the Fig. 5.5, the a_0 and b_0 denotes the center of circles $\texttt{a},\texttt{b}$ respectively. We just draw two circles with radius $2r$ concentric to a_0 and b_0 respectively. Both of the circles are shown by dashed line in Fig. 5.5. Since the center c_0 of the circle $\texttt{c}$ must be with the range of $2r$ from both a_0 and b_0, c_0 must lie inside the intersecting area of the two outer circles with radius $2r$. The enclosed area by the arc pqr and psr is the intersection area of this two outer circles.

The area of the square A is equivalent to a unit square. Therefore, the area enclosed by the arc pqr and psr is equivalent to the probability of having the center of an arbitrary circle. The distance between the centers of the outer circle is ℓ. Therefore, the enclosed area is

$$\varphi = 4r^2 \cos^{-1}\left(\frac{\ell}{4r}\right) - \frac{\ell}{2}\sqrt{16r^2 - \ell^2} \tag{5.11}$$
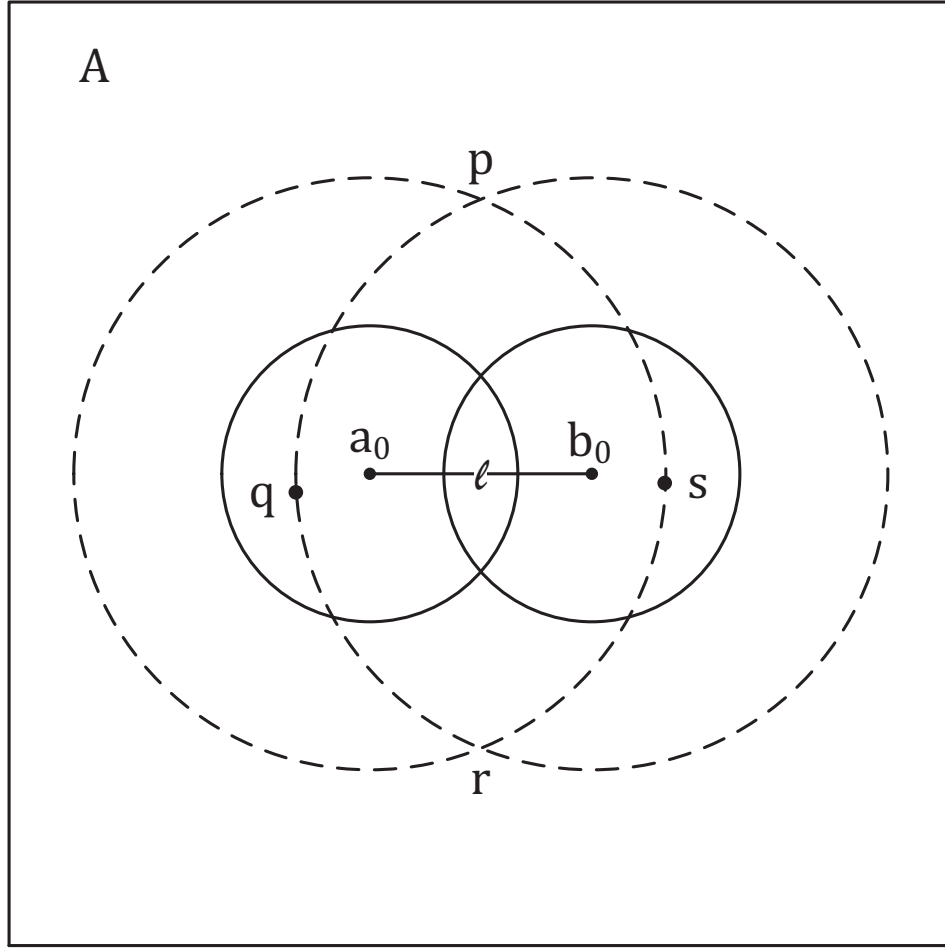
Figure 5.5: Possibility of Third Circle for Intersection

The probability of mutual intersection of three circles is

$$\wp = \left(2\ell(\ell^2 - 4\ell + \pi)\right) \times \left(4r^2 \cos^{-1}\left(\frac{\ell}{4r}\right) - \frac{\ell}{2}\sqrt{16r^2 - \ell^2}\right) \qquad (5.12)$$

$\square$

Corollary 1. *The expected mutual intersecting area of three circles is*

$$\omega = \int_0^{2r} \int_0^{2r} \wp \times p(s) \times \phi_3 \, d\ell \, ds \qquad (5.13)$$

where $p(s)$ denotes the probability density for distance s between the center c_0 and

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any of the centers a_0 and b_0 [78]

$$p(s) = \left[\frac{2s}{r^2}\left(\frac{2}{\pi}cos^{-1}\left(\frac{s}{2r}\right) - \frac{s}{\pi r}\sqrt{1 - \frac{s^2}{4r^2}}\right)\right]$$ (5.14)

and ϕ_3 denotes the intersection area of three circles [23].

Case 4: Calculating of intersecting area geometrically for more than 3 circles is (almost) unsolvable. Because, exponential number of combinations in the arrangement of 4 or more circles exhibit the complexity for finding a closed form equation to calculate the intersection area. Moreover, the intersecting area for 2 and three circles dominate results than intersection of more circles with small number of circles compared to large area. Therefore, we restrain to find the closed form equation of finding the expected area of intersection for more than 3 circles.

In [51], Librino et al. devise a trellis-based iterative algorithmic solution to compute the intersection area for more than 3 circles. The expected mutual intersection area can be calculated using this algorithm with the intersection probability for more than 3 circles. We find combination the arrangement of different number of circles in an area experimentally and generate the probability of intersecting more than 3 circles in an area from this combination.

