HIGH PERFORMANCE OPPORTUNISTIC ROUTING ALGORITHMS FOR POWER CONSTRAINED NODES WITH MESSAGE DELIVERY DEADLINE IN SPARSE NETWORK ENVIRONMENT

BY

JIRADETT KERDSRI

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF
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SIRINDHORN INTERNATIONAL INSTITUTE OF TECHNOLOGY
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A Thesis Presented

By
JIRADETT KERDSRI

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Abstract

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Opportunistic Network (OppNet) is a network exploiting contact opportunities and node mobility to route the messages even a complete path from source to destination never exists.

The example applications for such extreme networks are in the environments of battlefield network, wildlife monitoring or disaster response where movements are random with highly intermittent connections. This opportunistic routing relies on store-carry-forward paradigm, which a data holding node can carry the data and find an opportunity to forward data while moving via encountering nodes until the data reaches to the destination. However, the performance of such store-carry-forward scheme largely depends on node encountering opportunity which will become lower in more sparse network. There are several proposed routing algorithms in the literature but only few have addressed routing problems in high sparse network environments especially with strict constraints in energy consumptions and message delivery deadlines. In order to improve the delivery ratio in such sparse network while minimizing the energy consumption, we proposed a novel Dynamic Rendezvous based Routing Algorithm on Sparse Opportunistic Network Environment where the rendezvous concept is implemented to increase indirect node encountering opportunity in such extreme environment. In addition, we proposed DORSI: Data-wise Opportunistic Routing with Spatial Information where more significant data has more chances to be forwarded and occupies system resources.

This algorithm leads to higher effective delivery ratio in the system. The extensive simulations are used to evaluate the performance of the proposed algorithms compared to the tradition OppNet routing algorithms.

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List of Acronyms

BWMNs	Battlefield Wireless Military Networks
DTNs	Delay/Disruptive Tolerant Networks
EMNs	Exotic Media Networks
GPS	Global Positioning System
ICNs	Intermittently Connected Networks
IETF	Internet Engineering Task Force
IRTF	Internet Research Task Force
IPN	Inter-Planetary Network
MANET	Mobile Ad-Hoc Network
MWSNs	Mobile Wireless Sensor Networks
OppNet(s)	Opportunistic Network(s)
OR	Opportunistic Routing
PSWN	Pocket-SwitchedWireless Networks
QoS	Quality of Service
RF	Radio Frequency
RD	Random Direction
RW	Random Walk
RWP	Random Waypoint
SANs	Sensor/Actuator Networks
SCF	Store-Carry-Forward routing
VANETs	Vehicular Ad-Hoc Network
WSNs	Wireless Sensor Networks

Chapter 1

Introduction

Opportunistic networks (OppNets) are one of the most interesting advancement of multi-hop wireless network especially in Mobile Ad-hoc Networks (MANETs). On the one hand, MANETs characterize an approach to conceal the mobility of the nodes by constructing stable end-to-end paths for communications. On the other hand, opportunistic network consider a problem of node mobility in MANETS as an opportunity to exploit [30]. In this network paradigm, mobile nodes are enabled to communicate with each other even without prior network topology knowledge and connected route [84]. The studies on DTN provide several concepts behind opportunistic network that led to its architecture specification [28, 123, 73, 92]. In OppNets, the source and destination nodes might never have concurrently connection, therefore the forwarding algorithms in these type of networks follow a *store-carry-forward* paradigm [117, 114, 112] by exploiting opportunistically connections arising from mobility nature of nodes and temporary wireless links.

Commonly, the difference in algorithms are based on their decisions as: at what time the data are forwarded, how to forwards the data, and to whom the data are sent [53]. Nevertheless, the algorithms to decide of what data to be sent have never completely implemented. Messages are routed between the sender and the recipient on the dynamically built routes, and the next opportunistically hop can be any possible node which likely to bring the message near the final destination. With the opportunistic paradigm, the data can be delivered from a source toward a destination by exploiting the connectivity graph sequences generated by the mobility of the nodes [2, 35].

In real world scenario, there are numerous examples of such networks implemented for specific applications. These applications are mainly based on the effect from environments causing the extreme network scheme. The interferences and jamming in military operations are the examples of opportunistic environments, thus there are many opportunistic routing proposals for military domain [57, 93, 61, 40]. The chaotic situation, in which the nodes are moving disorderly and aimlessly, is best fit for tracking wildlife animal such as ZebraNet [125] for tracking zebra, SWIM [96] for tracking whales, Seal-2-Seal [70] to model the social contact patterns of Grey seal or naturally exploiting the animals behaviors to develop the feasible routing pattern which is not completely random [108]. In the recent years, vehicle communications have attracted a great deal of attention with an aim to provide connectivity to commuters. The Vehicle-Infrastructure Connectivity [59, 77, 95, 67, 13, 37, 50, 26, 32, 63] make an appearance as a method to improve traffic safety and reduce the vehicle collisions costs [60] utilizing the opportunistic network concept. The most interesting direction of opportunistic network is social networking which exploits the social behavior of users occupying a large slice of an individual's normal daily life to define the basic mechanisms of user's movements [11]. This increasing trend basically comes from the rapidly growth of smart mobile devices to enable the concept of *people-centric networking* [30] since these mobile phones can move with people. Such mobile multi-hop networks present numerous research challenges such as PeerSoN [15, 14], PeopleNet [78], The Haggle Project [76, 83] and COSN framework [36]. Furthermore, *opportunistic sensing* such as the MetroSense project [20] is operated by exploiting the people-centric mobility to sense the devices available in the environment matching with the application requirements. This mobile sensing concept can be used as the instruments of location-aware data collection for real world observations [30]. Moreover, the opportunistic network can be exploited to provide the connectivity in underdeveloped regions. For example, DakNet [85] is a project that aims to provide network connectivity for remote villages using any connection-enabled vehicle passing by. In fact, there are several applications in opportunistic networks [64] from different approaches such as mining, message-based applications, stream-based applications or floating content that provides an abstraction of communication to allow applications to post contents to the form of message boards that offers accessibility with limited geographic [82].

1.1 Problem Statement

Typically in OppNets, a Store-Carry-Forward (SCF) technique has been employed on the mobile nodes which enables them to indefinitely carry the messages until they can be further forwarded. In this SCF paradigm, the network suffers the decreasing of performance in the insufficient collaborating nodes environment [6, 101]. Since the node holding the data requires the next-hop neighbor nodes to forward the data to, the sparse network environment is basically unable to satisfy opportunistic routing. Therefore, such SCF routing technique cannot guarantee 100% delivery rate. Moreover, the delivery ratio becomes remarkably low in the sparse network environment especially when there is a strict constraint on message delivery deadline. To the best of our knowledge, the problem of performance degradation in such extreme sparse opportunistic network environments have not been precisely addressed. Considering this problem, there is a need for an innovative protocol designed to address this deficiency of OppNets. In this thesis, we propose the algorithms to address the mentioned critical problem of OppNet routing. In the proposed approaches, we use different routing techniques and work on different OppNet scenarios, however our common aim is to increase the delivery ratio in sparse network.

1.2 Objective and Scope

The objective of this research is to define the methods to increase the delivery ratio of messages with limited deadline in opportunistic networks. For this thesis, we focus on the routing protocol implementation with the scope of sparse network environments.

1.3 Proposed Approaches

From aforementioned problem statements, this thesis proposes the following approaches:

- In order to address the problems in sparse networks, we need to increase the message transfer opportunities as much as possible. In the first approach, we propose the use of Rendezvous based concept in order to maintain the messages in one place as long as the messages are delivered. By injecting a special Rendezvous node (N_{rv}) into the network, the gap between time and space domain of the mobile nodes can be bridged.

Messages can be transferred from source node to destination node even if they are not in the same location at the same time with the help of the Rendezvous node. The results clearly show that the delivery ratio of proposed Rendezvous based protocol significant improve over traditional protocol especially in the sparse environment.

- Nevertheless, the delivery ratio cannot further maximize in the extremely low node density. Therefore, we aim to increase the deliver probability of significant messages to assure the critical data delivery especially for messages with the expiration time constraint. We propose a protocol to classify the messages based on the information sensitivity along with the node prioritization technique corresponding to their delivery probability computed by spatial data. This protocol classifies the messages according to their significance level, security level and deadline relative to the sensitivity level of data. In addition, we adapt the geographical routing technique to select the best candidate node to forward the messages to the destination. Simulation experiments clearly illustrate that two key performance indexes: (1) effective delivery ratio and (2) effective replication ratio remarkably improve over the traditional routing.

1.4 Our Contributions

In this thesis, we propose two new opportunistic routing algorithms.

- We propose the Dynamic Rendezvous based Routing Algorithm (DRRA) on Sparse Opportunistic Network Environment which introduces the novel concept of rendezvous place where the passing nodes can announce, deposit or pickup their own messages without having to meet the other nodes carrying the desired message. In the proposed scheme, we implement the Rendezvous place to be detected automatically and its area's size and shape are dynamically changed according to the interaction among nodes passing around the area [1]. The results from extensive simulations show that our proposed routing algorithm can achieve higher delivery ratio and utilize lower energy consumption than traditional opportunistic routing algorithms especially in sparse network environment.
- We propose the Data-wise Opportunistic Routing with Spatial Information (DORSI), based on the classification level of the data in addition to the spatial information of the nodes. The forwarding algorithm of this routing is determined by significance level, security level and deadline of messages. To conform with actual applications, the scenario of multi-level security in military tactical network is designed as a test bed. Simulation results of DORSI show that the key performances improve over the traditional opportunistic routing. As a result, this novel protocol can achieve higher delivery ratio on data with higher priority within time limit while, restricts the replicas of data with higher security level.

1.5 Thesis Structure

This thesis contains five chapters. Chapter 1 gives an introduction of the research. In addition, the problem statement, objective and scope, and proposed approaches are included in this chapter. In Chapter 2, the background and related works on opportunistic networks

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[1] The detail of Rendezvous place and example applications is elaborated in Chapter 3

are provided. Chapter 3 presents our approach of using the rendezvous place concept to overcome the limitation of insufficient collaborating nodes in sparse network environment. The details of proposed method, simulation model, and performance evaluation are included in this chapter. Chapter 4 describes our message prioritization technique to differentiate the forwarding decision based on the significant level of messages. The details of proposed method, simulation model, and performance evaluation are included in this chapter. Chapter 5 includes the discussion, the conclusion and the recommendations for future studies.

Chapter 2

Background and Related Work

Recently, wireless networking is experiencing several deployments in diverse extreme environments where they usually suffer from different link disruptions levels depending on the severity of the operations. Commonly, these networks are known as Intermittently Connected Networks (ICNs) or Challenged Network. An ICN is an infrastructure less wireless network that supports the functionality of the wireless applications operating in stressful environments with no existence of end-to-end path between any arbitrary source-destination pair and excessive delays which result from high repetitive link disruptions [60]. In order to handle ICNs, the Internet Engineering Task Force (IETF) [23] proposed an architecture called Delay/Disruption-Tolerant Networks (DTNs). DTNs can basically be categorized into 3 types: scheduled networks, predictable networks and opportunistic networks. In this thesis, we focus on the research on the most extreme case of DTNs which is the opportunistic networks.

This chapter gives the background knowledge of this thesis. The background of Delay Tolerant Networks is presented in Section 2.1. Additionally, an explanation of Opportunistic Networks is presented in Section 2.2.

2.1 Delay Tolerant Networks

DTNs is an overlay architecture with aims to operate over the protocol stacks of the ICNs in order to enable the functionality of gateway between them through the use of a variety of protocol techniques, replication and parallel forwarding, storage capacity, forward error correction to overcome the communication impairments [60]. DTNs enable the data transferring in extremely environments, where networks are assumed to experience recurrent, long-duration partitioning with no end-to-end from source and destination connectivity [72]. Therefore, the timer and acknowledgement mechanisms of the traditional TCP/IP protocol is definitely failed in such circumstances [33]. In addition, the routing algorithms designed for MANETs are unable to perform effectively under aforementioned constraints, since the contemporaneous available end-to-end connectivity is crucial for conventional routing algorithms [21]. In such extreme condition such as military tactical network, DTNs and MANETs are among several promising challenged researches aiming to improve network performance [68]. Typically, DTN protocols are designed to address sparse networks with intermittently connection while MANET protocols are deployed on the fairly stable and fully connected ones. However, many intermediate situations may occur on radio link instability or mobility dynamics.

Basically the types of DTNs can be classified into 3 categories: scheduled networks, predictable networks and opportunistic networks as seen in Figure 2.1. In DTNs, predictable and scheduled networks are the common aim in designing the routing protocols in the highly

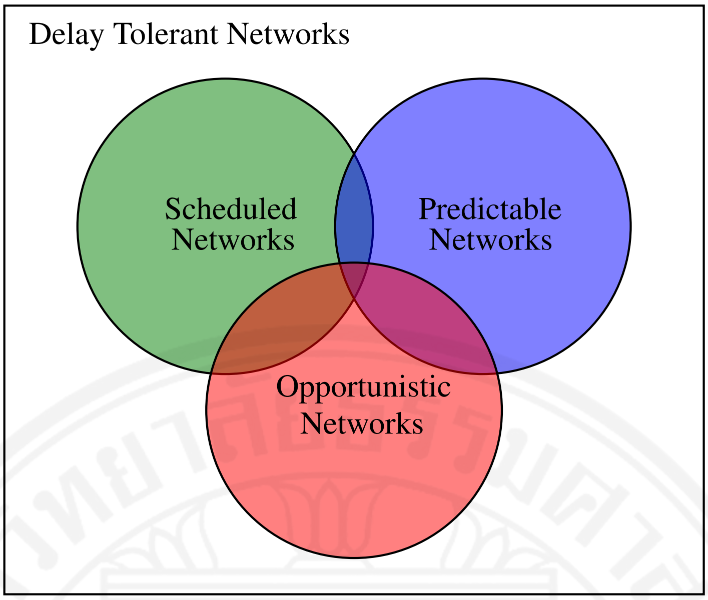

Figure 2.1: Types of DTN

disruptive environments such as Interplanetary Internet (IPN) [18] where the contact time is not completely random but in periodic interval. In the thesis, we study the most extreme case of DTNs which is opportunistic networks where the contact time is undetermined along with stochastic movements. In addition, in some large scaled scenarios, the network environment can be consisted of multiple types of DTN categories. Taking the Battlefield Wireless Military Networks (BWMNs) as an example, the controllable mobile robot can be in the schedule network class while moving soldiers are accounted as opportunistic nodes [60].

2.2 Opportunistic Networks

An OppNet is an extreme type of DTNs where the source and destination nodes might have never been fully connected simultaneously which means that the communication contacts are intermittent. Basically, the terms OppNet and DTN are often used interchangeably [84]. DTN usually calculated the delivery delays estimation in advance from some degree of system variable determinism. This network scheme is suitable for extreme dynamic evolving network topology and limited information scenarios. On the other hand, opportunistic link in OppNet is highly dynamic and unpredictable so routes are computed at each hop when forwarding messages [16]. This challenged network which is also referred as Intermittently Connected Mobile Network (ICMN), is involving mobile nodes to communicate with each other without any existing complete end-to-end path from source to destination. Thus, there is no guarantee on the existence of a complete path between two nodes wishing to communicate [124]. This intermittent connection may result from many factors such as environmental interference and obstruction, low node density,high node mobility ,short radio range and malicious attacks [88]. The node movement in OppNet is extremely random in some networking environment, thus the probability of message delivery from source to destination is difficult to be assured. Traditional routing protocols have been shown to be ineffective in coping with unreliable and unpredictable wireless mediums [120] since they implicitly assume that the network is connected and an end-to-end path always exists between any source and destination. This conventional infrastructure network commonly utilizes the network topology to route the message, thus it presents inadequate performance in highly dynamic topological environment. In fact, none of the conventional routing algorithms are fully satisfactory when the network often splits into evolving connected groups [109]. To address the problem of intermittent links and node mobility, local forwarding are exploited in order to transfer the messages. The application of opportunistic network is typically used in an environment that is tolerant to long delay and high error rate such as MANET in battlefield communication [4] or DTN for interplanetary networking [49]. Examples of such networks are sparse mobile ad hoc networks [3], military tactical networks [93, 58] or sensor networks, such as ZebraNet [125], SWIM [96] in which nodes move throughout an environment, and work to gather and process information about their surroundings. Commonly, the key differentiating factors among these scenarios are the levels of predictability and control over the contacts between the message carriers [54]. Routes in opportunistic network are built dynamically based on knowledge about topological evolution of the network. Routing performance improves when acquiring more knowledge about the expected network topology. Nevertheless, a trade-off between performance and knowledge requirement must be met since this kind of knowledge is difficult to acquire. If the knowledge is not available or difficult to achieve, epidemic routing (context-oblivious) might be the best option for communication [12]. While this flooding based routing tends to minimize the latency, it consumes network resource and tends to degrade performance. Most of the existing routing schemes for opportunistic network rely on a priori knowledge of topology information [84], especially focusing on the dissemination algorithms and policy to control or limit flooding [86]. In fact, Opportunistic networks focus on mobile ad-hoc DTNs, where tolerant delayed routes between the source and the destination are built dynamically. However, OppNets is different from MANETs that it does not assume the existing end-to-end connectivity. Therefore, instead of depending on end-to-end MANETs routing protocols, the messages are delivered through one hop data transmission among opportunistic node encounters with intermediate node's storage and mobility, called *Store-Carry-Forward paradigm* [43, 117]. The opportunistic routing pattern, called store-carry-forward, takes an advantage of node mobility to forward the data buffered in the carrying node to the next connected node during the opportunistic contacts. In essential, there are three common steps of routing in OppNet [42]:

- Broadcast the messages to candidate relayed nodes.
- Select the best candidate node.
- Forward the messages.