In above description, we have perceived the way of calculating the mutual intersection area for different number of circles. This values can be inscribed in the (5.7) to calculate the actual coverage area by different number of overlapping circles in an area. Consider the total area covered by the infected nodes C_t is A_1. Then, the value of number of neighbors, k is

$$k = \frac{A_1}{A} \times \frac{N}{C_t}$$ (5.15)

5.3.3   Mobility Parameter

In (5.3), meeting probability β among the nodes is a pivotal parameter. Since we consider a mobile network, the nodes' movement pattern influences the meeting probability. If the transmission range r is small compare to the area size A, it has been shown that the exponential inter-contact time is a good approximation for both random way point and random direction mobility (RDM) model [39]. In [39], Jindal et. al. presented a meeting rate between any two nodes in an area where all nodes follow the random direction modeling. Let $\bar{L}$ is the epoch length, $\bar{v}$ is the average node speed, $\bar{T}_{stop}$ is average pause

time after an epoch, and $\bar{T}$ is the expected epoch duration. Let a node x moving according to the RDM from its stationary distribution at time 0. Let y be a static node uniformly chosen from the total nodes N. The expected hitting time ET_{rd} of node x and node y for the Random Direction model is given by:

$$ET_{rd} = \left(\frac{A}{2r\bar{L}}\right) \left(\frac{\bar{L}}{\bar{v}} + \bar{T}_{stop}\right) \tag{5.16}$$

If we consider the node y is also moving according to the RDM, then the probability distribution of the meeting time EM_{rd} for the RDM has an approximately exponential distribution and the expected value

$$EM_{rd} = \frac{ET_{rd}}{p_m \hat{v}_{rd} + 2(1 - p_m)} \tag{5.17}$$

where $\hat{v}_{rd}$ is the normalized relative speed for RDM, and $p_m = \frac{\bar{T}}{\bar{T}+\bar{T}_{stop}}$ is the probability that a node is moving at any time. The normalized relative speed for this RDM model is $\hat{v}_{rd} = 1.27$ [39].

The expected time it takes for any node x to reach any other node in the network is

$$\tau = \frac{EM_{rd}}{N - 1} \tag{5.18}$$

Therefore, the rate of contact between any of two nodes in a network with N nodes which are moving according to RDM model is

$$\lambda = \frac{1}{\tau} = \frac{N - 1}{EM_{rd}} \tag{5.19}$$

Since the inter-contact times among the nodes are exponentially distributed, we can calculate the value β of (5.1) as

$$\beta = 1 - e^{-\lambda} \tag{5.20}$$

5.3.4 Scheduling Parameter

The contact between an infected and susceptible is not always guaranteeing a successful transmission of an object. There are three folds of contention may occur for the event of transmission in a wireless network. They are *Finite Bandwidth, Scheduling, and Interference.* Here, we only consider the scheduling issue for the transmission. We have also

utilized the transmission probability due to scheduling presented by Jindal et. al. [39]. Let E_{sch} represents the event that a scheduling mechanism allows nodes x and y to exchange a object in a time unit. The scheduling mechanism prohibits any other transmission within one hop from the transmitter and receiver in the same time unit. The probability of this event $P(E_{sch})$ is dependent on the interested transmitter-receiver pair that contending with the $x - y$. Since we consider only the scheduling issue in the wireless network, it is obvious that

$$\gamma = P(E_{sch}) \tag{5.21}$$

Consider there are a nodes within the one hop of the transmitter and receiver pair and there are c number of nodes within two hopes but not in one hop of the $x - y$ pair. Event E_a denotes the existence of a nodes and E_c denotes the existence of c nodes. Let $t(a, c)$ denotes the expected number of possible transmission within the range of $x - y$ pair. By symmetry, all contending pairs have equally liked to capture the time slot and start transmission. Therefore,

$$P(E_{sch}|E_a, E_c) = \frac{1}{t(a, c)} \tag{5.22}$$

Now, we need to calculate the value of $t(a, c)$. We can find the value $t(a, c)$ using (5.22).

$$t(a, c) = \left(1 + p_a p_{ex} \left(\binom{a}{2} - 1 \right) \right) + \frac{a c p_c p_{ex}}{2} \tag{5.23}$$

where

$$p_a = \frac{1}{16} + \frac{A}{4\pi r^2} \tag{5.24}$$

$$p_c = \frac{3}{20} - \frac{A}{5\pi r^2} \tag{5.25}$$

$$\begin{aligned}
A = \int_r^{2r} \frac{x}{2r^2} (r^2 &\cos^{-1}\left(\frac{x^2 - 3r^2}{2rx} \right) \\
&+ 4r^2 \cos^{-1}\left(\frac{x^2 + 3r^2}{4rx} \right) \\
&- \frac{1}{2}\sqrt{(x^2 - r^2)(9r^2 - x^2)})\, dx
\end{aligned} \tag{5.26}$$

The only unknown value of the (5.22) is p_{ex}. The value of p_{ex} can be calculated using (5.23)

$$p_{ex} = \sum_{m=1}^{N-1} \frac{2m(N-m)}{N(N-1)} \sum_{i=m}^{N-1} \frac{1}{N-1} \frac{1}{m(N-m)} \frac{1}{\sum_{j=1}^{i} \frac{1}{j(N-j)}} \qquad (5.27)$$

5.3.5 Getting the Final Result

The value of α, β, γ are derived analytically and can be substituted in the (5.1). Using these values, we can calculate the expected number of new infected nodes from (5.3). In the next section, we will present the rigorous simulation result and compare the result with analytically derived values of infected nodes in each time unit.

5.4 Simulation Results

To verify the analytical model of epidemic diffusion of data, we developed a discrete event simulator in C++. In simulation, we mimic the real time scenario for mobile network. We consider peers use a distributed maximal independent set (MIS) algorithm [60, 75] to find non-interfering nodes in a network. Members of an independent set can transmit simultaneously without network interference. Note that, MIS of a wireless mobile network changes due to mobility of nodes. Consider L be the number of maximal independent sets during the cycle t, $S_i(t)$ be the i-th independent set. Now, the following equality holds,

$$N = \sum_{1 \leqslant i \leqslant L} |S_i(t)| \qquad (5.28)$$

The distribution cycle is divided into the L number of slots, i.e., total number of slots in a cycle is equivalent to the number of maximal independent sets. A peer $p \in S_i(t)$ transmits only during the i-th slot.