2.3 Opportunistic Routing

In opportunistic routing, the nodes can exchange data in a spontaneous manner whenever they are in the transmission range of each other [87]. If there is no direct connection from source to destination, data holding nodes will discover their nearest neighbor nodes to forward messages toward the destination node. Thus, this opportunistic route is determined at each hop when messages traverse through different hops. In this routing scheme, mobile nodes are normally equipped with local knowledge of the best nodes around them to determine the best path to transmit the messages with this knowledge. In the case of such nodes absence, the node currently holding the message simply stores the messages and wait for an opportunity to forward the packets. This infrastructure-less wireless network environment requires common two factors to facilitate the opportunistic routing [87] :

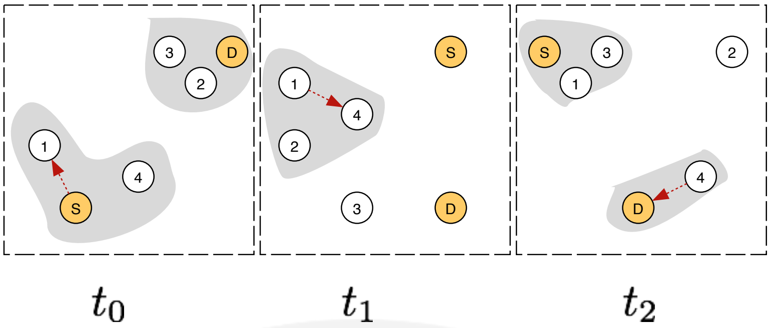

Figure 2.2: Store Carry and Forward routing model

- Destination path finding: Intermediate nodes are used to form paths dynamically since there is no fixed path from source to destination nodes.
- Next hop forwarder selection: Data holding nodes need to find a helper node that can forward the messages to the destination as soon as possible.

A key concept behind Opportunistic Routing (OR) is overhearing and cooperation among relaying nodes to overcome the drawback of unreliable wireless transmission [71]. Since the mobile nodes are not always connected to each other, the forwarding algorithms in such networks commonly follow a store-carry-forward (SCF) paradigm as shown in Fig.2.2. This SCF employs storage space and node mobility to overcome the intermittent connectivity [74]. The messages sent from the source node are carried by intermediate nodes to other geographical areas and transfered to adjacent nodes until the destination node receives these messages. Since this fundamental SCF routing model realistically requires a certain sufficient occurrence of *direct* encounter among moving nodes to exchange messages, its routing performance will highly degrade in the low-node-density sparse network [101]. Although there are several existing OppNet routing solutions [127, 44, 97, 39, 104, 58] proposed in the literature, very few proposals address the problem in this sparse network environment especially when the OppNet nodes are energy-constrained [116, 34] and the direction of their movement cannot be controlled. One interesting application of such OppNet environment is the sensor OppNet for wildlife monitoring and tracking [125, 96].

2.3.1 Classification of Opportunistic Routing

Several researches proposed opportunistic routing algorithms based on store-carry-forward mechanism. The existing common OR algorithms can be classified based on their data forwarding behavior as shown in Figure 2.3

Direct Transmission

The source node in direct transmission routing generates the messages and stores it until it directly meet the destination node. Spyropoulos et al [97] proposed a single-copy routing in intermittently connected mobile networks using hop-by-hop routing model. In this single-copy routing, only one copy per message can be transmitted from source node to destination node. This routing algorithm significantly reduces the resource requirements of flooding-based algorithms [99]. However, this scheme produces significantly long delays since the delivery delay is unbounded for this direct transmission routing [39].

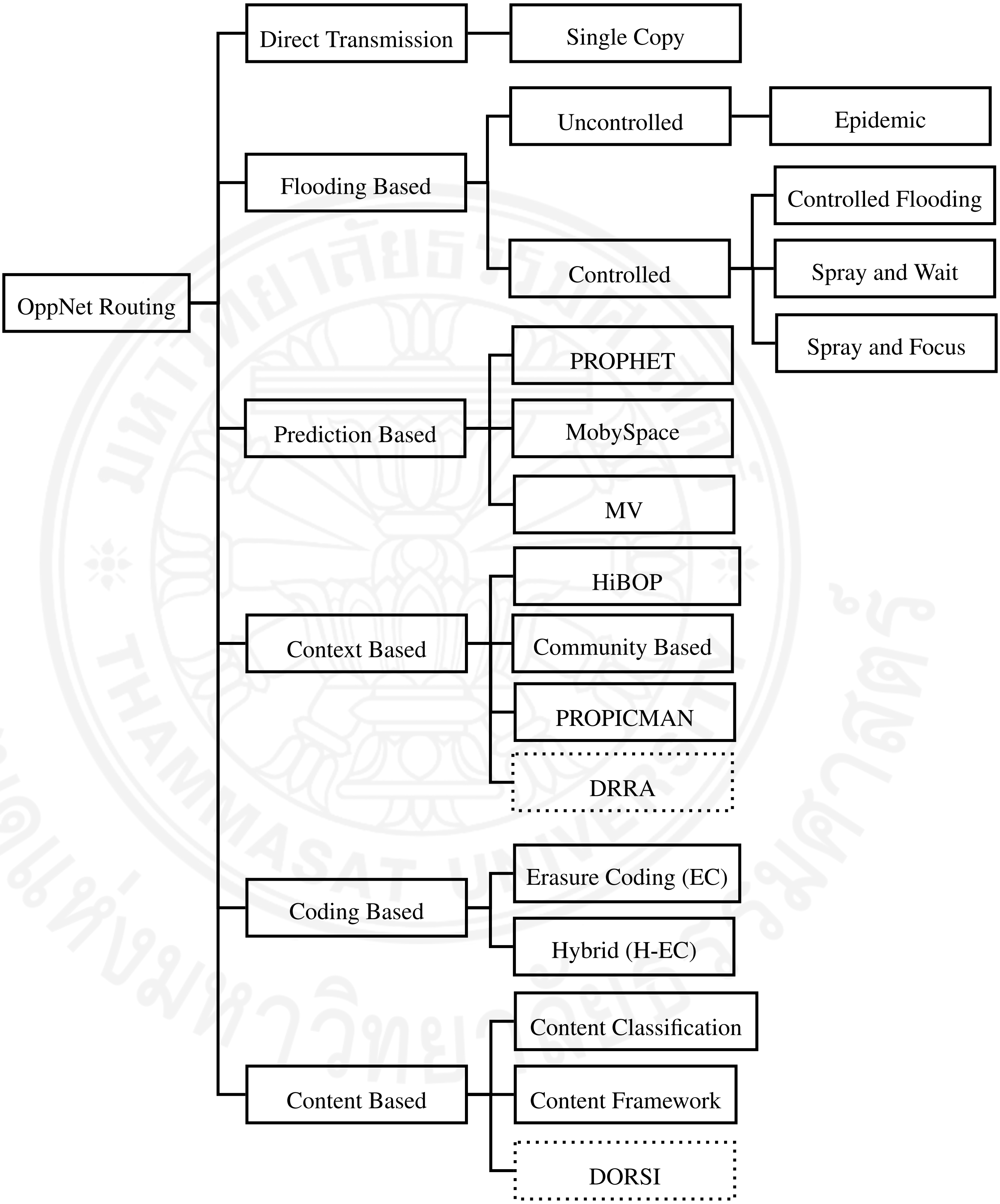

Figure 2.3: Classification of Opportunistic Routing

Flooding Based

The flooding based routing (multiple copies) approach may generate several copies of the same message to be routed independently to increase the efficiency and robustness [44]. This flooding based routing can be divided into 2 types:

- Uncontrolled: In this approach, each node broadcasts the received packet to all of the neighbors without restrictions. Epidemic routing [104] utilizes epidemic algorithm to send each message to all nodes in the network. Even though the Epidemic routing can guarantees that all nodes will eventually receive all messages, it incurs significant demand on both bandwidth and buffer.

- Controlled: Undoubtedly, uncontrolled flooding consume network resources which can seriously degrade the performance if the resources are scarce [103]. Therefore, there is a need to control the flooding by limiting the number of packets to be replicated to reduce the network contention. Several researches proposed the algorithms to control the flooding such as controlled flooding, spray and wait and spray and focus.
    - Controlled Flooding: Khaled et al [41] proposed a set of Controlled Flooding schemes to address the excessive network resources from flooding. Four schemes have been examined in this study: Basic probabilistic (BP), Time-to-live (TTL), Kill time and Passive one. The extensive experiments show that proposed schemes can save substantial network resources while incur a negligible increase in the message delivery delay. As a result, the ability to provide reliable data delivery while resolving excess traffic overhead, controlled flooding protocol can greatly reduce the network overhead.
    - Spray and Wait: Spyropoulos et al [100] introduced a Spray and Wait routing scheme consisting of two phases: first, *sprays* a number of copies into the network, and then *waits* till one of these nodes meets the destination to bound the overhead of delivering the message. In the *spray* phase, L messages are created in which L indicates the maximum allowable copies of the messages in the network to L distinct relays. In the *wait* phase, when the destination nodes are not encountered by a node with a copy of the message in the spraying phase, each node with a copy of message will perform the direct transmission.
    - Spray and Focus: Another controlled flooding approach by Spyropoulos et al [98] was designed to eliminate some deficiencies of Spray and Wait routing algorithm in some network schemes. Similar to Spray and Wait protocol, this algorithm consists of two phases: Spray phase and Focus phase. The *spray* phase is operated the same way as in Spray and Wait which L message copies are spread to all L different nodes for every message created at source node. The difference from the *wait* phase is that in the *focus* phase, each copy in a single node is attempted to be routed to a closed node using a single-copy utility based scheme [99].

Prediction Based

The prediction based routing algorithms are proposed to overcome the overhead carried by flooding based routing schemes. In Prediction based routing, nodes estimate the probability of forwarding messages to the destination based on the history of observations instead of blindly forward the messages to all/some neighbors. With the information, nodes can decide whether they should store or wait for the better chance to forward the messages as well as deciding which nodes to forward the messages to.

- PROPHET: Lindgren et al [69] proposed PROPHET (Probabilistic Routing Protocol using History of Encounters and Transitivity) as a probabilistic routing protocol. This protocol estimates a probabilistic metric called delivery predictability to indicate the probability of successful delivery of a message from the local node to the destination. Two nodes can exchange a summary vector containing delivery probability when they meet. The delivery probability metric is derived from previous encounters and subject to an aging factor, meaning if two nodes are often encountered, they have high delivery probability to each other. On the other hand, if a pair of nodes rarely encounter, they are intuitively not a good candidate to forward messages to each other. The results from the simulations show that PROPHET is able to deliver more messages than Epidemic Routing with a lower communication overhead.
- MobySpace: Leguay et al [65, 66] proposed MobySpace: Mobility Pattern Space Routing for DTNs which uses a high-dimensional Euclidean space constructed upon nodes' mobility patterns. In this MobySpace protocol, the routing decisions are taken using nodes'virtual Euclidean space with the notion that a node is a good candidate for taking custody of a bundle if it has a mobility pattern similar to that of the bundle's destination. The results from the simulations show that MobySpace outperforms the other single copy schemes in delivery ratio while keeping a low number of transmissions.
- MV: Burns et al [19] proposed the MV algorithm, which is based on observed meetings between nodes and visits of nodes to geographic location. This protocol learns the meeting frequency between the nodes and which cells in the grid are frequently visited by each node in order to rank the likelihood of delivering a bundle through a path of meetings. The experiment shows that this algorithm can achieve delivery rates closer to the true optimal rate.

Context Based

Nevertheless, predication based routing failed in several scenarios with a reduction in delivery rates compared to the flooding based approach. The context based approach is proposed as a revision of prediction based protocols in order to gain higher delivery ratio. The concept of context is commonly defined as a collection of information by taking the *social aspect* of nodes in to the account as an important parameter to route the messages [79], which motivated by the fact that the mobility decision is relied on the carriers such as human, animals or vehicles. In fact, both MobySpace and MV can be also viewed as one type of context based routing exploiting the mobility pattern and places that nodes frequently visit, but the prediction capability of those protocols are considered as a major factor to categorize them in the prediction based routing.

- HiBOp: A History Based Routing Protocol for Opportunistic Networks or HiBOp were proposed by Boldrini et al [10] as a general framework for managing and using context for forwarding decisions. In HiBOp, nodes can share their own information locally storing in the *Identity Table (IT)* during contacts. The *IT* consists of personal information of users carrying the devices while the nodes keeping the record of current neighbors' *ITs* which can be called *Current Context*. In addition, mobile nodes are also maintaining the information of encountered history about their habits and past experiences. The key idea behind HiBOp forwarding is to select the candidate nodes that showing the increasing match with known context attributes of the destination. The comparison with Epidemic and PROPHET shows that HiBOp can reduce resource consumption and message loss rate while preserving the performance in terms of message delay.

- PROPICMAN: Nguyen et al [80] proposed the Probabilistic Routing Protocol for Intermittently Connected Mobile Ad hoc Network (PROPICMAN) in which the context information is represented by the *node profile*with evidence/value pairs upon contact opportunities to forward the messages. The main idea behind PROPICMAN is to look for the increasing matching user profiles between destination and encountered nodes, similarly to HiBoP. However, a distinctive function between PROPICMAN and HiBOp is the exploitation of decision trees to select the next hop [29]. This method exploits the mobility as well as reduces the number of nodes involved in the forwarding process, which results in the low overhead comparing to the other dissemination-oriented routing algorithms, such as Epidemic or PROPHET [111].
- Community Based: The types of opportunistic networks that consist of mobile nodes with social characteristics are called community based opportunistic network (CON) or Mobile social networks (MSNs). Niu et al [81] proposed Community-based Data Transmission Scheme (CDTS) by utilizing the characteristics of social networks. The idea behind CDTS is based on the observation that social nodes always have different social roles which can determine the activity area and mobility pattern. Moreover, the social nodes tend to have higher probability to move within their community while containing lower chance to leave the local community to other community. The mobility model of this scheme has been designed to match the real mobility characteristics of CDTS. The simulation results show that by adjusting the number of data copies and forwarding condition, CDTS can achieve efficient data transmission with less resource consumption. In addition, Xiao et al [115] proposed a distributed optimal Community-Aware Opportunistic Routing (CAOR) algorithm by modeling an MSN into overlapping home-aware community. The first step is to turn the routing among a number of nodes into the routing between community homes. Then, an optimal relay set of each home is maintained and each home can only forward the messages to the nodes in its relay set and ignores the others. Comparing with previous social-aware routing such as Bubble rap [45], this algorithm can achieve the optimal routing performance with a very low maintenance cost.

Coding Based

The coding based routing is proposed to apply coding techniques to improve the transmission performance under intermittent network connectivity. By transforming a message into another format prior to the transmission with embedded additional information, the coding based schemes are more robust than replication based routing because the original message can be reconstructed with only a certain number of the code blocks.

- Erasure Coding (EC): The main idea of Erasure coding [107] is to convert a message into a larger set of code blocks in which the original message can be reconstructed by large subset of the generated code blocks. To delineate the detailed process, an algorithm produces $M \cdot {}^{r}/_{b}$ equal sized code blocks of size b of a message of size M a replication factor r. Consequently, the messages can be reconstructed by $(1+\varepsilon)\cdot {}^{M}\!/\!_{b}$ erasure coded blocks where ε is a small constant varying by the utilizing algorithm, such as Reed-Solomon codes or Tornado codes [27]. Due to the additional information embedded in the code blocks, coding based schemes are less efficient when the network is well connected [46].

- Hybrid (H-EC): Chen et al [24] proposed A Hybrid Routing Approach for Opportunistic Networks (H-EC) to fully combine the advantage of EC robustness while maintaining the efficient of flooding based routing technique. In H-EC algorithm, the sender will transmit two copies of EC blocks. The first copy is transmitted in the same manner of the original EC scheme. After sending the first EC block, the second EC block is transmitted using A-EC algorithm during the residual contact duration. With A-EC algorithm, the source sends as many coded blocks as possible during each contact in order to gain better utilization of the network contact. As a result, H-EC can gain better forwarding performance in the worst delay performance. The simulation results suggest that H-EC achieve good performance in small delay performance cases while offering robustness in worst-case delay performance cases.

Content Based

Since the nature of SCF paradigm involves with data content stored in node storages, this content based routing utilizes the information of the delivered content to make the routing decision.

- Content Classification: JIAO et al [51] proposed the data dissemination method that classified the forwarding messages based on their content to reduce the transmitted messages in the network. The idea behind this method is that every node only requests the message that it is interested in, so that the delivery rate can be improved. This method can largely cut down the number of messages transmitted in the the network since it avoids sending all messages when nodes get contacted. In addition, a buffer management scheme based on the content popularity is proposed, by managing the buffer based on the time that messages are requested. The simulation results show that the content classification can maintain high delivery ratio while attaining low over head and low delay.