In simulation, we focus on a wireless network with different node densities on a square area of $500m \times 500m$. The total number of nodes varies in the areas from 100 nodes to 200 nodes. Initially, these nodes are randomly distributed throughout the simulation area. We assume that nodes mobility pattern follows RDM model with a mean speed of 1 m/s to 5 m/s and mean pause time before changing direction of movement is 0 second. We consider this setting which will represent the customers mobility within a mall to a slow moving vehicle in a city. We assume nodes to be equipped with a standard 802.11 interface. We experiment with different radio transmission ranges from $20m$ to $30m$. Since
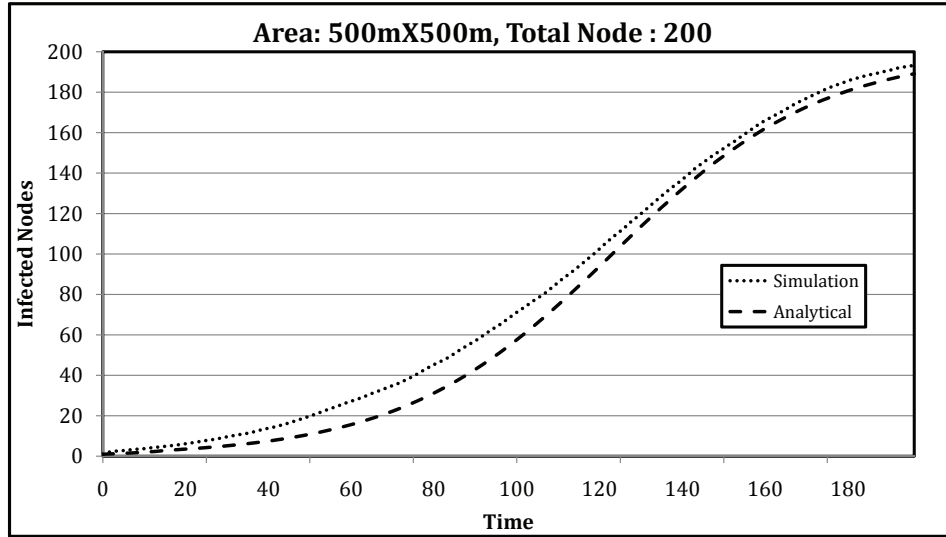
Figure 5.6: Comparison of Analytical and Simulation Model for radio range 20m

we focus on data dissemination in on demand network, we do not simulate cellular access network. However, we account for the delay associated with the download of information items from the cellular network, by assuming a throughput that is 100 times less than the 802.11 network, matching that typically provided by 3G technologies to outdoor mobile users.

This section discusses the validity of the presented analytical model for single object data diffusion through simulation. In this simulation, an object is given to a randomly chosen node in the network. This nodes broadcast this object to its neighbor. This process continues until all the nodes in the network gets that object.

Fig. 5.6 shows the comparison of the analytical model with the simulation result. In this figure, the number of infected nodes is plotted with the passage of time. The result shows that both the analytical model and the simulation result match with close proximity. The analytical model shows little slower infection rate than the simulation result in the beginning. Later, the analytical model coincides with the simulation result. This behavior is expected since all the neighbors of the infected node in simulation effected immediately and so on. On the contrary, every step in the analytical model, the number of neighbors is calculated on the average of the entire area.

In the epidemic data dissemination, the number of nodes and their speed of moving are key factors. We consider different number of nodes moving in a $500mX500m$ area where each node has a radio range of 30 meters. In fig. 5.7, we can observe that the time for object diffusion among all the nodes decreases with the increase of nodes. However, the enormous increase of nodes in terms of data distribution area may not follow the same
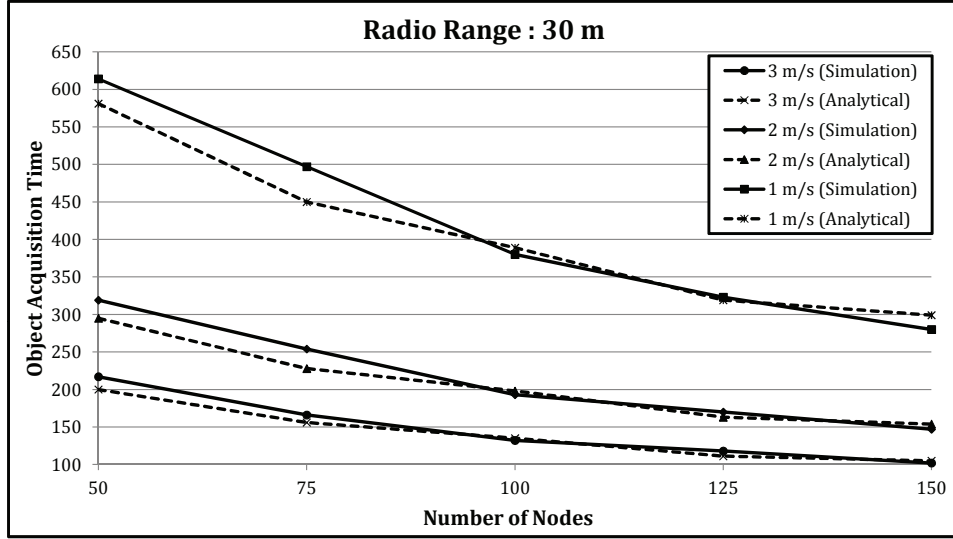
Figure 5.7: Comparison of Analytical and Simulation Model for different number of nodes

result. This fact can also be observed from the same figure. The rate of decrease for data diffusion time decline with the increase of the number nodes. The similar argument also holds for the speed of the nodes. The data diffusion rate increases (alternatively, data dissemination time decreases) with the change of speed of the mobile modes from 1 m/s to 2 m/s. Nevertheless, data diffusion rate increases when the nodes move with 3 m/s. However, the rate of increase is sufficiently lower than the previous step. Our proposed analytical model is able to anticipate all the above scenarios as expected. In our analytical model, we consider the number of nodes, the scheduling among the nodes for data broadcasting as well as the speed of the nodes. Fig. 5.7 shows that our analytical model gave the almost accurate result.