- Content Framework: A content-centric framework was proposed by Chen et al [25] to better facilitate content dissemination based on the characteristics of the content of the messages. Three message scheduling algorithms were proposed: Sequential Forwarding (SF), Full Interleaving (FI), and Block-based Interleaving (BI). The evaluation were performed on three types of content, including file, video and web documents with the Layered Multiple Description Coding (LMDC) based dissemination methods and file-based. The simulation results as well as synthetic and realistic network scenarios show that the proposed schemes can achieve much better latency performance for file transfer.

In this chapter, we summarize and categorize the characteristics of routing algorithms in opportunistic networks. For more extensive researches on OppNet on the related works in the literatures can also look at some surveys such as [21, 33, 87, 6, 48, 105]. In conclusion, several opportunistic routing approaches have been proposed to address the issues of MANET which only exploits the insufficient topological information. The early approaches proposed the flooding techniques from *blindly* flooding method to controlled flooding solutions in order to reduce the network overhead from flooding based routings. Later on, more advanced approaches have been proposed with the higher-level of information rather than only the topological information such as forwarding the messages to the nodes with higher chance of meeting the destination in PROPHET. Then several aspects of OppNet routing approaches have been proposed to address different issues of opportunistic routing. In content and context based routing, the forwarding decisions are based on the additional information acquired by the mobile nodes such as the node's social behaviors in context based routing and the information inside the data packet in the case of content based routing. The coding based schemes tend to be more robust than the replication based schemes in the worst delay performance cases while they are less efficient on the very small delay performance cases All in all, most of the previously proposed routings work well in the moderate to dense node density environments because they require the collaboration among mobile nodes. To the best of our knowledge, the attempt to address the delivery performance of OppNet in extremely sparse networks has not been proposed. In order to address aforementioned issue, the DRRA algorithm in context based routing and DORSI algorithm in content based routing are proposed in chapter 3 and 4.

Chapter 3

Dynamic Rendezvous based Routing Algorithm on Sparse Opportunistic Network Environment

3.1 The proposed Rendezvous based OppNet system

In this chapter, we proposed a novel Dynamic Rendezvous based Routing Algorithm (DRRA) to increase message exchanging opportunity even in the sparse network environment. We utilize the fact that there should be some node-gathering (Rendezvous) places forming somewhere at some specific time in the real network. These Rendezvous places may be either predictable such as mobile command post in military tactical network applications, or non-predictable such as disaster and emergency networks. An energy constrained node should maximize its resource usage to communicate with the others only when entering into the rendezvous area. In the proposed scheme, the rendezvous place is dynamically marked by the help of a special controllable Rendezvous node and the proposed rumor protocol to let nodes in the rendezvous area exchange messages more efficiently without having to directly meet with the other nodes.

3.1.1 System model

The proposed system is designed to efficiently use the node-gathering area, i.e. Rendezvous place, for depositing the delivered messages as much as possible so that the messages can be picked up by the destination node without requiring the exact timing of direct contact between the node carrying a message and the desired destination node. In addition, all nodes should reserve its energy as much as possible when they are out of the Rendezvous area.

As shown in Fig. 3.1, the OppNet node, N_c, whose movement direction is uncontrollable, moves in the system using *Power Saving Mode* until it reaches the Rendezvous place where it will turn itself to *Full Power Mode* in order to announce its arrival, deposit its carried messages and pick up the messages destined to itself, to/from the Rendezvous place. The Rendezvous Rumor protocol and the Rendezvous Node Sweeping mechanism are used inside the Rendezvous area to facilitate the message exchange more effectively without the need of direct contact between the OppNet nodes and the high-resource direction-controllable Rendezvous node, N_{rv}, which acts as the center of the Rendezvous place. The Rendezvous nodes will move around the OppNet network to create suitable Rendezvous places according to the proposed *Rendezvous Place Searching algorithm.*

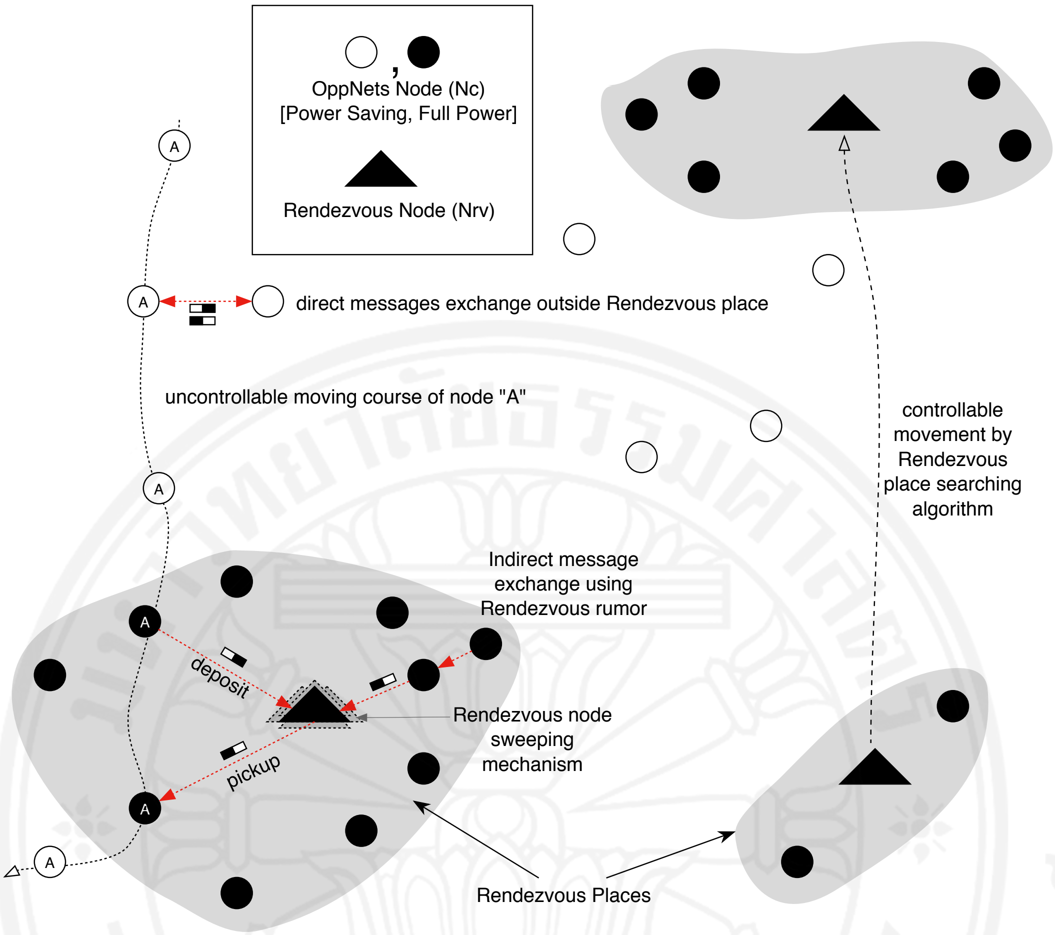

Figure 3.1: System model

3.1.2 OppNet node's operational modes: "Full Power" and "Power Saving"

The OppNet node (N_c) is a mobile node equipped with a radio interface whose transmission range is adjustable in range of $[r_c^{min}, r_c^{max}]$. The node will operate in either *Full Power mode* or *Power Saving mode* according to its location.

Full power mode

In this mode, the node will use its full transmission power, r_c^{max}, to search for nearby nodes and exchange messages. It will switch to this mode only when getting into the Rendezvous area.

Power saving mode

The node, by default, operates in this mode if it is outside the Rendezvous place. In this mode, it will alternately change its transmission range between r_c^{min} and r_c^{max} in the process of searching for nearby nodes. However, if it receives the searching signal from the other node, it will switch to its full r_c^{max} immediately in order to increase opportunity to exchange messages with the encountered node as much as possible. Then, it will switch back to minimum r_c^{min} when departing from the communicating node. Besides the r_c^{min} and r_c^{max} values, the ratio of the time interval being in its full r_c^{max} over the whole time period is a configurable parameter, τ_s , as shown in Fig. 3.2.

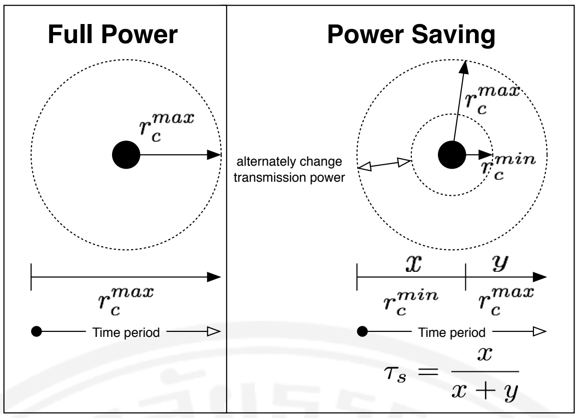

Figure 3.2: Operational modes

3.1.3 Rendezvous place and its Rumor protocol

The Rendezvous place is a dynamic area centered by a special controllable Rendezvous node, N_{rv}. This N_{rv} node is full of resources such as large message storage and high radio power with maximum transmission range R_{rv}. The Rendezvous place is controlled by the Rendezvous node using the Rendezvous rumor protocol.

The area in a Rendezvous place is not fixed as the maximum radio range, R_{rv}, of the Rendezvous node, instead it is virtually determined by the covering radio range of the most outer OppNet nodes which can relay the data messages from the Rendezvous node, as shown in Fig. 3.1. The center location of sweeping algorithm is where a Rendezvous node stops after moving from other locations.

When an OppNet node detects the *Rendezvous Area rumor message* (*RA*) broadcasted from the Rendezvous node, it learns that it has entered to the Rendezvous area. Then, it will switch its operational mode to *Full Power mode* and try to rebroadcast a *Rendezvous Area* rumor message so that the other reachable nearby nodes can learn about the Rendezvous place and adaptively expand the area on-demand. Additionally, the OppNet node in the Rendezvous area will periodically announce its arrival and upload its carried data messages to the Rendezvous node via the *Keep-Alive* rumor message (*KA*) and the *Deposit* rumor message (*DP*), respectively. Note that, all types of rumor messages will be automatically repeated with a *duplication filtering* function throughout the area by other OppNet nodes.

Once the Rendezvous node receives the *Keep-alive* rumor message which contains the sending node ID, it will gather all data messages destined to the node with that ID from its message storage, encapsulate those found messages into the created *Pick-up* rumor message and then broadcast the *Pick-up* message (*PU*) throughout the Rendezvous area. On the other hand, the Rendezvous node will keep all of data messages contained in the received *Deposit* rumor messages in its storage for later sending out to the area when the target node appears later, as seen in Fig. 3.3. The messages will be indefinitely store in the Rendezvous node buffer waiting for the destination nodes to pickup the messages. However, the expired messages will be removed once they reach the message deadline (Time-To-Live) in order to clear the storage in the buffer.

In addition to the Rendezvous rumor protocol, the Rendezvous node implements the rumor message sweeping algorithm in order to increase the chance to collect as many rumor messages as possible. Instead of always being stationary at the center location of the Rendezvous place, the rendezvous node will periodically move to its four cardinal directions (North, East, West, South) by the distance of its radio transmission range as shown in Fig.

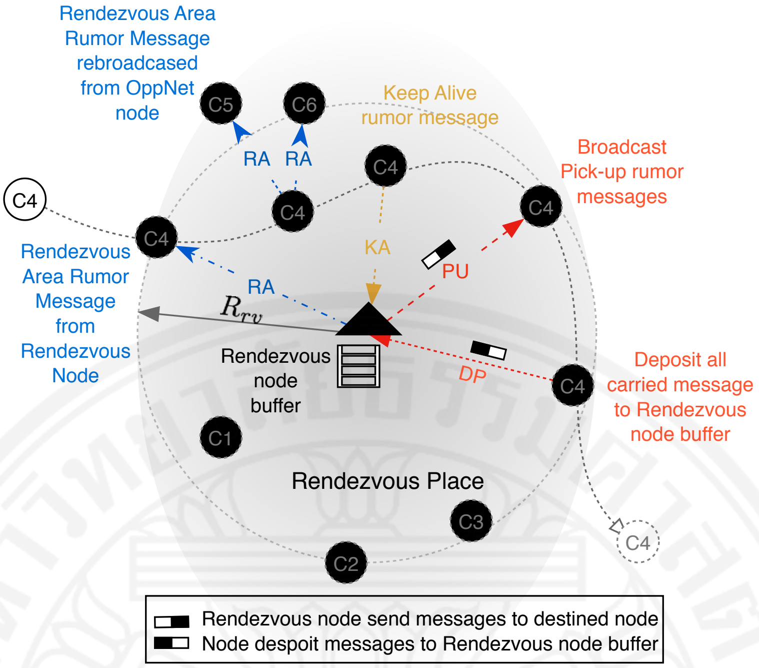

Figure 3.3: Rendezvous Place

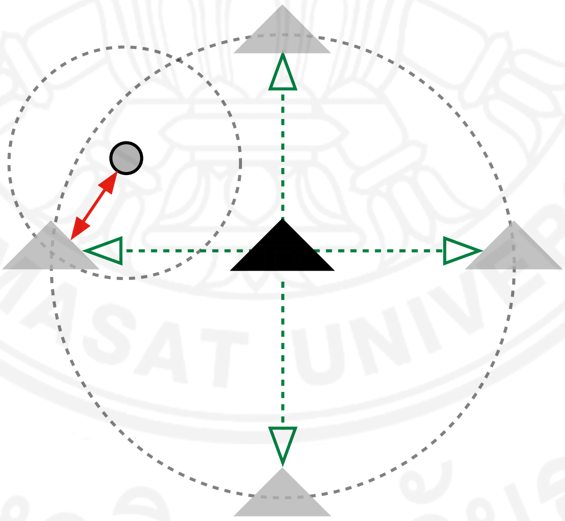

Figure 3.4: Sweep mechanism

3.4. This design lets the OppNet nodes on the edge of Rendezvous node's radio range, whose radio signal may not reach to the Rendezvous node due to the difference in their radio transmission range, can speak back to the Rendezvous node. The duration that OppNet nodes can stay in the Rendezvous place depends on the speed and direction of the nodes. Basically, the nodes can start receiving the messages once they are in the range of the Rendezvous node. In fact, higher number of nodes can facilitate higher message exchange mechanism among nodes.

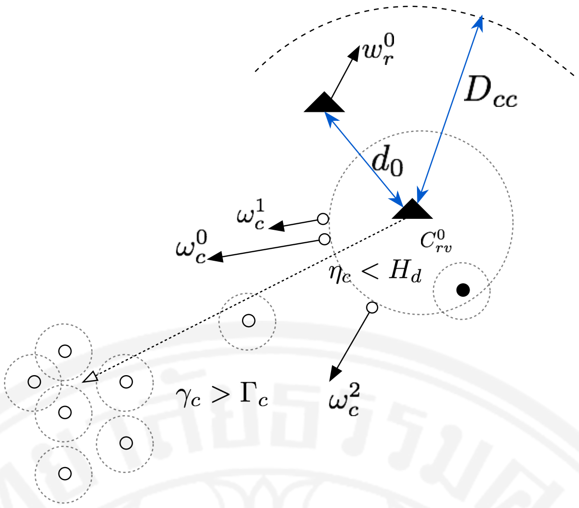

Figure 3.5: Rendezvous place searching

3.1.4 Rendezvous place searching algorithm

In the proposed system, the Rendezvous node should move to find the node-gathering area corresponding with the real behavior of OppNet nodes.

Predictable behavior OppNet nodes

In some applications, the movement of OppNet nodes is somehow predictable. For example, the movement of human during the day can be predicted in the opportunistic mobile social network environment [113]. In these applications, the Rendezvous nodes can be programmed to station at those areas at the proper time in order to maximize the effectiveness of the proposed system.

Non-Predictable behavior OppNet nodes

Without a priori knowledge about OppNet nodes, the proposed *dynamic Rendezvous Place Searching Algorithm* can be used to guide the Rendezvous nodes to the node-gathering area. The Rendezvous node will decide to move to the new node gathering location if the number of OppNet nodes in the current Rendezvous place (η_c) falls below the predefined departure node threshold, H_d. The movement direction, $\vec{\Delta}$, will be determined periodically based on the collected statistical data from both previously contacting OppNet nodes and other neighboring Rendezvous nodes as in Eq.3.1. In the equation, $\vec{w_c}$ is the departure directional unit vector of the contacted OppNet nodes, $\vec{w_{rv}}$ is the directional unit vector of the other Rendezvous nodes and φ is a configurable weighting factor between a group of OppNet nodes and a group of other Rendezvous nodes in the area.

$$\vec{\Delta} = \sum_{i=1}^{C} \vec{\omega}_c^i + \varphi \sum_{j=1}^{R} \delta\left(d_j\right) \vec{w_{rv}^j} \tag{3.1}$$

While $\delta\left(d_j\right)$ is the on-off function to include only the other Rendezvous nodes whose distance d_j is the range of cut-off distance perimeter, D_{cc}, and C and R are the number of contacted OppNet nodes and the number of other Rendezvous nodes, respectively.