Fig. 5.8 shows the impact of radio range and the speed of nodes for data dissemination. It is obvious that larger radio range will disseminate more data. In that situation, a node can communicate with more nodes at a time. However, it also apparent that larger radio range will incur more collisions. The scheduling among the nodes permits less frequently data broadcast than the smaller radio range. So, the data dissemination does not increase linearly with the increase of radio range. In the previous paragraph, we have already discussed the impact of the mobility for data dissemination. Fig. 5.8 shows the analytical model and simulation result of data dissemination among 100 nodes with different radio range and the speed of nodes. The difference of data diffusion time in between the analytical model and simulation results is less than 10% in all cases. Therefore, the result reveals that our proposed analytical model provides an optimistic prediction about data diffusion pattern and delay for entire network. The main reason of near perfect prediction is that this model also considers the average number of neighbors of infected nodes at each step
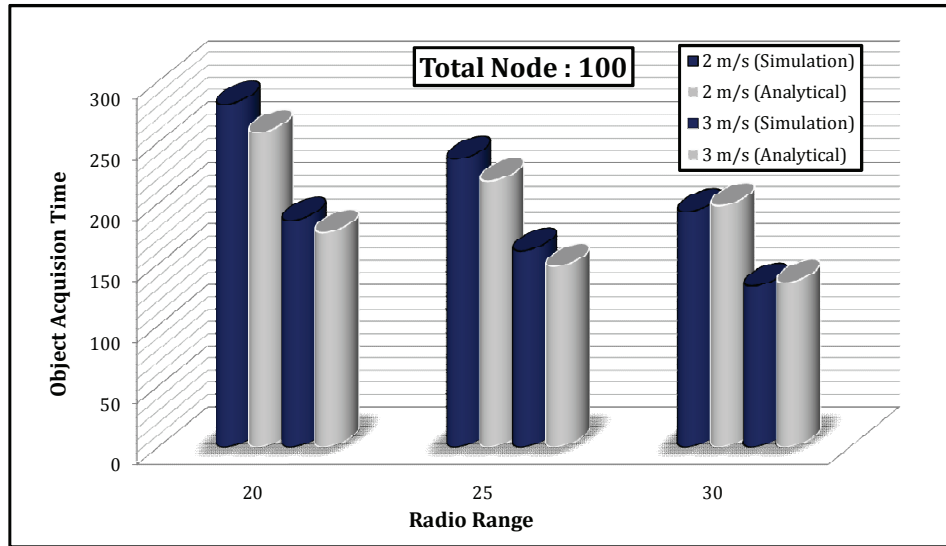
Figure 5.8: Comparison of Analytical and Simulation Model with the impact of mobility

of progression.

5.5 Conclusion

We have developed an analytical model for contagion data dissemination in wireless mobile network. Our analytical model estimates the expected time/delay of object diffusion among the nodes in a mobile network. In this chapter, the suitability of the epidemic process using spatial demand-based algorithm for information diffusion is analyzed. Since, the number of nodes in the system is fixed and the next state of the system completely depends on the current state, we have modeled the whole system as continuous time Markov chain without any assumption. In wireless mobile network, mobility and scheduling among the nodes for data broadcast, play an important role. Therefore, we adopt the mobility and scheduling uncertainties in the transition probabilities of the whole system from one state to another. This model has been verified with rigorous event-based simulation. Simulation results show that our analytical model is accurately apprehended the dynamics (the number of nodes, their radio ranges and speed of the nodes) of data dissemination in wireless mobile network.

Chapter 6

Analytical Model for Multiple Object Diffusion

In the previous chapter, we have discussed about the necessity of an analytical validity of a scheme. In that chapter, we have presented the analytical model for single object dissemination in wireless mobile network. The emerging results from the analytical model of single object dissemination inspired us to delve into the probabilistic analysis of multiple object dissemination in wireless mobile networks. The multiple object dissemination is the building block for any size of object dissemination. Nevertheless, any size of an object can be chopped into small fixed pieces for easy distribution. In the chapter 4, we have shown the methodology of multiple object dissemination where each object is split into smaller fixed size pieces. The priority assignment module of SPID, assign priority for each of the pieces independently according to the urgency of pieces in the locality by the neighbors. Therefore, the analysis of multiple object dissemination depicts the clear picture of correlation between the different parameter object dissemination with the performance of the proposed data dissemination scheme SPID.

In single object dissemination, a node receives an object once. Then the node becomes a sender and transmits this object to any number of nodes. Therefore, single object dissemination can be modeled with epidemic disease spreading due to the similarity. On the contrary, in multiple object data dissemination, a node is going to receive multiple objects from different neighboring nodes as long as it is interested on those objects. A node also disseminates several objects to its neighbors according to the need of that objects in the neighborhood. Thus, the epidemic decease spreading model cannot be applicable for the analysis of multiple object dissemination. The multiple object dissemination requires the probabilistic analysis for spreading objects in each round of data dissemination among the nodes.

The remainder of the chapter is organized as follows. Section 6.1 discusses the prob-

abilistic calculation to formulate the multiple object dissemination problem. The model has been verified with simulation results and the discussion takes place in the section 6.2. Section 6.3 conclude the chapter with concluding remarks.

6.1 Description of the Model

In this section, we derive the probability of unique objects and expected number of unique objects received by a node in each round. Later, we incorporate the wireless scheduling and mobility parameter in the derivation. Thus, the final equation gives the details about the relationship of different parameters with the object acquisition time.

6.1.1 Preliminaries

Consider a system where multiple objects will be disseminated in a network. Let there be m number of objects to be distributed in a network of N nodes where $N \geq m$. Initially, each of the m objects will be held by a single node. Therefore, the probability for a node of holding any object is $\frac{m}{N}$. Consider that a node n_0 has O_t objects at any instant t. The initial and terminal condition of O_t can be described as,

$$O_0 = \frac{m}{N} \tag{6.1}$$

$$O_\infty = m \tag{6.2}$$

Each node has k average neighboring nodes. Without loss of generality, we can consider that each of the neighbors has also O_t number of objects at the time instant t. Consider a node n_0 and the neighboring nodes of n_0 have w different objects than the node n_0. Consider V_k denotes the set of unique objects among k nodes where each of the k nodes contains $O_t^1 \ldots O_t^k$ objects respectively. O_t^0 denotes the set of objects in node n_0. Formally,

$$\begin{aligned} V_k &\subseteq O_t^1 \cup \ldots \cup O_t^k \\ w &\subseteq V_k \setminus O_t^0 \end{aligned} \tag{6.3}$$

In the next we will show the derivation for calculating the value of w.