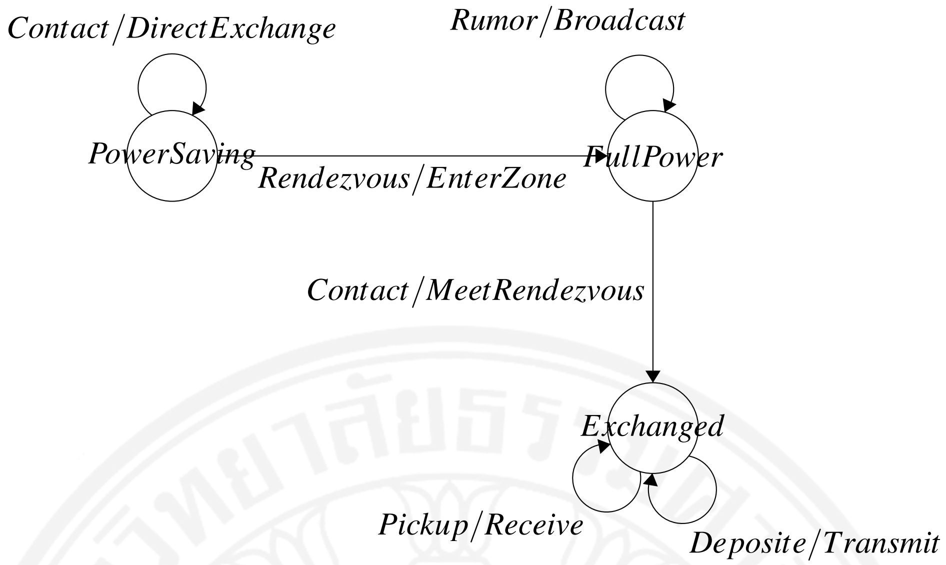

Figure 3.6: FSM Description for OppNet node in DRRA

$$\delta\left(d_j\right) = \begin{cases} 1 \quad ; \quad d_j \quad \leq \quad D_{cc} \\ 0 \quad ; \quad d_j \quad > \quad D_{cc} \end{cases}$$

The Rendezvous node will decide to stop at the expected node-gathering area when the number of OppNet nodes in the current Rendezvous place (γ_c) becomes greater than the predefined Rendezvous place node threshold, Γ_c as shown in Fig. 3.5.

Note that, the Rendezvous nodes will keep moving until they meet the desired conditions. In addition, in the process of moving, the Rendezvous node will keep broadcasting the Rendezvous Area rumor message (*RA*), so the OppNet nodes can learn that they are in the Rendezvous zone when they detect the *RA* messages.

In fact, the ratio of Rendezvous node movement (in searching) time and stop (sweeping) time might be an indicator for the spareness of the OppNet nodes in the network.

In order to clarify the DRRA system model, we simply describe the algorithm in basic Finite State Machine (FSM) as in Fig. 3.6. From the diagram, the nodes in *PowerSaving* state can exchange the messages outside the Rendezvous place when they get contacted with other nodes. When the nodes enter the Rendezvous place, their states are changed into the *FullPower* mode and start the rumor messages broadcasting. Subsequently in *Exchanged* state, nodes can exchange the messages with a Rendezvous node by depositing the messages and picking up the messages destined to them. On the other hand, Fig. 3.7 presents the FSM of Rendezvous place in DRRA. From the *Empty* state, when the OppNet nodes are in the zone, they can exchange the messages with Rendezvous node in *Exchanged* state. For insufficient contacts on specific time threshold, node can enter the *Searching* state using Rendezvous place searching algorithm while broadcasting Rendezvous Area rumor message. Once the Rendezvous node meets the desired condition, it can start message exchanging process with the contacted nodes.

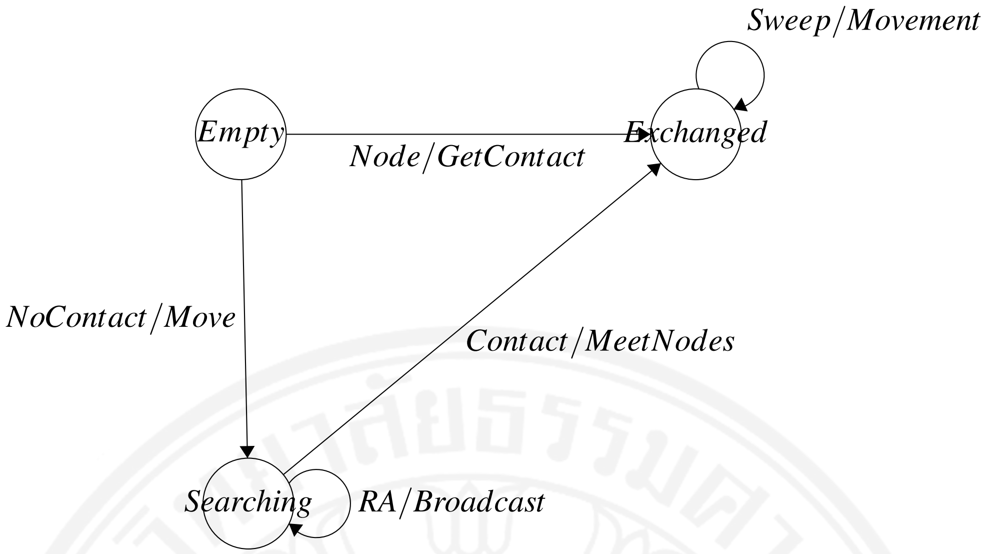

Figure 3.7: FSM Description for Rendezvous place in DRRA

3.2 Evaluation

The objective of the evaluation is to analyze the performance of our proposed algorithm on the sparse network environment comparing with traditional OppNet protocols. We compare both predictable and non-predictable behavior OppNet nodes with the commonly well-known Epidemic protocol[104] under different node-density environments. In addition, we compare the DRRA with two existing fixed-infrstructure protocols in context based routing: Relay Points and Plan Path.

3.2.1 Simulation setup

We setup a simulation environment using ONE (Opportunistic Network Environment) [55], which is a powerful tool designed for running opportunistic network simulation with various routing protocols and different movement models. All the results are obtained by extensive simulation runs with different seeds. For the OppNet simulation model, the main parameter that largely affects the evaluation performance is the movement model. In our evaluation, we deploy the Group movement model instead of the most commonly used, Random Way Point (RWP) model [7], to correctly capture the the actual behavior of node movements. In fact, several multi-hop wireless network scenarios are most realistically represented using the Group movement model [9] which represents the random motion of a group of mobile nodes as well as the random motion of each individual mobile node within the group. This is the vital case for modeling the routing simulation in OppNet since the movements in several cases are in swarm behavior, in which nodes are aggregating together and moving in some directions, such as the movement of human in disasters or military tactical operations. The other parameters that mainly effect the evaluation performance are the area of operation, the wireless range of the nodes, node velocity and spatial locations of the nodes [7]. In our simulation, we fix the number of nodes while increasing and decreasing the area of operation which results in a wide range of node density parameters for evaluation. Node density (λ) is defined as the number of nodes per unit area. If N nodes are distributed in a square grid of size $M \times M$ m^2 then the λ is given by $\lambda = \frac{N}{M^2}$. The wireless range of our OppNet node can be adjusted depending on the environment, while the node velocity is equal to the normal human walking speed. The common parameters are summarized in Table 3.1.

3.2.2 Metric

Table 3.1: simulation variables

Parameters	N_c	N_{rv}
Message Size	500 KB - 1 MB	
Node buffer	500MB	10GB
Maximum Radio Range	30 Meters	100 Meters
Transmission Speed	54 Mbps	
Router	DRRA	Epidemic
Moving Speed	0.5 - 1.5 m/s	
Data Generate Rate	one new message every 25 to 35 seconds	
Movement Model	Group Movement Model	

Opportunistic routing protocols are commonly evaluated by delivery ratio, median latency and network overhead. In this chapter, we focus on delivery ratio and network overhead in terms of energy consumed to deliver a message within a specific message deadline. We assume that all messages delivered within the deadline has no difference in protocol performance.

Delivery ratio (D_r) is defined as the ratio of the total number of messages successfully delivered within the deadline ($M_{delivered}$) to the total number of unique messages generated within the duration of simulation [121] and created from the source nodes that need to be delivered ($M_{created}$) as shown in Eq. 3.2.

$$D_r = \frac{M_{delivered}}{M_{created}} \tag{3.2}$$

Energy consumption (E_c) is defined as the amount of energy consumption required by all related OppNet nodes to deliver one message ($M_{created}$). We simplify the energy consumption model by considering the energy consumed by the wireless interface to transmit a message by determining the number of all necessary protocol packets, M_{packet} per number of $M_{created}$ messages. To transmit an L bit-length packet using a radio interface with transmission range, d, the consumed energy, E_T, can be determined by Eq.3.3 [119, 106], where α is the power loss component with $\alpha \in [2,4]$ and $\varepsilon f_s \, [J/(bit/m^{\alpha})]$ is the amount of energy consumed by an amplifier to transmit one bit data at an acceptable quality level including the energy consumed during the idle listening.

$$E_T = L \cdot \varepsilon f_s \cdot d^{\alpha} \tag{3.3}$$

As a result, the energy consumption (E_c) of the wireless interface can be derived as Eq. 3.4

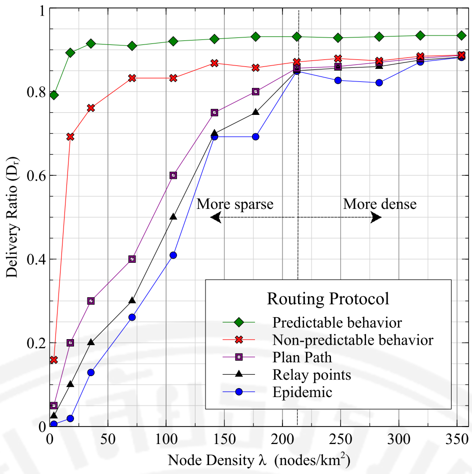

Figure 3.8: Delivery Ratio per Node Density

$$E_c = \frac{M_{packet}}{M_{created}} \cdot L_p \cdot \varepsilon f_s \cdot r^2 \tag{3.4}$$

Note that, L_p is the size of a protocol packet, r is the radio transmission range of the protocol packet and α is equal to two in our simulations.

Protocol performance (P_Ψ) is a composite metric to capture the gain in both delivery capability and energy saving capability of a specific protocol, compared with the baseline protocol, Epidemic. The P_Ψ can be calculated from Eq. 3.5.

$$P_\Psi = D_r^{P,B} \cdot \frac{1}{E_c^{P,B}} = \frac{D_r^P}{D_r^B} \cdot \frac{E_c^B}{E_c^P} \tag{3.5}$$

In this Equation, P is the target protocol while B is the baseline protocol (Epidemic protocol, for example) to be used as comparative energy reference.

3.2.3 Simulation Results

This section shows the results of the different sets of simulation runs that have been performed to study the performance of the proposed routing protocol and its behaviors when changing the protocol's key parameters.

General protocol performance

Firstly, the comparison of delivery ratio is shown in Fig. 3.8, where $x-axis$ represents the node density (the number of nodes in the area of one km^2) and $y-axis$ shows the delivery ratio. The vertical line shows the boundary between *more sparse* and *more dense* which defines by the point when the delivery ratio starting to decline. In our simulation, we assume the environment of one Rendezvous node and the ratio of time interval between full power and power saving, τ_s of 0.5. Fig. 3.8 shows that our proposed protocols gain slightly better delivery ratio in the dense environment. On the other hand, the proposed protocols gain

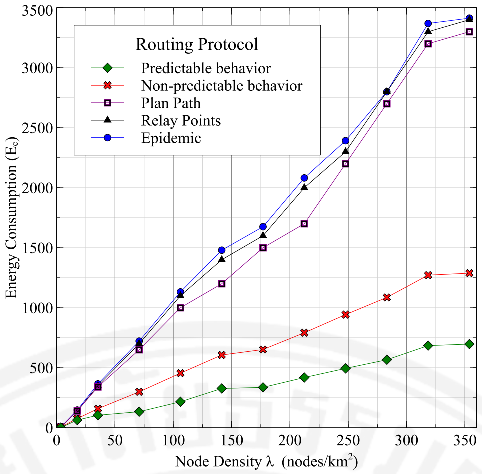

Figure 3.9: Energy Consumption per Node Density

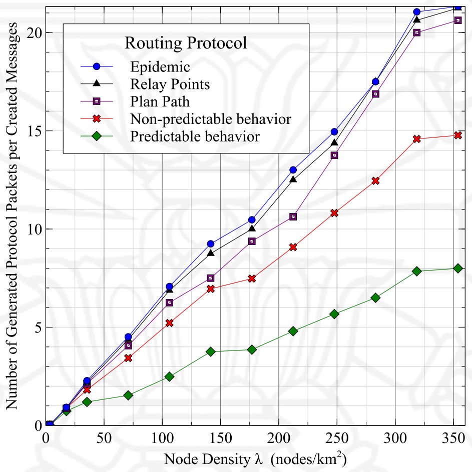

Figure 3.10: Number of Generated Protocol Packets per Created Messages on Node Density

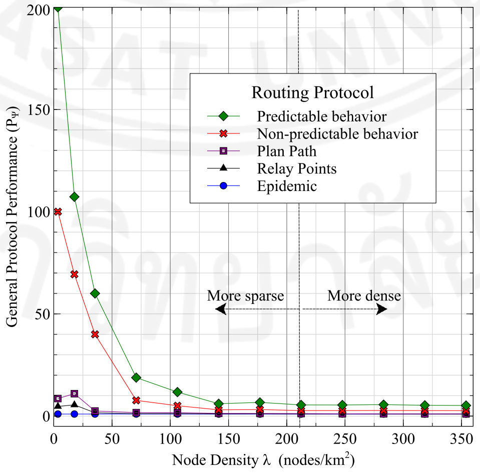

Figure 3.11: General Protocol Performance per Node Density

significantly higher delivery ratio in the sparse environment by maintaining the ratio up to 80%, even when node density is as low as 50 $nodes/km^2$ in non-predictable behavior or as low as 5 $nodes/km^2$ nodes in predictable behavior. Overall, on average, our proposed protocols gain approximately 40% higher delivery ratio than existing traditional Epidemic routing in sparse networks.

The reason behind this is that the proposed Rendezvous concept can facilitate a message exchanging process between nodes passing through the same area but on the different time-line as designed. Those nodes cohabiting on both time and space domains are more likely to appear in dense networks but less likely to emerge in sparse networks. In addition, with the knowledge of node gathering areas (predictable behavior), the delivery ratio of the proposed protocol can be further increased especially in the extremely low node density scenario.

Additionally, if the nodes passively wait for the target node to enter the Rendezvous place, it can harm the efficiency of packet delivery as in Fig. 3.8. The Relay points algorithm is a relay node implemented from the concept of recent relay node protocol [5, 122] such as Throwboxes which is a passive stationary node waiting for the target node to encounter. The result shows that the Relay Point gains slightly higher delivery ratio than Epidemic protocol, but significantly lower than Rendezvous protocol especially in the sparse area. The reason behind this is because Rendezvous protocol can increase the zone of transmission range, thus facilitate in gaining efficient node contact opportunities. In the Plan Path, the relay nodes are moving according to the designed plan. In the simulation, the plan path is a zigzag path which can cover all coverage area in a certain time. The result from Fig. 3.8 shows that the Plan Path presents a similar trend to Epidemic protocol while gain slightly delivery ratio than Fixed Relay Points. However, it cannot achieve delivery ratio as high as of the proposed Rendezvous based due to the dynamic non-stationary movement of OppNet node and the lack of contact activity enhancement like Rendezvous protocol.

Secondly, the energy consumption (E_c), which is another vital factor in opportunistic networks where most mobile nodes are usually equipped with limited power resources, is shown in Fig. 3.9. The $x-axis$ represents node density and $y-axis$ is the E_c in unit of energy consumption per 1,000 messages. This graph shows that the value of E_c linearly increases when a network become more dense. The trend on the graph is similar to the number of generated protocol packets per created messages on the node density graph in Fig. 3.10. The predictable behavior saves energy consumption by 80% compared to the Epidemic protocol while the non-predictable behavior can save around 60% compared to the Epidemic counterpart. On the other hand, the number of generated protocol packets per created message of the predictable behavior scenario is 60% and for the non-predictable behavior is 30% lower than the Epidemic protocol. The reason of E_c rising in the dense environment results from the increasing of node meeting activities from the growing number of nodes generating messages. The trend similarity in Fig. 3.9 and 3.10 is derived from the increasing number of messages in Eq. 3.4 which results from the rising energy consumption. Our proposed protocols require the lower number of generated messages while presenting a significantly lower E_c which results from the fact that the Rendezvous protocols utilize a shorter average wireless radius.

Combining both gains in delivery ratio and energy consumption savings, the proposed general protocol performance can be seen in Fig. 3.11. The Epidemic protocol is used as the basedline protocol in P_ψ calculations so its value in Fig. 3.11 is 1. The proposed general protocol performance can rise up to 20 times compared to the existing Epidemic protocol when a network is very sparse and on average about 5-10 times in general network environments compared to the Epidemic protocol.