6.1.2 Derivation of Unique Objects

The k neighbors of node n_0 holds total $k \times O_t$ elements on average at any time t. We should consider two aspects for calculating the object difference between the node n_0 and the rest of the k neighbors. The aspects are:

1. All the objects which are held by k neighbors may not unique

2. There could be overlap of objects in between the node n_0 and the k neighbors.

To compute the first aspect, we must find the probability of unique objects among two nodes. The following theorem gives the probability of unique objects in k nodes in a network.

Theorem 5. *The total expected number of unique objects held by k nodes in a network is*

$$V_k = V_{k-1} + \sum_{l=0}^{O_t} \frac{\binom{O_t}{l}\binom{m-O_t}{V_{k-1}-O_t+l}}{\binom{m}{V_{k-1}}} \times l \tag{6.4}$$

where there total number of objects prevail in a network is m and each node holds O_t number of objects at time instant t.

Proof. To proof the theorem, we need to establish the base case when the number of node is 0 and 1.

Case k=0 When the number of node is 0, e.g., $k = 0$, then

$$V_0 = 0 \tag{6.5}$$

Case k=1 If we consider only one node, then total number of objects held by this node represents the total number of unique objects. Here, each node contains O_t number of objects at any time instant t. Therefore,

$$V_1 = O_t \tag{6.6}$$

Case k≥2 Consider, two nodes n_a, n_b in a network where each of them holds O_t^a and O_t^b objects at any time instant t among the total m objects in network. The are g objects are in common between O_t^a and O_t^b. The n_b node contain z number exclusive objects
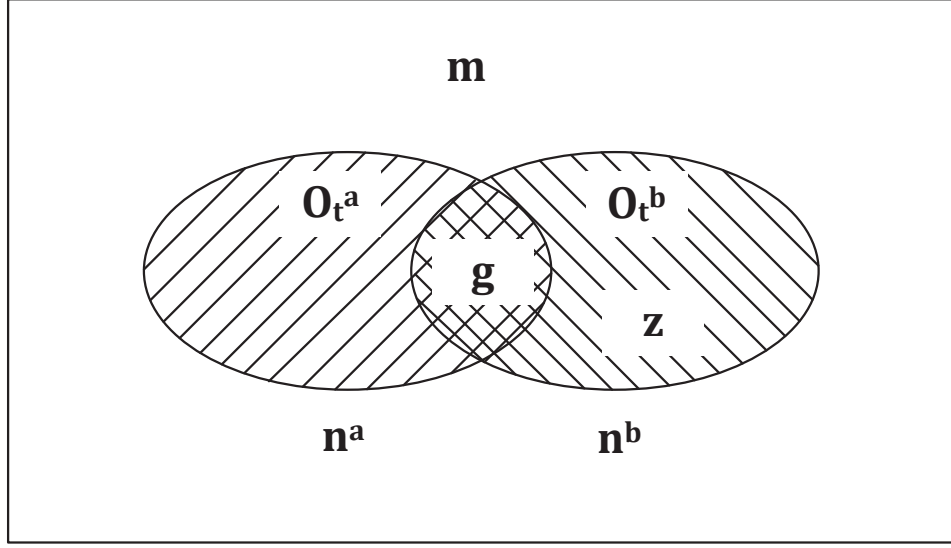
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Figure 6.1: Set representation of object allocation between node n_a and n_b

than the node n_a. Fig. 6.1 represents the object allocation between the node n_a and n_b, the common objects g and the exclusive objects z in the node n_b. Formally,

$$g \subseteq O_t^a \cup O_t^b$$
$$z \subseteq O_t^b \setminus O_t^a \tag{6.7}$$

The probability of z exclusive objects in n_b than n_a is

$$p(z) = \frac{\binom{O_t^b}{z}\binom{m-O_t^b}{O_t^a-O_t^b+z}}{\binom{m}{O_t^a}}, \qquad where \quad O_t^a \geq O_t^b \tag{6.8}$$

The expected number of exclusive objects held by the node n_b is:

$$E[z] = \sum_{l=0}^{O_t^b} \frac{\binom{O_t^b}{l}\binom{m-O_t^b}{O_t^a-O_t^b+l}}{\binom{m}{O_t^a}} \times l \tag{6.9}$$

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Therefore, the total number of unique objects held by these two nodes is:

$$V_2 = O_t^a + \textit{Total number of exclusive objects held by node b}$$
$$= O_t^a + E[z]$$
$$= O_t^a + \sum_{l=0}^{O_t^b} \frac{\binom{O_t^b}{l}\binom{m-O_t^b}{O_t^a-O_t^b+l}}{\binom{m}{O_t^a}} \times l \qquad (6.10)$$

Consider, both the nodes n_a and n_b contain the average number of objects, O_t. Therefore, $O_t^a = O_t^b = O_t$. Since, $O_t^a = O_t$, the O_t^a can be replaced by V_1. The (6.10) can be expressed w.r.t. (6.6) as:

$$V_2 = V_1 + \sum_{l=0}^{O_t^b} \frac{\binom{O_t^b}{l}\binom{m-O_t^b}{V_1-O_t^b+l}}{\binom{m}{V_1}} \times l$$
$$= V_1 + \sum_{l=0}^{O_t} \frac{\binom{O_t}{l}\binom{m-O_t}{V_1-O_t+l}}{\binom{m}{V_1}} \times l \qquad [\because \quad O_t^b = O_t] \qquad (6.11)$$

Thus, we can write a general equation for total unique objects held by k nodes in a network in a recursive fashion of (6.11),

$$V_k = V_{k-1} + \sum_{l=0}^{O_t} \frac{\binom{O_t}{l}\binom{m-O_t}{V_{k-1}-O_t+l}}{\binom{m}{V_{k-1}}} \times l \qquad (6.12)$$

$\square$

Now we need to calculate the second aspect where the node n_0 have some objects which are also held by the k neighbors. Since V_k denotes the total number of unique objects held by the k neighboring nodes of n_0 and O_t represents the total objects in n_0, we should find the number of common objects in between O_t and V_k. It is inevitable that $V_k \geq O_t$ where $k \geq 1$. The probability that there are g number of common objects in V_k and O_t is

$$p(g) = \frac{\binom{O_t}{g}\binom{m-O_t}{V_k-g}}{\binom{m}{V_k}} \qquad (6.13)$$

The expected number of common objects held by the two nodes are:

$$E[g] = \sum_{l=0}^{O_t} \frac{\binom{O_t}{l}\binom{m-O_t}{V_k-l}}{\binom{m}{V_k}} \times l \tag{6.14}$$

Thus the total number of objects in V_k which are not in the node n_0 is

$$w = V_k - E[g] \tag{6.15}$$

6.1.3 Incorporation of Scheduling and Mobility

In the system model, consider that every node posses enough bandwidth to send all the objects it holds and receives all the object it gets from its neighbors in a single transmission. Thus, in an ideal condition, the node n_0 will receive all the w objects in the next round (t+1). However, in wireless mobile network, the mobility and transmission error play crucial role for data dissemination. The meeting probability β between nodes in a mobile network is given in (5.20) . The (5.21) provides the successful transmission probability γ of objects in wireless network where multiple nodes can transmit simultaneously. Thus the expected number of objects that the node n_0 will get in the $t+1$ round is

$$\begin{aligned} O_{t+1}^{\exp} &= w \times \beta \times \gamma \\ &= (V_k - E[g]) \times \beta \times \gamma \\ &= \left(V_k - \sum_{l=0}^{O_t} \frac{\binom{O_t}{l}\binom{m-O_t}{V_k-l}}{\binom{m}{V_k}} \times l \right) \times \beta \times \gamma \end{aligned} \tag{6.16}$$

In (6.16), the variable V_k is dependent on the value of O_t. The O_t is a time varying variable which denotes the average number of objects in a node in the network at time t. The m is constant for particular network. The values of β and γ are dependent on the network parameter which have been shown in the previous section. Therefore, the (6.16), gives the near perfect approximation of acquiring objects by a node in a network of epidemic dissemination for multiple objects.

6.2 Simulation Results

In simulation, we focus on a wireless network with different node densities on a square area of $500m \times 500m$. The total number of nodes varies in the areas from 100 nodes
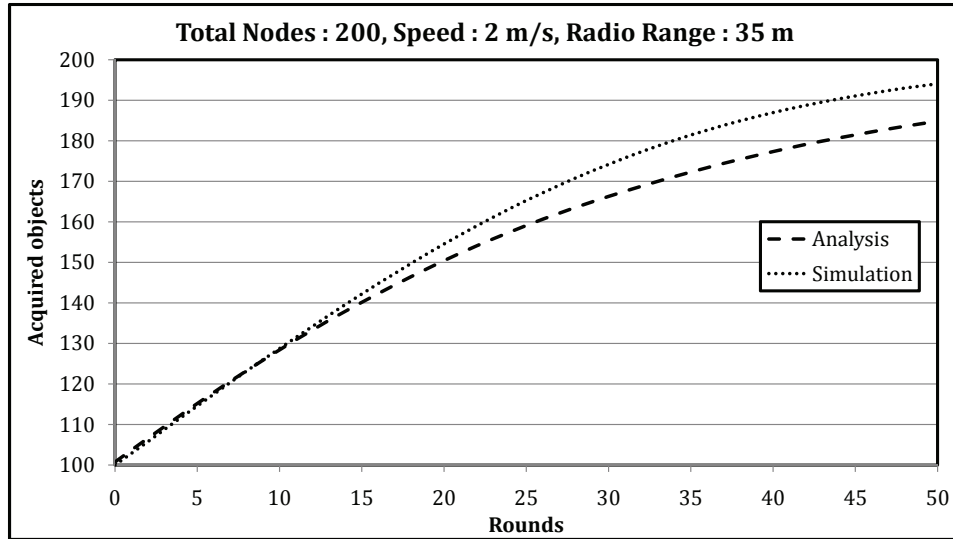
Figure 6.2: Comparison of Analytical model and Simulation of Data Dissemination

to 200 nodes. Initially, these nodes are randomly distributed throughout the simulation area. We assume that nodes mobility pattern follows RDM model with a mean speed of 1 m/s to 5 m/s and mean pause time before changing direction of movement is 0 second. We consider this setting which will represent the customers mobility within a mall to a slow moving vehicle in a city. We assume nodes to be equipped with a standard 802.11 interface. We experiment with different radio transmission ranges from $35m$ to $60m$. Since we focus on data dissemination in on demand network, we do not simulate cellular access network. However, we account for the delay associated with the download of information items from the cellular network, by assuming a throughput that is 100 times less than the 802.11 network, matching that typically provided by 3G technologies to outdoor mobile users.

In the beginning of the simulation, each node is given a unique object randomly. A node transmit all the objects it has in the meeting with other nodes. Similarly, a node receives objects from its neighboring nodes whatever they transmits. The simulation terminates when all the nodes in the network acquired all the objects prevail in the network.

Fig. 6.2 shows the analytical model and simulation results for object dissemination pattern in the network for 200 nodes. The speed of each node is 2 m/s and the radio range of each node is 35 meter. A node will get 200 objects at the data diffusion process. The figure displays the result for required rounds for a node to acquire last 100 objects among 200 objects. The initial round for achieving first 100 objects for a node in the simulation is considered as the stability phase. The fig. 6.2 depicts that the progression of data dissemination among the nodes according to the analytical model almost coincides