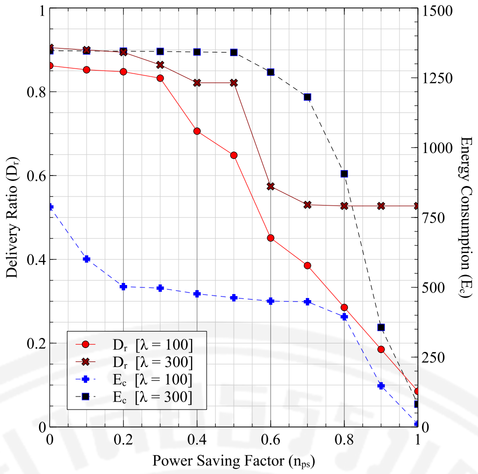

Figure 3.12: Delivery Ratio and Energy Consumption on Power Saving Factor

Impacts of the power saving factor

In this subsection, we study protocol parameters relevant to the power saving factor and the tradeoffs between power consumption and delivery ratio. We define the power saving factor, n_{ps}, as the composite parameters of the proposed protocol as in Eq. 3.6.

$$n_{ps} = \tau_s \cdot \frac{r_c^{max} - r_c^{min}}{r_c^{max}} \tag{3.6}$$

The n_{ps} is mainly calculated from the time being in power saving mode, τ_s, and the portion of energy consumption used when being in such power saving mode. The value of n_{ps} is in range [0,1] where its minimum value (no saving) represents either OppNet nodes never operate in power saving mode of the proposed protocol or the maximum energy consumption ($r_c^{min} = r_c^{max}$) is used in such mode. The opposite behavior in power saving mode applies for the maximum n_{ps}. Fig. 3.12 shows both delivery ratio (D_r on solid line) and energy consumption (E_c on dash line) when varying the power saving factor (n_{ps}) for the node density (λ) = 100 and 300 $nodes/km^2$. The graph shows that when n_{ps} increases, the value of E_c and D_r decreased as expected. The delivery ratio for more sparse networks significantly drops when the n_{ps} increases because the saving factor can degrade the delivery performance if the nodes spend more time in saving mode. In fact, the optimum of n_{ps} depends on the real applications. In the application with the level of acceptable minimum D_r as a threshold, we can select the n_{ps} that gives the minimum E_c. On the other hand, we can select the n_{ps} that gives the maximum D_r if the threshold of acceptable maximum E_c is defined. Finally, if both the minimum D_r and maximum E_c are defined, we can get the n_{ps} value that suits the application.

Other network environment parameters

In this subsection, we investigate other protocols and environmental parameters which may have effects on the proposed protocol performance. Fig. 3.13 presents the variation on the number of Rendezvous nodes to analyze the impacts on delivery ratio per node density. This graph shows that more Rendezvous nodes can achieve more D_r as expected. In Fig. 3.14, the effect of R_{rv}/R_c^{max} ratio on delivery ratio is studied. By increasing R_{rv} (maximum radio transmission of Rendezvous node), the D_r will not increase but slightly decrease. This is

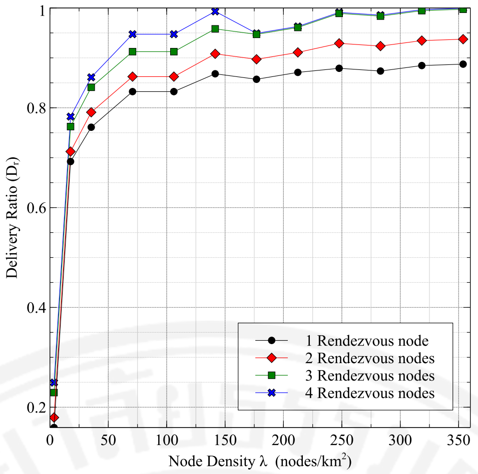

Figure 3.13: Multiple Rendezvous Nodes

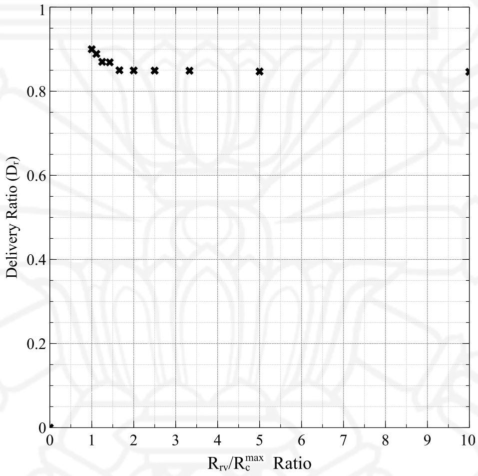

Figure 3.14: R_{rv}/R_c^{max} ratio

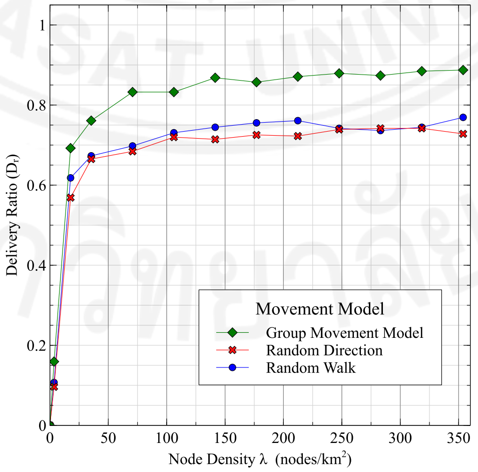

Figure 3.15: Movement Model Comparison

the result from the asymmetric in transmission ranges of OppNet nodes which can degrade the delivery ratio performance in the Rendezvous area, since the nodes with a longer trans-

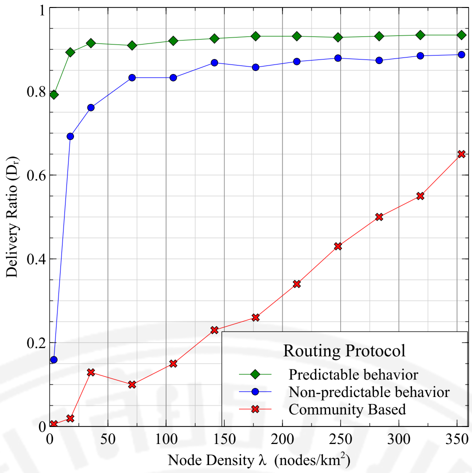

Figure 3.16: DRRA comparison with the same routing category

mission range can send the messages to other nodes with shorter ranges, but cannot receive the messages back. Subsequently, Fig. 3.15 shows that our proposed Rendezvous protocol performance will drop if node movements become more random since the proposed protocol utilizes the group gathering behavior to increase message exchanging activities. Finally, we compare the delivery ratio of the DORSI with the Community-Based routing (CR) [75] as in Fig. 3.16. This graph shows that DORSI in both predictable and non-predictable behavior gain significant higher delivery ratio than CR especially in the sparse network. Basically, CR utilizes the social attributes of nodes in which nodes determine the community they belong to and select a proper next hop node in order to reduce the number of forwarding. As a result, the delivery ratio of CR is lower substantially in low node density because CR requires sufficent number of nodes even though it can record the contact history in order to calculates the tie strength with other nodes to optimize the forwarding path.

3.3 Conclusion

Opportunistic Routing techniques can be applied in a plentiful variety of scenarios such as Social Mobile Network, Disaster Recovery Networks or Military Tactical Network. In this chapter, we investigate the use of Rendezvous points in opportunistic network routing to increase the delivery ratio in extreme sparse network environment. This novel protocol proposes the two new types of nodes, Rendezvous node and OppNet node, which can help maintaining the messages in one place as long as possible in order to bridge the gap of time and space domains. In this Rendezvous place, the passing nodes can announce, deposit and pickup their own messages without meeting with other nodes that carried desired messages. The size and shape of a Rendezvous place can be adapted to the environment of OppNet nodes in the area. We define our routing model in two functions: predictable and non-predictable behavior OppNet node functions. The results suggest that our protocols perform significantly higher in terms of general protocol performance which is the tradeoff of delivery ratio per energy consumption. This implies that if the location of rendezvous place can be predicted, we can achieve the highest overall performance.

Chapter 4

Data-wise Opportunistic Routing with Spatial Information (DORSI)

As for now, the routing algorithms for opportunistic network has been barely concerned about the content of data. The routing decision for this type of network is usually based on node topology environment. However, there are several data dissemination methods based on the context of data. Yazhou et al. [51] proposed the data dissemination in DTN based on content classification which classifies the forwarding messages by their content, every node only requests the message that it is interested in. This research showed that this method can provide low overhead while maintaining high delivery rate and low delivery latencies compared to epidemic routing. While in other content-based network protocols [22], message content is structured as a set of attribute/value pairs, and a selection predicate is a logical disjunction of conjunctions of elementary constraints over the values of individual attributes. Both techniques differ from DORSI in the sense that they route all messages by sets of rules while our protocol route messages differently depend on their priority class.

A number of related researches attempt to address the main criticism of flooding based routing protocol in term of network congestion. APRA [52] arranges the forwarding sequence and the dropping sequence based on their assigned priority. This priority is determined by the TTL, Delivery Predictability, and Replication Density. While Joe et al. [53] developed a DTN message priority routing protocol by modify the spray and wait [100] flooding-based routing protocol. However, these prioritizing mechanisms aim to rank the messages by defined matrices which involving network topology. In contrast, DORSI routes the data based solely on the content of data itself.

Although all of the above mentioned the routing method by the content of message to limit the number of message flooding in the network. The messages traversing in the network are treated the same except containing different attributes. The routing decision depends on the sets of rules and nodes. In this chapter, we propose a new routing algorithm to assure the deliverable of important data while maintain the lower message replicas. The routing decision depends on the class of data itself. In addition, we improve the overall performance by appending the geographic information for forwarding node selection.

This routing algorithm dynamically prioritizes the candidate messages based on the content of the data. Since security is an increasing concern in military and other critical operation missions, it is vital to route data of different sensitivities differently. The most significant and sensitive data should be assured its higher level of delivery and protection than the common data. However, only few works have applied the well-defined information sensitivity concept such as Multi Level of Security (MLS) [62, 1] to network information such as routing information, QoS signaling and other management information [110].

In this routing algorithm, we purpose to incorporate the information sensitivity concept into the messages in order to route the data differently in compliance with the classes of messages. To the best of our knowledge, this method has not been fully explored in the

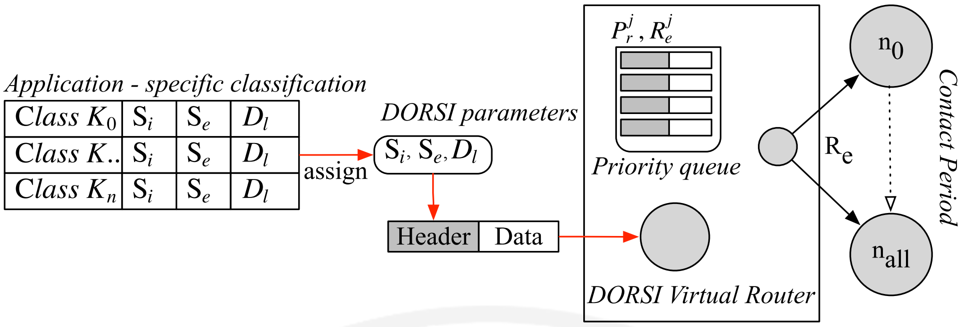

Figure 4.1: DORSI system model

existing literatures. In this research, we extend our previous work [56] which is our initial message classification concept proposal by generalizing information sensitivity parameters and involving spatial information into routing decision to improve the network efficiency. We conducted Opportunistic Network Environment (ONE) simulation [55] to evaluate the performance of DORSI algorithm.

4.1 DORSI routing algorithm

The design goal of DORSI is to distinguish the data with different information sensitivity concept. We implement this protocol in order to guarantee that the important message can reach the destination within the time limit resulting in higher delivery ratio. Additionally, we need to control the security risk of the message with higher security level by limiting the number of message replica in this network according with information sensitivity concept [62, 1]. The final goal of this protocol is to increase the bandwidth efficiency by selecting the candidate nodes with higher probability of delivering the message to the destination.

Fig. 4.1 shows the proposed DORSI system model implemented as a virtual (software) router in an OppNet node. In DORSI, besides common routing information such as source and destination addresses, every delivered message is associated with 3 additional DORSI parameters which are Significant level (S_i) Security level (S_e), Delivery deadline (D_l). The S_i represents how important of this message while the S_e defines the level of this data that needs to be protected. The D_l element is the message expiration time. If the delivery deadline is reached, the message will be dropped. The value of these DORSI parameters are determined in accordance with the application specific requirement. For example, the contents in military domain are divided into several classifications based on the multilevel of security which is intended to prevent unauthorized personnel from accessing information at higher classification than their authorization [110]. Therefore, different classes of message in military perspective are treated differently.

At DORSI router, a time-constrained priority queue is used to carry DORSI messages waiting for being forwarded to the next node. The DORSI parameters: S_i , S_e and D_l are used in forwarding decision of DORSI virtual router on a node when this node opportunistically contacts to the other nodes. Upon node contact, messages will be processed orderly according to their up-to-date priority value, however the message whose delivery deadline is reached will not be considered and will be removed out of the queue. The priority value (P_r^j) of a specific message, j, is calculated based on its significant level and its expediting factor, $\xi(D_l^j, t)$, as in Eq. 4.1

$$P_r^j = w_p S_i^j + (1-w_p)\xi(D_l^j,t) \tag{4.1}$$

where

$$\xi(D_l^j,t) = \begin{cases} 0; \tau_t > \tau_{max} & \\ \frac{\tau_{max}-\tau_t}{\tau_{max}-\tau_{min}} & ; \tau_{min} \leq \tau_t \leq \tau_{max} \\ 1; \tau_t < \tau_{max} & \end{cases}$$

The W_p is the priority weight coefficient which is used to balance the effect between the significant level and expediting factor components. We define τ_t as residual lifetime of message which is calculated from $D_t^j - t$. The expediting factor value, in the range [0,1], is composed from the message residual lifetime, compared with the maximum and minimum countable message lifetime, τ_{max} and τ_{min}, in the system. The message with the residual lifetime τ_t = τ_{max} is considered as no need to expedite the message delivery while the message with τ_{min} is considered for maximum expediting. Note that, the P_r^j value will be recalculated at every time a node get contacted. When a specific message,j , is being processed, the determination whether it should be copied and sent to a specific contact node is controlled by the replication probability value, R_j^e, calculated at a contact time as in Eq. 4.2.

$$R_e^j = (1-R_{min})[w_r P_r + (1-w_r)(1-S_e^j)] + R_{min} \tag{4.2}$$

The replication probability value, in range of [R_{min}, 1], is based on the concept that a message with high priority, P_r^j, should be disseminated more in order to increase delivery ratio while the message with high security level should be replicated less in order to tighten security risk. In the formula, the replication weight coefficient, w_r , is used to balance effect between both components. The R_{min} is the minimum guaranteed replication probability value in the system so that even a message with very low priority and very high security still has a chance to be forwarded. This R_{min} is a configurable system parameter according to the application requirement. In our experiment, the good value of R_{min} is 0.5 which is the result from varying the parameter in 4.2. In the case that there are several nodes simultaneously contacts when processing a specific message, the node with higher rank will be considered before the lower one. The ranking value of a contacting node, n, is calculated according to its departure probability representing the relative chance to move away from the DORSI router node, r.

$$N_r^n = \sqrt{(x_n \cos\theta_n - x_r^t \cos\theta_r^t)^2 - (y_n \sin\theta_n - x_r^t \sin\theta_r^t)^2} - \sqrt{(x_n - x_r^t)^2 - (y_n - x_r^t)^2} \tag{4.3}$$

It can be estimated as the difference in distance between the current DORSI router, r, and the contacting node n , after they moves one unit distance further in their current direction. Given that the positions of the router r and the contacting node n are (x_r, y_r) and (x_n, y_n). In addition, their moving direction vectors are $\vec{d_r} = \cos\theta_r \hat{x} + \sin\theta_r \hat{y}$ and $\vec{d_n} = \cos\theta_n \hat{x} + \sin\theta_n \hat{y}$, respectively. The ranking value, N_r^n is defined by formula in Eq. 4.3. The positive N_r^n value means the contacting node is moving away while the negative value means that it becomes closer. The contacting node with higher N_r^n is needed to be considered since there is higher probability that it will be out of reach soon, compared with the other nodes. In Fig. 4.3, D_0 represents the distance between node r and n at time t = 0 while D_1 is a distance at the time

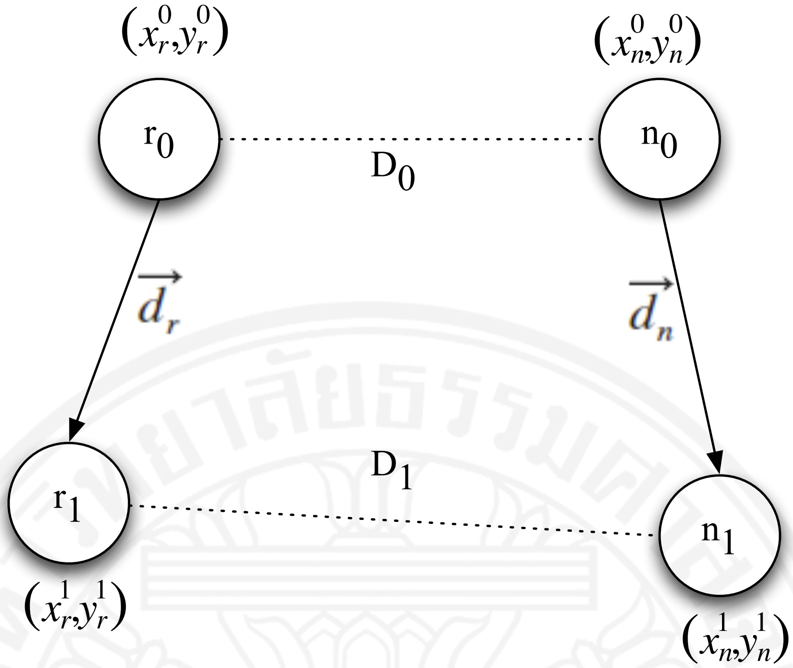

Figure 4.2: Node ranking model

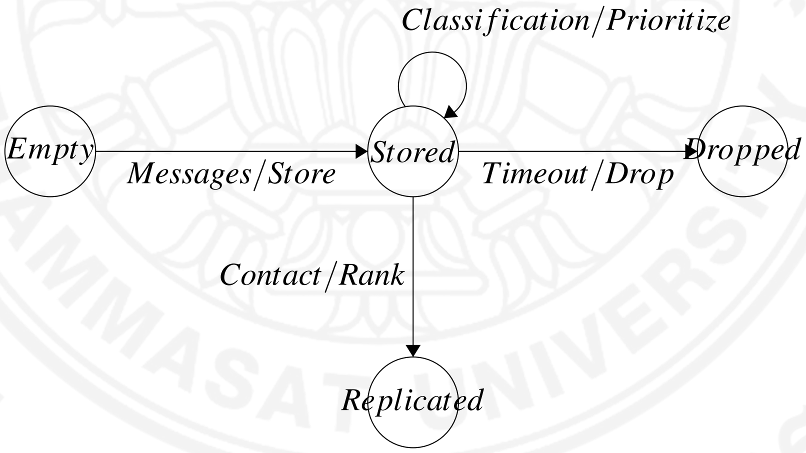

Figure 4.3: FSM diagram of DORSI

t=1. If $D_1 > D_0$, both nodes tend to move away from each other which results in higher node ranking. Note that all messages where lifetime reach their deadline are discarded from the carried node. In addition, DORSI node will not receive the same copy of a specific message.

In order to clarify the DORSI system model, we describe the algorithm with the simple Finite State Machine (FSM). From the empty state, the messages are stored in the buffer when the new messages arrive. Subsequently, the messages are classified and prioritized according to their class. If the specific messages meet their deadline, they are dropped from the system. When the nodes get contacted, they arrange the contacted node according to the ranking value previously described.

Parameters	DORSI	Epidemic
Operation Time	3600 Seconds	
Message Size	500 KB - 5 MB	
Node Buffer	1000 MB	
Transmission Range	150 Meters	
Transmission Speed	54 Mbps	
Node Density	0 - 100 %	
Router	DORSI	Epidemic
Deadline	Relative to data class	
Movement Model	Random Waypoint	
Wait Time	0 - 180 Seconds	
Number of classes	5	

Table 4.1: DORSI Simulation variables

4.2 Evaluation

4.2.1 Simulation setup

This protocol is designed to implement on any network that messages can be classified by data content. We select the military tactical network as a sample application to present and evaluate this protocol because of its opportunistic behavior. Since military tactical networks are subject to frequent disruption of end-to-end communication, current traditional network protocol tends to poorly handle these disruptive environment. In this extreme scenario, opportunistic network with store-carry-forward routing can be integrated into this tactical network to aid significant and secure operations. In addition we employ MLS [110] as a classification of data in this military scenario environment, consisting of 5 classes.

We conduct the extensive simulations using the ONE 1.4.1 (The Opportunistic Network Environment simulator) [55]. ONE is a powerful JAVA tool for generating different movement models, running simulation with various routing protocols, visualizing simulations in real time and generating results, and post processing the results.

We implement new DORSI router with the designed simulation scenario to compare with modified traditional Epidemic routing protocol [104]. The Epidemic router is modified with the same classification as DORSI router in order to compare the actual performance between them. However, the classification implemented in modified Epidemic router is not effected the message routing decision. The Epidemic router treats every messages the same while DORSI router routes messages differently according to their DORSI parameters. Basically, the performance of opportunistic network correlates with the simulation parameters. In our tactical network simulation environment, we implement the scenario corresponding to the actual military operation. The common message in this tactical network traffic is usually commands in short message format, locations or images which the size of approximately 500 KB to 5 MB. A mobile node is assumed to be a soldier equipped with modern communication equipment with transmission speed and range of 54 Mbps and 150 Meters respectively. In addition, each node can hold up to 1 GB of storage for buffering the in-transmitted messages while randomly moving at a speed of 0.5 to 1.5 m/s. The simulation time is set for

1 hour to study the behavior of messages inside the network traffic. To evaluate the impact of message classification, we compare the performance of each router by varying the node density. Note that, we select the Random Way Point (RWP) mobility as the evaluation model because of its widely adoption in the OppNet simulations. Additionally, our work is focused on the sparse network environment in which the distribution on RWP is relatively uniform, thus this model is appropriate with the scenario. The detail of the study of mobility model can be found on Appendix B. In RWP, nodes can move around in random zigzag paths. The nodes can move around randomly in a 1,000 m x 1,000 m area with walking speed. In our experiment, the total number of nodes in a network per a one km^2 area denotes its node density. Each message embedded with the deadline value correlative to the degree of that data sensitivity.

4.2.2 Metric

To evaluate DORSI with Epidemic routing protocol, we define two keys performance index corresponding to our design concept: Effective Delivery Ratio (EDR) and Effective Replication Ratio (ERR). Our protocol disseminates the data by its degree of sensitivity, therefore in order to analyze actual performance this evaluation requires appending higher credential weight on the successful delivery of data with higher significant level. Basically, delivery ratio is defined by the ratio of the total number of messages delivered to the total number of messages created. In our evaluation, EDR can be computed by introducing significant level (S_i) into the number of delivered messages within the deadline (M_d) from each class to the number of created messages (M_c) as in equation 4.4.

$$EDR = \frac{\sum_{j=1}^{m} S_i^j M_d^j}{M_c^j} \tag{4.4}$$

On the other hand, we can compute ERR by the number of replicated messages (M_r) that incorporate with security level (S_e) to the total created messages as in equation 4.5. The higher ERR means more message replicas in the network resulting in excessive network resource consumption and higher security risk.

$$ERR = \frac{\sum_{j=1}^{m} S_e^j M_r^j}{M_c^j} \tag{4.5}$$

4.2.3 Result

Our implementation consists of two presenting keys: deliverable of significant data and security risk. Firstly, we analyze the EDR value to determine the delivery guarantee for important data. Figure 4.4 presents the relationship between effective delivery ratio and node density comparing DORSI to the epidemic routing. This graph illustrates that DORSI gains remarkably higher EDR than the Epidemic, approximately 35%. By the common nature of flooding based routing, the EDR increases with the node density because node can obtain higher tendency of successful message delivery when the number of nodes increase. In addition, at sparse node density condition (less than 10%), the EDRs of 3 simulated routing protocols are similar because of our prioritization technique requires specific amount of nodes in order to efficiently perform. Nevertheless, achieving 100% EDR is impractical

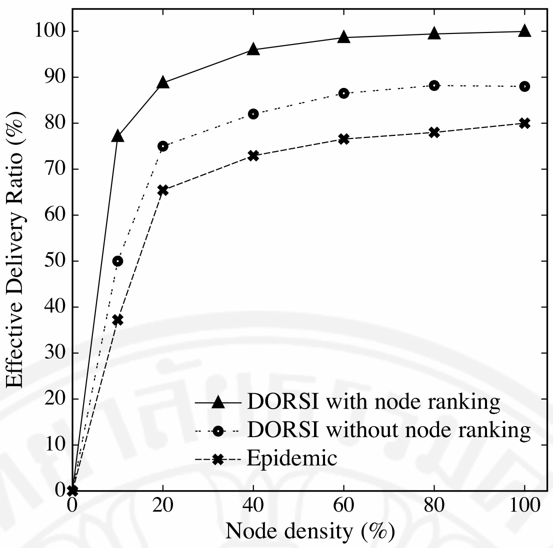

Figure 4.4: Effective Delivery Ratio comparison

even though all resources are utilized for this purpose. Message prioritization can improve the overall EDR about 10% over epidemic while node ranking mechanism can increase approximately more 25% EDR than DORSI without node ranking.

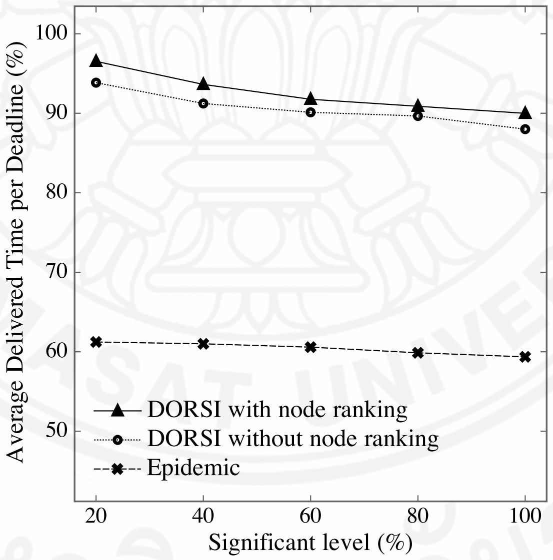

Figure 4.5: Average Delivered Time per Deadline on Significant Level

As a result, DORSI outperforms Epidemic due to these design components: Firstly, by introducing deadline into our message prioritization method, the message with higher significant level can reach the destination faster. This concept is supported by the Average Delivered Time (ADT) per deadline to significant level as shown in Fig. 4.5. This graph presents that the messages routing with DORSI can reach the destination closer to their deadline than the epidemic counterpart. The consequence from Fig. 4.4 and 4.5 shows that higher EDR of DORSI is a result from optimizing the time of delivery to their deadlines.

Message prioritization technique can increase the delivery ratio of important data as in Fig. 4.6. This graph shows the relationship between delivery ratios of each class in DORSI

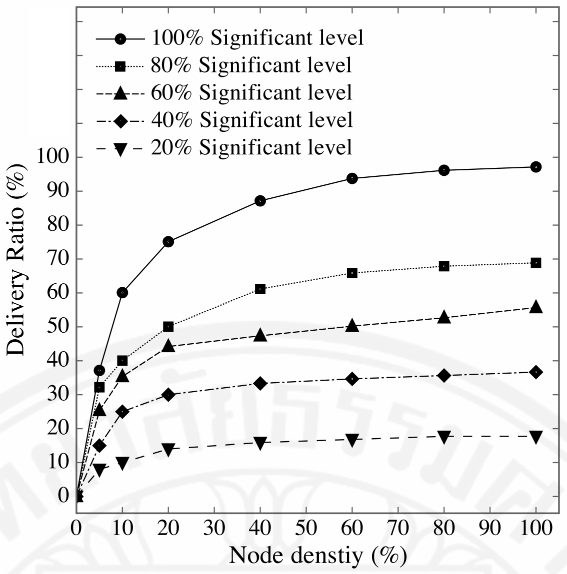

Figure 4.6: DORSI Delivery Ratio on each class

and the node density. Normally, messages with higher significant level (such as top secret or secret data) obtain more chance of successfully reaching the destination than others. The result clearly suggests that the delivery ratio of data with higher significant level is higher than less important data. Comparing delivery ratio on each class of DORSI and Epidemic, the message prioritization can distinguish the significant level of messages. On the other hand, the delivery ratio of all classes on the Epidemic routing in Fig. 4.7 are similar while the delivery ratio of DORSI increases by its classes. Consequently, the message prioritization can control the delivery time of each class resulting in overall deliverable improvement.

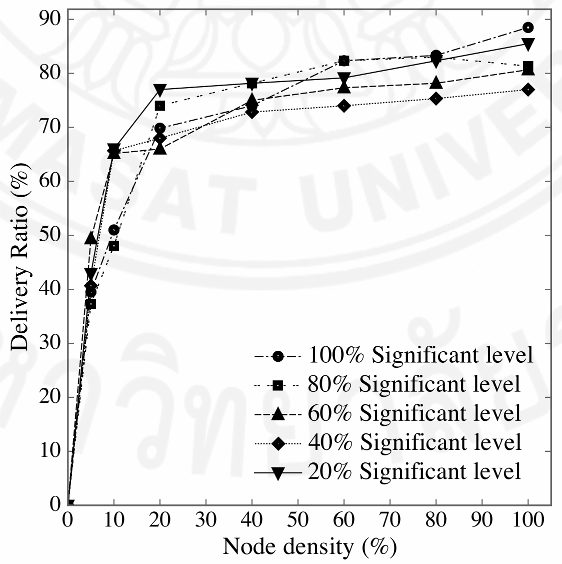

Figure 4.7: Epidemic Delivery Ratio on each class

Node ranking mechanism can enhance more EDR of DORSI over this same protocol without node ranking. By selecting the best candidate nodes to transmit the data, the important messages can gain more chance of reaching the destination. Fig. 4.4 and 4.8 clearly shows that the node selecting technique can improve the performance of DORSI without node ranking. This significantly benefits the network resource consumption and higher chance of deliverable of important data.

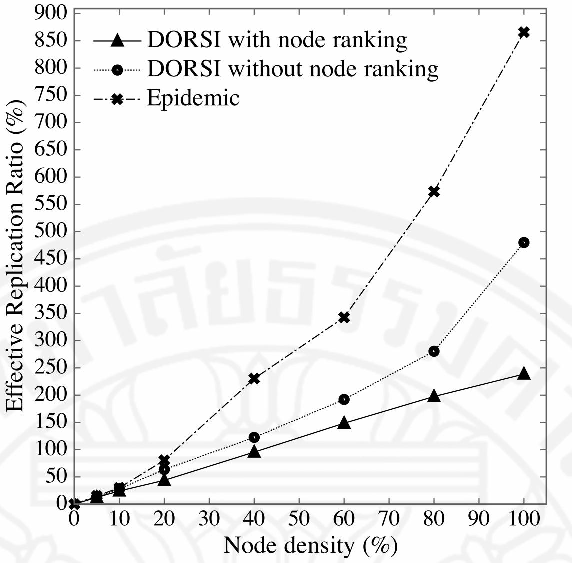

Figure 4.8: Effective Replication Ratio Comparison

On the other hand, the ERR is analyzed to assess the security risk. The ERR of Epidemic and DORSI without node ranking exponentially increase while DORSI with node ranking gradually rises as in Fig. 4.8. This graph shows the relationship between effective replication ratio and node density. The lower number of ERR means that less message replicas in the network resulting in less security risk. Because the DORSI protocol can efficiently control the number of message replication in the network traffic, the number of message copies are remarkably lower than that of the Epidemic. This result proves our design concept of security risk and aids in the optimum network bandwidth utilization.

To study the behavior of our protocol, we analyze the result of various numbers of classes as well. In our scenario, we divide the data classes based on British MLS scheme with 5 level of security: Top Secret (T), Secret (S), Restrict (R), Confidential (C) and Unclassified (U). However, there are other MLS schemes for different zone of military, for example, the US. DoD employs only 4 level of security: T, S, C and U. In order to deploy our method to different classes of data, we simulate the data with different scales of classes. Fig. 4.9 shows the comparison of effective delivery ratio and node density between different class scales from 1 to 5 classes. This graph shows the similar trend between all classes which is the more node density the higher the delivery ratio. The overall EDR increases when the messages are classified with more number of classes. This is the outcome from DORSI routing which requires some amount of nodes to process the node ranking mechanism. This result proves that the classification technique can be deployed to various numbers of classes in any application.

To study the behavior of DORSI, we select scenario with 20% node density aiming to analyze its performance by varying the transmission range of simulation parameters. Fig. 4.10 presents the relationship of EDR to the node transmission range. The result shows that the EDR increases with transmission range especially after 50 meters. However after the range of 150 meters, the EDR tends to slightly decline. By increasing the transmission range, transmitting node in DORSI can increase its opportunity to select the candidate nodes, resulting in more chance of reaching the destination.