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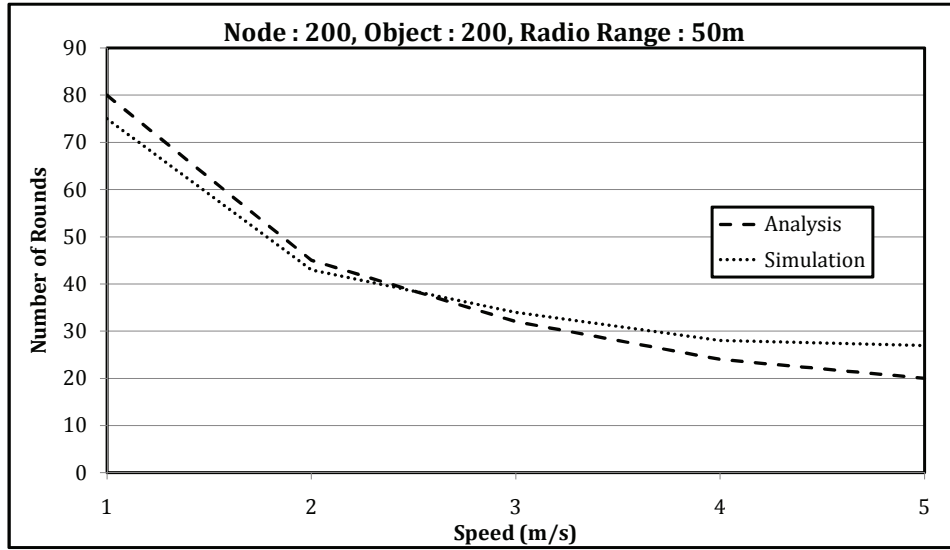**Node : 200, Object : 200, Radio Range : 50m**

Figure 6.3: Comparison of Analytical model and Simulation with the impact of mobility

with simulation result.

Different from other related works in the literature, our analytical model is that it considers the mobility and speed of the nodes for data dissemination. Fig. 6.3 shows the impact of nodes' speed in data dissemination. In simulation, the nodes' speed is varied from 1 m/s to 5 m/s. With the increasing speed, the dissemination of data among the nodes' are faster. Since, the radio range is 50 meters in this experiment, the increased speed up to 5 m/s second also increases the number of new neighbors per round. Therefore, the exchange of objects between the nodes increases. The analytical model also reveals the similar results as shown in the fig. 6.3.

The counter impact of radio ranges for multiple object dissemination is shown the fig. 6.4. With the larger radio range, the number of neighbors of node increases. Therefore, a node distribute objects to more nodes in a single broadcast. Besides, a node also receives more object from its neighbor with larger radio range. However, the larger radio range has also negative impact on data dissemination. Nevertheless, the large radio range increases the collision of data in simultaneous broadcast. Moreover, the scheduling probability γ for a node also decreases with larger radio range. The simulation result clearly reveals this scenario in fig. 6.4. The total number of rounds to acquired all the objects does not decline in a straight line with the increase of radio range. The analytical model also follows same trend with the simulation results.

We have simulated the impact of data dissemination on node densities. The number of nodes is varied from 100 to 200. At the beginning of the simulation, each node carries a unique object. For, example, when the number of nodes is 150, the total number of
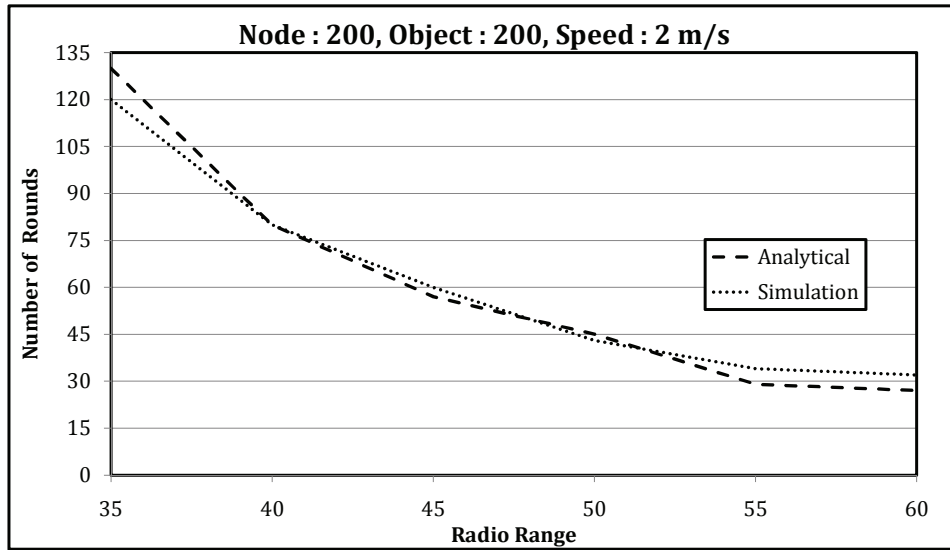
Figure 6.4: Comparison of Analytical model and Simulation with the impact of radio range
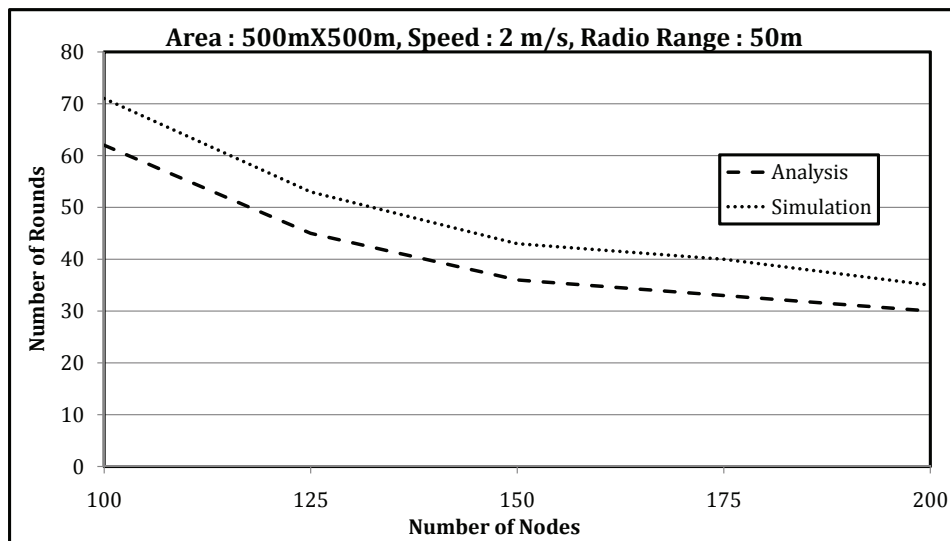