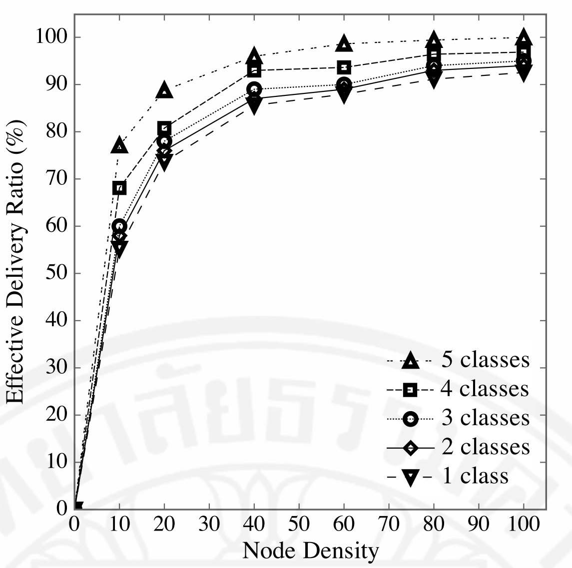

Figure 4.9: EDR on different classification scale

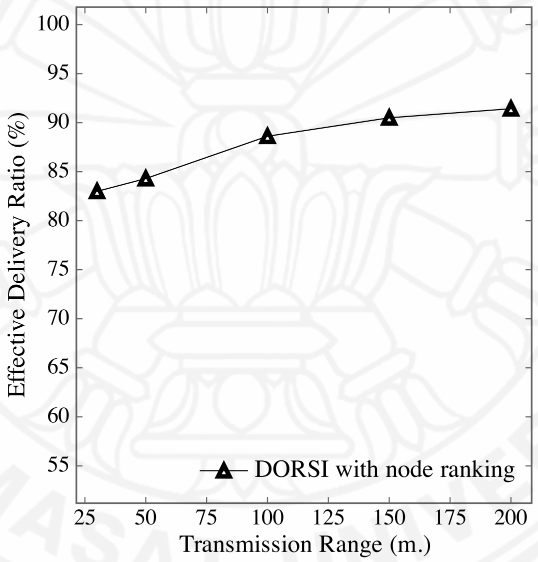

Figure 4.10: EDR comparing varied by transmission range

All in all, the key performance from the simulation results confirms with our design goals. In DORSI, the values of EDR and ERR show that we can control the message replication thus the message with higher priority can reach the destination faster proving the concept of significant level and security level. In addition, the value of ADT proves that we can control the messages to reach the destination before their expiration. Normally, the delivery ratio increases with the number of message copies. However, our approach can maintain the delivery ratio while reducing the message replicas in the network. As a result, this method significantly optimizes the network utilization. The drawback of this protocol is high processing time since these executable nodes require amount of computation time.

Subsequently, we compare DORSI with Content Classification (CC) [51] which is in the content-based forwarding according to Fig. 2.3 classification. Fig. 4.11 shows the delivery ratio comparison of DORSI with node ranking, Epidemic and Content Classification. In CC data dissemination method, the forwarding decision is classified based on the content.

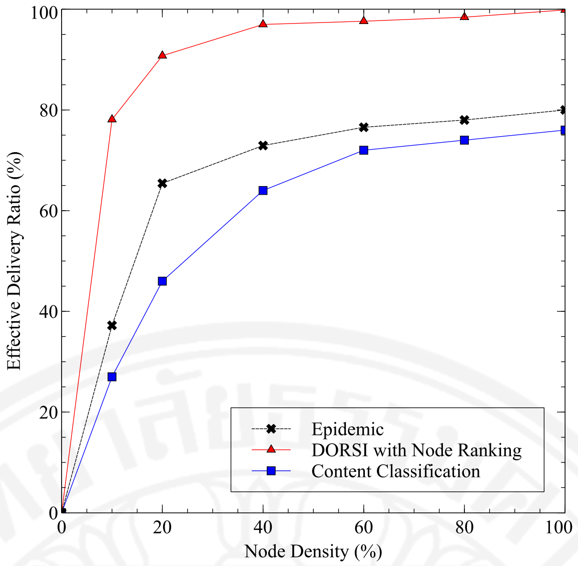

Figure 4.11: Comparison of Content-Based Classification

Every node only requests the messages that it is interested in with the objective of reducing the transmitted messages in the network. The graph shows that DORSI gain approximately 20% higher delivery ratio than CC. On the other hand, CC's delivery ratio trend is similar to Epidemic with only about 5% lower in the ratio.

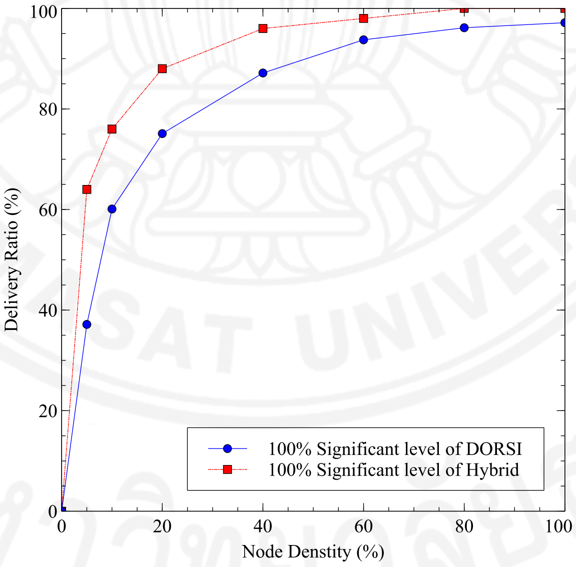

Figure 4.12: Hybrid and DORSI comparison at 100% significant level

In fact, we aim to achieve 100% delivery ratio on the extreme environment. With both our implementations of DRRA in Chapter 3 and DORSI this chapter, both algorithms can perform the maximum delivery ratio just close to 100%. Finally, we combine both algorithms using the non-predictable behavior of DRRA classified with DORSI forwarding algorithm which we call a Hybrid algorithm. Fig. 4.12 shows the delivery ratio comparison of DORSI with a hybrid for a 100% significant level messages. The result presents that the delivery ratio of a Hybrid can achieve 100% when the node density is more than 80%.

4.3 Conclusion

In this chapter, we propose a novel Data-wise Opportunistic Routing with Spatial Information (DORSI) in order to classify the messages based on the information sensitivity concept along with node prioritization technique corresponding to the their delivery probability computed by the spatial data. This protocol classifies the messages according to their significant level, security level and deadline relative to the sensitivity level of data. Meanwhile, this chapter adapts the geographical routing technique to select the best candidate node to forward the messages to the destination. Simulation experiments clearly illustrate that two key performance indexes, which are effective delivery ratio and effective replication ratio, are remarkably improved over the traditional Epidemic routing. Moreover, the delivery ratio of DORSI ,Epidemic and Content Classification comparison shows notable overall enhancement of the network routing efficiency. This means that DORSI protocol can achieve higher delivery ratio on more important data while limiting the replication of data with higher security level. The average delivered time of DORSI also shows the optimal bandwidth utilization since it can control the messages to reach the destination closer to their deadlines. Finally, we can finally achieve a 100% delivery ratio of highly significant message with the hybrid of DRRA and DORSI. In addition, this method can be applied to different scales of data classification to suit any application deployment. Furthermore, our work can be extended in various directions. An obvious extension of the work could be the evaluation of our approach on a virtualization network to physically obtain the real life results comparing to the results from this simulation result. Next, we will evaluate the performance of our method in different conditions in order to apply data classification routing technique on more general applications.

Chapter 5

Conclusions and Discussions

This chapter provides a summary overview of this thesis work and discusses how the proposed algorithms in this thesis can contribute to the field of opportunistic network routing.

This thesis has made two major research contributions in the opportunistic routing algorithms to address the problem in sparse network environments. First we discuss about how the Rendezvous based routing algorithms can improve the delivery performance of routing. Then, a data-wise routing in opportunistic networks is discussed.

In chapter 3, we present the routing technique based on the meeting point of Rendezvous concept to bridge the gap between the space and time domain. At first, we introduce the *store-carry-forward* paradigm employed by most routing algorithms,in which a node can receive messages, carry the messages while moving and then forward the messages copies to the opportunistic meeting nodes when possible. Then, we point out the problem of most existing routing models since they work well in the networks with high-to-moderate node density in which the opportunity that the moving nodes can meet with each other is rather high. As a result, most opportunistic routing algorithms perform poorly with delivery ratio becomes remarkably low in the sparse network environment especially when there is strict constraint on message delivery deadline. Our proposed system introduces the novel concept of rendezvous place where the passing nodes can announce, deposit or pickup their own messages without having to meet the other nodes carrying the desired message. In the proposed scheme, the rendezvous place can be detected automatically and its area's size and shape are dynamically changed according to the interaction among nodes passing around the area with our proposed *Rumor protocol* and *Sweep protocol*. The OppNet node can be performed in two operational modes: *Full Power* and *Power Saving* mode, in order to best utilize the power consumption. For the evaluation, the experiments are performed on two rendezvous place searching algorithms: predictable behavior and non-predictable behavior OppNet nodes. In this chapter, we also analyzed the delivery performance, power saving factor and rendezvous node factor to the density of OppNet nodes. By simulation results, we demonstrated that our proposed protocols can improve the delivery performance on the sparse network environment. This means that we can increase the delivery ratio while maintaining the energy utilization. We believe that the optimum of delivery ratio and delivery performance on the power saving factor can be a significant factor to design an practical applications on the extreme opportunistic networks.

Chapter 4 describes a technique to classify the data message in order to differentiate the messages to route differently on the opportunistic networks. Most of the routing protocols in opportunistic networks consider forwarding decision based solely on locally collected knowledge about node behavior in order to predict the delivery probability of each node. However, only a few of these routing techniques concerns about the data content, and none of them involves the practical scenario of data classification. This chapter proposes a novel routing scheme called Data-wise Opportunistic Routing with Spatial Information (DORSI), based on the classification level of the data in addition to the spatial information of the nodes. The forwarding algorithm of this routing is determined by significant level, security level and deadline of messages. We introduced three key parameters for the routing decision: *priority value*, *replication probability value* and *node ranking value*. To conform with actual applications in the real world environments, the scenario of multi-level security in military tactical network is designed as a test bed for our simulations. In addition, two composite metrics are proposed to analyze the key performance of our designed protocols: *effective delivery ratio* and *effective replication ratio*. The results show that the key performances improve over the traditional opportunistic routing. As a result, this novel protocol can achieve higher delivery ratio on data with higher priority within time limit while restricting the replicas of data with higher security level. We believe that this proposed method can further increase the delivery performance of the Rendezvous based routing protocol. Finally, we can achieve a 100% delivery ratio of highly significant message with the hybrid of DRRA and DORSI.

All in all, our proposed protocols can address the delivery efficiency issues of sparse opportunistic network environment especially the messages with deadline constraints. The advancement in the software defined or virtualized nodes has made it possible for our proposed protocols to be implemented in the real world scenarios.

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Appendix A

List of Publications

International Journals

- Jiradett Kerdsri, Komwut Wipusitwarkun, ”Dynamic Rendezvous based Routing Algorithm on Sparse Opportunistic Network Environment”, *International Journal of Distributed Sensor Networks*, Vol. 2015, 12 pages, 2015 (in ISI, impact factor=0.923)
- Jiradett Kerdsri, Komwut Wipusitwarkun, ”DORSI: Data-wise Opportunistic Routing with Spatial Information”, *Journal of Convergence Information Technology*, Vol. 8, No. 13, pp. 91-103, 2013 (in INSPEC)

International Conferences

- Jiradett Kerdsri, Komwut Wipusitwarkun, ”Data-wise Routing in Virtualization Environment (DRIVE) with multiple level of security for tactical network” *2012 IEEE/SICE International Symposium on System Integration (SII)*, pp.933-938, 16-18 Dec. 2012
- Jiradett Kerdsri, Komwut Wipusitwarkun, ”Network virtualization for military application: Review and initial development of conceptual design”, *14th International Conference on Advanced Communication Technology (ICACT)*, pp.61-66, 19-22 Feb. 2012

Appendix B

Mobility Models

The most widely used mobility model for MANET simulation is the Random Waypoint Model (RWP) [90] in which each node moves independently of each other in the obstacle-free environment. In fact, RWP is normally used in OppNets simulation such as in [94, 118, 126, 89] where every node chooses a random location in the simulation area and moves towards it at a random speed uniformly chosen from (V_{min}, V_{max}). The simplicity of analysis of this stochastic RWP has made it a benchmark for multi-hop mobile network simulation [38]. In the simulation, V_{min} is the minimum and V_{max} is the maximum speed of the nodes.

Figure B.1: Random Waypoint Model Example Topography

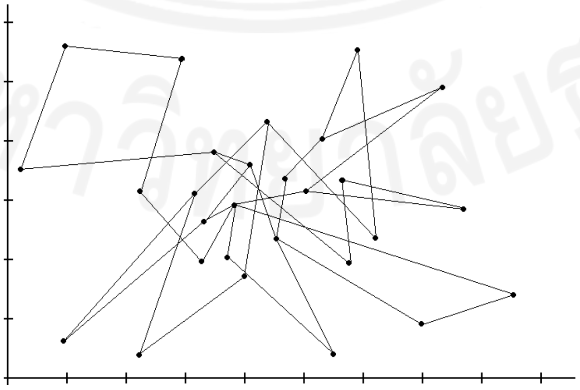


Figure B.2: Random Waypoint mobility movement pattern [31]

In RWP model which is a generalization of Random Walk (RW), a new destination inside the network area is chosen randomly. Then the node moves towards that destination with a randomly selected speed as in Fig. B.1 and B.2. Normally the Network Simulator implements this mobility model as follows:

- A node randomly chooses a destination and moves towards it with a velocity chosen uniformly and randomly from pre-defined ranges $[0, Vmax]$
- The direction and velocity of a node are chosen independently of other nodes.
- Upon reaching the destination, the node stops for the pause time parameter, T_{pause}, duration.
- After this duration, it again chooses a random destination and repeats the whole process again until the simulation ends.

Nevertheless, RWP suffer from the *density wave phenomenon* where the spatial node uniform distribution is transfered to non-uniform distribution with the progress of time. Finally, it reaches the state where the node density is maximum at the center of the area while the node density is reduced to zero towards the border region as in Fig. B.3 which shows the result of normalized distribution and contour line of certain occurrence values. Moreover, the distribution is symmetric in four axis direction of the center.

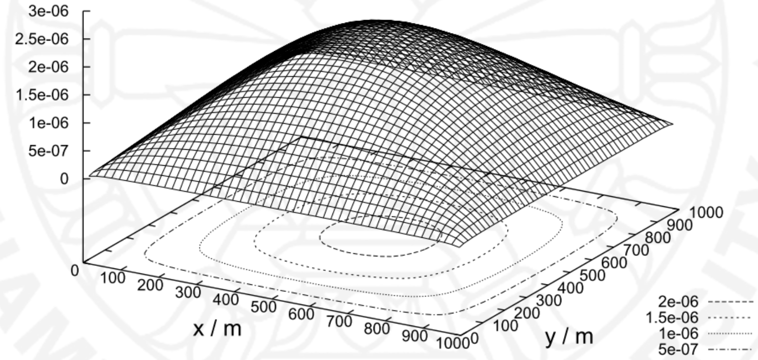
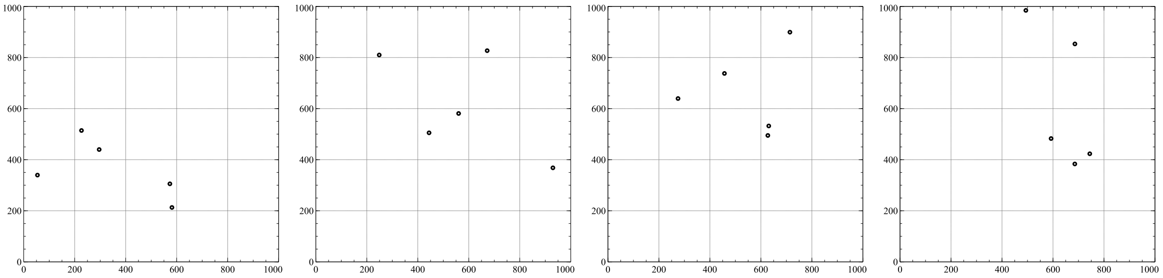


Figure B.3: Square simulation distribution [8]

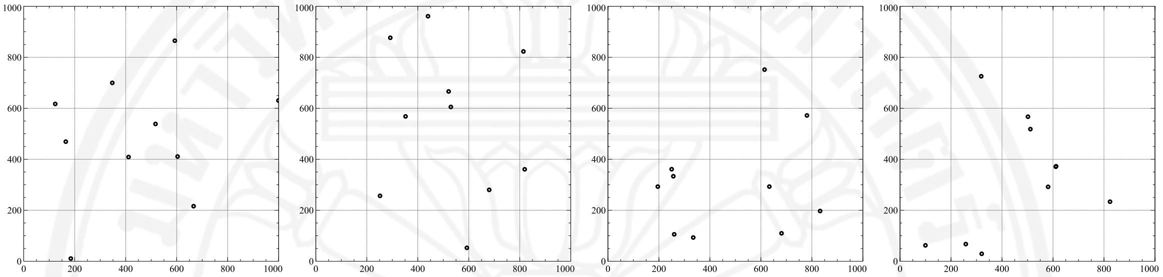
Since the RWP mobility model is one of the models used in our simulation, we studied the node distribution in order to analyze the affect on performance. Firstly, we aim to examine the node distribution on the different node density. We capture the snapshot of node distribution during each time interval during the simulation time varying by the number of nodes. Fig. B.4 to B.15 shows the 5, 10, 15, 25, 35, 50, 100, 150, 200, 250,300 and 350 nodes distribution in the operational area of 1000 m^2 on the simulation time of 3600 s. with 900 s. interval. From visual observation, when the node density increase more than 35 nodes, most nodes tend to be more dense in the middle of the play-field comparing to the near border edges. On the other hand, nodes tend to be more uniformly distribution on the more sparse network environment (less then 35 $nodes/km^2$ in our experiment)

After we studied the relationship of node density on the node distribution, we aim to study the affect of simulation duration to the node distribution. Figure B.16 and B.17 shows the 100 and 200 nodes distribution on the four different simulation time of 3600, 36000, 360000, 3600000 s. respectively. The graphs present that the nodes tend to be more slightly accumulate in the center with the progress of time. However, the differences in the node clustering overtime are not significant. Therefore, we can conclude that the nodes using



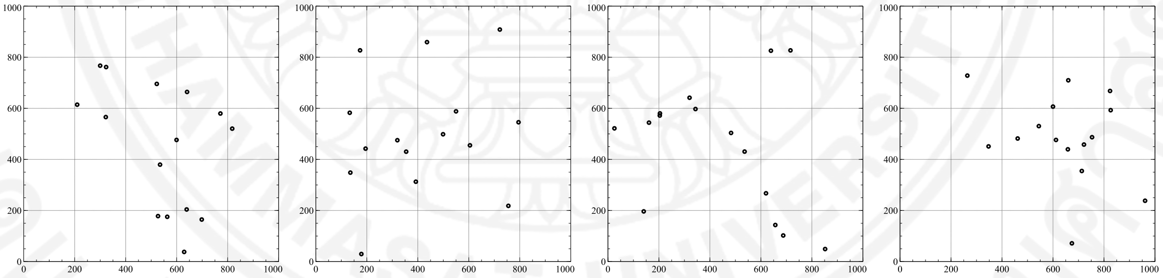
(a) 900 s. (b) 1800 s. (c) 2700 s. (d) 3600 s.