Figure 6.5: Comparison of Analytical model and Simulation with different node densities

objects in the system is also 150. Fig. 6.5 shows the data dissemination pattern with the varying number of nodes. It considers the total round required for acquiring 80% of total objects. When the node density increased, the data exchange rate among the nodes also increased. As a result, the total number of rounds for acquiring objects is also decreased. However, the rate of decrease from 100 nodes to 125 is not equivalent to the decrease of total rounds from 175 to 200 nodes. Because, too many nodes in a

small area also increases the collision of data broadcast. In the fig. 6.5, the analytical model also follows the same pattern for decreased number of rounds with the increased of node densities. However, there is a difference in values in between the analytical model and simulation results. We have utilized data from simulation for calculating the average number of neighbors for a node. This average number of neighbors is fixed in the analytical model. However, in simulation, the average number of nodes is different at each step of the simulation. Moreover, the meeting and scheduling probability among the nodes in the analytical model are determined according to the number of nodes, their radio range, mobility pattern and the speed of the node. This probability values remain same in the stepwise calculation in analysis. The differences in the analytical model and simulation results in initial stage are propagated to the later stages.

6.3 Conclusion

In this chapter, we have proposed analytical model for multiple object diffusion in wireless mobile network. Our analytical model probabilistically estimates the object acquisition delay for a node in the network when multiple node exchanges different type of objects. This model also incorporates the uncertainty wireless network such as available radio ranges and the dynamics of mobile on-demand network such as the number of nodes and speed of nodes. Simulation results show that our analytical model accurately anticipates the multiple object dissemination in wireless mobile network.

Chapter 7

Conclusion and Future Work

In this dissertation, we have studied the local interaction based data dissemination in the context of wireless mobile networks. While studying data dissemination techniques, we came up with a novel P2P data dissemination protocol that offers a substantial contribution to the field. After elaborating on this contribution, we conclude this chapter with suggestions for future research directions.

7.1   Contributions

As a part of our research goal, we investigated the information dissemination problem in wireless mobile networks and proposed a novel information diffusion scheme exploiting a mobile peer-to-peer approach. Our scheme diffuses content in a network quickly with little control overhead. The proposed scheme is presented in chapter 4. Based on hosted content information from neighbors, a node disseminates only the contents that are useful in a neighborhood. Since the practical experiment is not feasible for hundreds of nodes, we verified our claims with a large-scale event-driven simulation. The simulation results demonstrate that the proposed scheme gives an immense performance gain over previously suggested rankings and traditional flooding based schemes.

We have also derived two analytical models to understand the behavior of our scheme at a fine-grain level. The analytical models reveal the interrelationship among the parameters for the scheme. Understanding this correlation among the different parameters is crucial because it allows for a better estimate of object diffusion delay in any particular scenario.

The first analytical model described in chapter 5 captures the randomness of the scheme for delivering a single object in the entire network based on the epidemic model of disease spread. This model also integrates the uncertainty of the wireless mobile network in epi-

demic data diffusion, which is the first time this has been done in the literature according to our knowledge.

Chapter 6 discusses the analytical model for multiple object diffusion and explores the probabilistic pattern of multiple object exchange among neighbors. This model also considers radio range, node mobility, as well as node density in an area.

Therefore, we claim that these analytical models successfully portrait the partial scenario of our novel demand based data diffusion technique, which has already shown its superiority in its class. The analytical models can also be used to find the upper bound of delay to disseminate a particular message or messages in an area using a wireless mobile network.

7.2 Future Work

In this section, we shed the light on possible extension of research from this dissertation.

7.2.1 Exploration of Storage Constrains

During this dissertation, we considered a limited set of parameters. Additional constraints can impose new challenges on the existing scheme. Storage constraint is one such parameter. There is a tradeoff between minimal replication of an object with object availability among the devices' storage capacity and system performance. Tradeoff analysis would provide the available storage space for this application. The addition of this constraint requires the reevaluation of the scheme and subsequent change in the analytical models.

7.2.2 Context-Aware Data Dissemination

Targeted advertisement and news distribution among users will be a popular approach in MP2P data dissemination. We plan to extend our system to disseminate context sensitive data among users by considering the vicinity of a user, time of a day, action a user is performing, and the intention with which that action is being performed. We also plan to find the access probability of an object based on the previous access pattern of that object in a network and develop an efficient method to disseminate context aware data to interested peers.

APPENDICES

Appendix A

Shanghai Urban Vehicular Network

In order to study the realistic on demand network, we have utilized the vehicle traces in the Shanghai city to simulate our protocol. Here is a brief description of this Shanghai Urban vehicular Network (SUVnet).

A.1 Network Description

Over 4000 commercial taxis are equipped with GPS devices running on the Shanghai City in China. Each of the vehicles report their location in real time with vehicle ID, time stamp and the direction of the taxi in 40 seconds interval to a central server. However, due to large interval time, this data may be incomplete and imprecise. Researchers in Computer Department, Shanghai Jiao Tong University, China have generated trace of taxi from this imprecise data using the map-matching algorithm [84]. The algorithm discard link that is more than 40 meters between two consecutive location of a taxi. Additionally, if the direction of a taxi deviated more the 45 degree in an interval, this link is also discarded. The link with the least distance chosen for the trace data. The error comes into the original data from two sources: the taxi either deviated from the road and went a park area or there is a GPS error. Both of the erroneous data have been stripped down through match mapping algorithm. Fig. A.1 shows visualization of the SUVnet in the morning at a certain day [29]. Every dots on the picture represents a taxi.

A.2 Customization of Data

We choose 500 vehicles among the 4000 vehicles' rigorous trace of data to fit in our simulation. Among the vehicles data, we first trim down the vehicles that live less than 5 hours in

Figure A.1: Visualization of SUVnet

the system. The we sort all the vehicles data according to the distance they traveled during their data log in period. We have chosen the 500 vehicles that travels larger distance in more that 5 hours period. Therefore, the vehicles' data used in our simulation show most geographical diversification. In this way, the realistic scenario of Shanghai city traffic is achieved in our simulation.

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