Figure B.4: The distribution of 5 nodes at different time



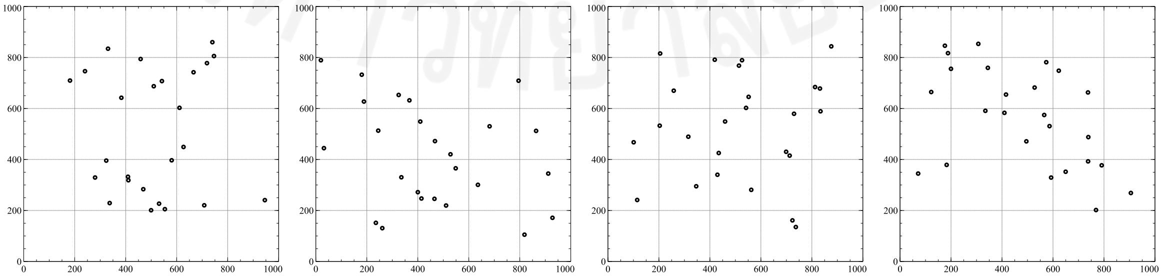
(a) 900 s. (b) 1800 s. (c) 2700 s. (d) 3600 s.

Figure B.5: The distribution of 10 nodes at different time



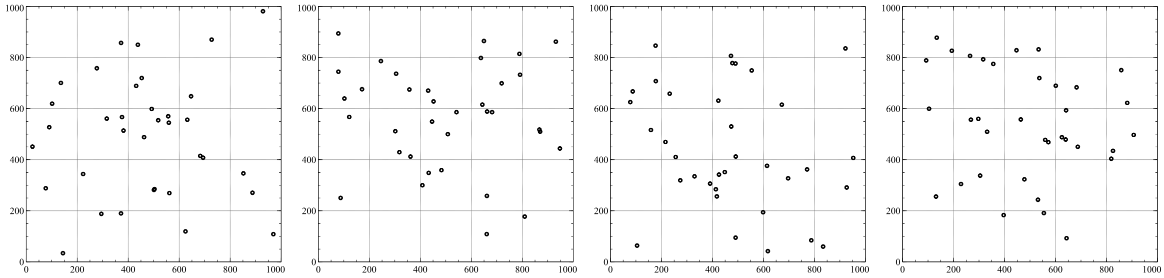
(a) 900 s. (b) 1800 s. (c) 2700 s. (d) 3600 s.

Figure B.6: The distribution of 15 nodes at different time



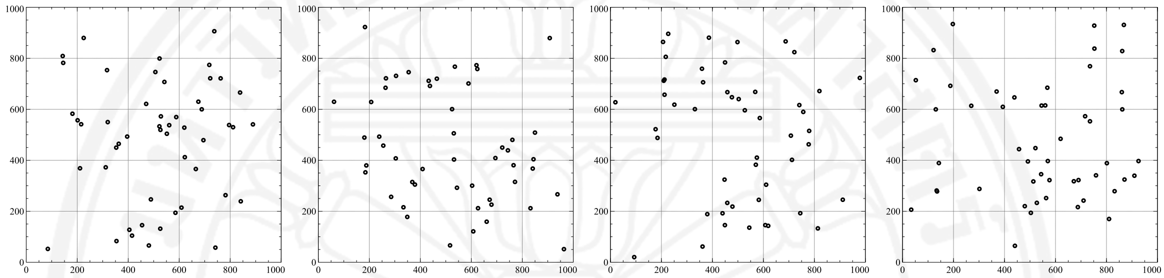
(a) 900 s. (b) 1800 s. (c) 2700 s. (d) 3600 s.

Figure B.7: The distribution of 25 nodes at different time



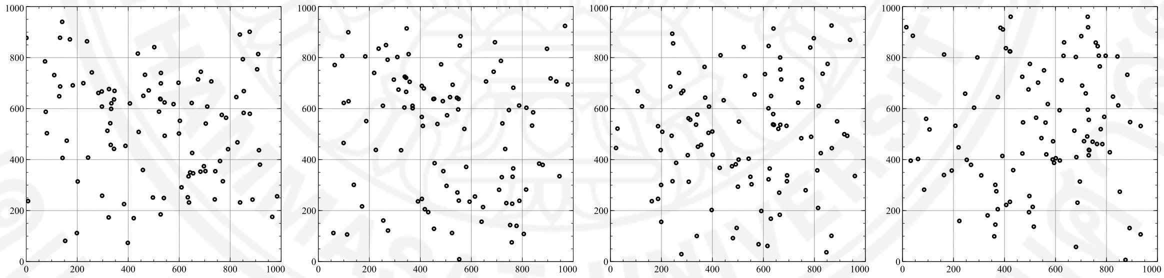
(a) 900 s. (b) 1800 s. (c) 2700 s. (d) 3600 s.

Figure B.8: The distribution of 35 nodes at different time



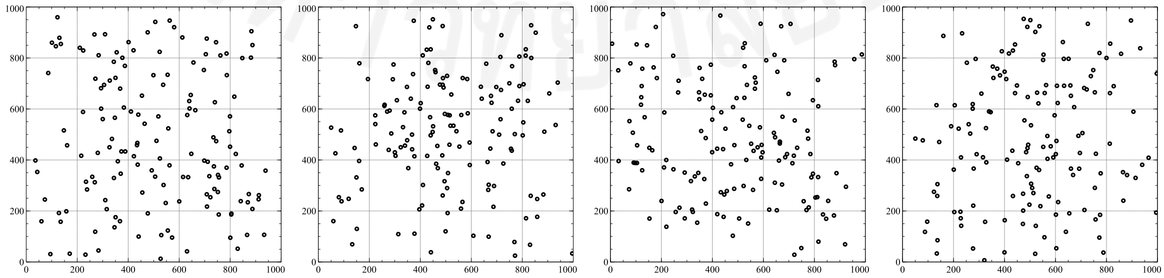
(a) 900 s. (b) 1800 s. (c) 2700 s. (d) 3600 s.

Figure B.9: The distribution of 50 nodes at different time



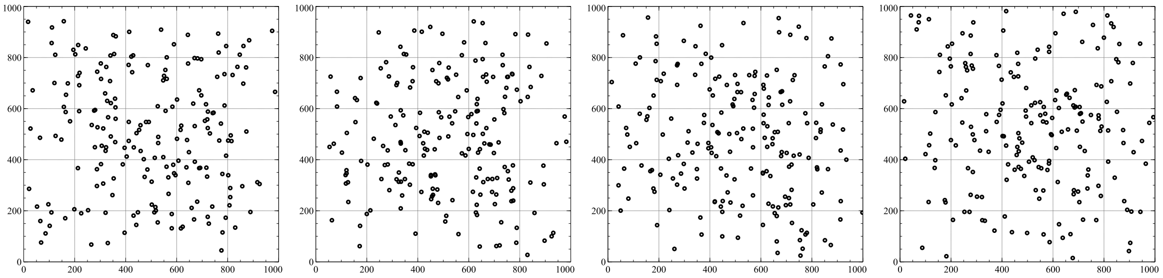
(a) 900 s. (b) 1800 s. (c) 2700 s. (d) 3600 s.

Figure B.10: The distribution of 100 nodes at different time



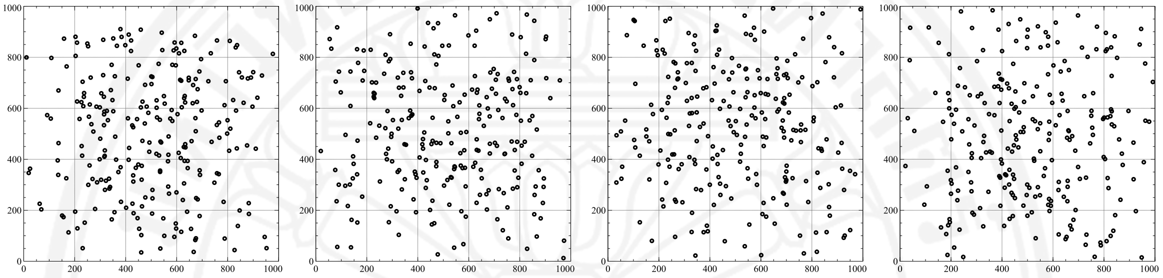
(a) 900 s. (b) 1800 s. (c) 2700 s. (d) 3600 s.

Figure B.11: The distribution of 150 nodes at different time



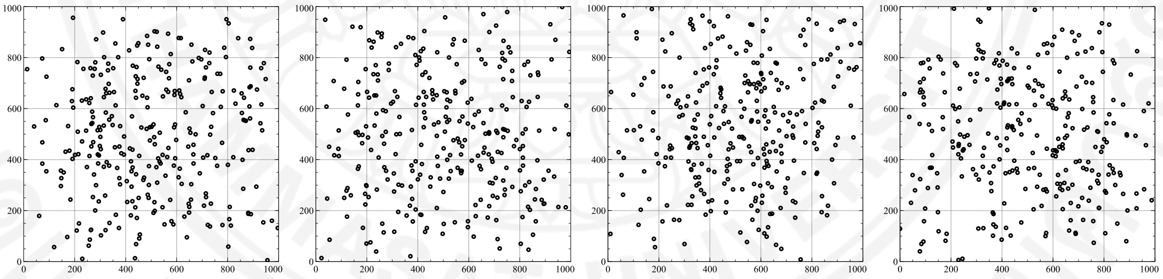
(a) 900 s. (b) 1800 s. (c) 2700 s. (d) 3600 s.

Figure B.12: The distribution of 200 nodes at different time



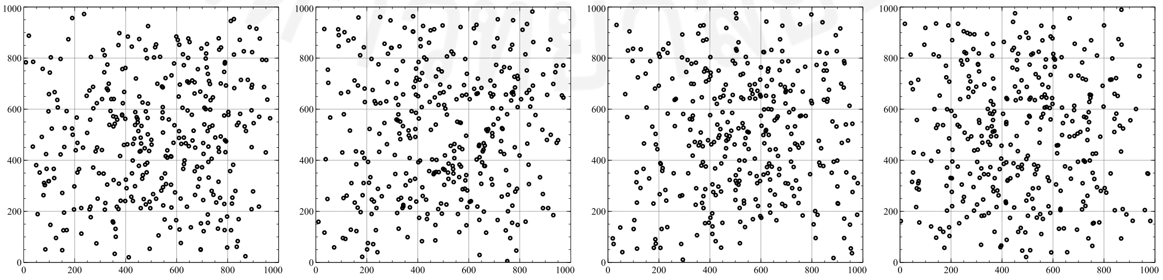
(a) 900 s. (b) 1800 s. (c) 2700 s. (d) 3600 s.

Figure B.13: The distribution of 250 nodes at different time



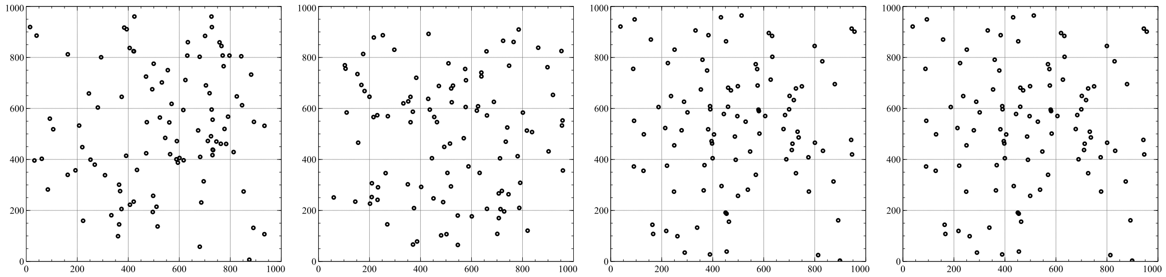
(a) 900 s. (b) 1800 s. (c) 2700 s. (d) 3600 s.

Figure B.14: The distribution of 300 nodes at different time



(a) 900 s. (b) 1800 s. (c) 2700 s. (d) 3600 s.

Figure B.15: The distribution of 350 nodes at different time



(a) 3600 s. (b) 36000 s. (c) 360000 s. (d) 3600000 s.

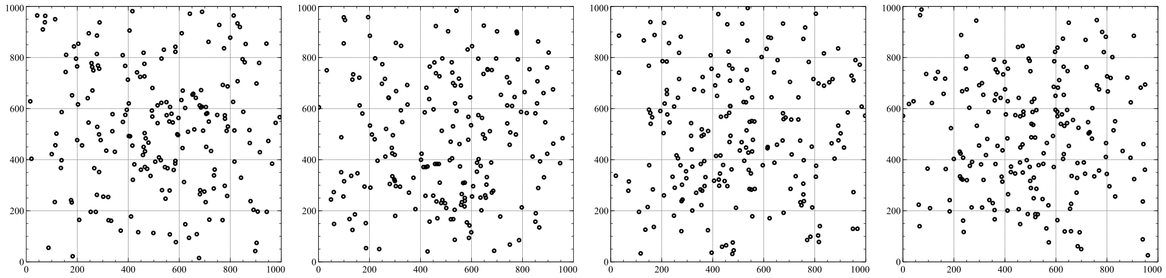
Figure B.16: The distribution of 100 nodes on different simulation duration

RWP mobility models in the simulation tend to be accumulate in the center of the area in the dense networking environment while the duration of simulation has minimal affect on the node clustering.

Consequently, we analyze the node distribution of the different mobility models: Random Waypoint, Random Walk (RW) and Random Direction (RD). Figure B.18 - B.20 show the distribution of 200 nodes at 4 different time interval. From visual observation, RWP comparing with RW and RD, tends to be more clustered in the center. On the other hand, RD tends to be uniformly distributed all over the area. In RW, The speed of a node is randomly selected and its direction is also randomly chosen. Then, each node goes in the selected random direction with the selected speed until the epoch lasts. Each epochs duration is again randomly selected as in Fig. B.22 [17]. However in RD model, a mobile node makes random mobility decisions with respect to current time or location, independent of other nodes. A node randomly picks a movement direction, and takes straight-line movement towards that direction for a given distance [102]. In this mobility model, the mobile node chooses any random direction to travel until the boundary of edge is found as in Fig. B.23. In conclusion, the uniformly node distribution of RD is the result from the node movement to the border of the simulation area.

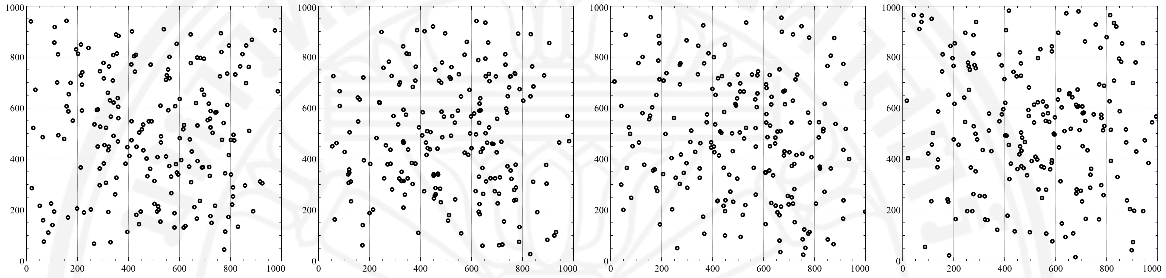
Finally, we studied the performance of each mobility model. Fig. B.21 shows the relationship of delivery ratio of Epidemic routing on the node density using the parameter from Table 4.1. This graph presents the similar trend between RD, RWP and RW that the delivery ratio increase with number of nodes. Comparing from these three random mobility models, RWP gains slightly higher delivery ratio than RW and RD respectively, especially in the node density of 40 - 200 nodes. When the nodes become more dense, the delivery ratios of all three random mobility models are getting similar. Since the delivery ratio of these three mobility models are moderately similar, we used the RWP as our mobility model in Chapter 4 because of its widely adoption in the OppNet simulations. Additionally, our work is focused on the sparse network environment in which the distribution on RWP is relatively uniform.

In Chapter 3, we deploy the Group Movement mobility model which is a modification of Reference Point Group Mobility Model (RPGM) [91]. This model best fits with the group movement behavior where every node follows a group leader which determines motion behavior of the group. The examples of this type of mobility model are military battlefield communications where a number of soldiers may move together in a group or during disaster relief where various rescue crews form different groups can work cooperatively [47]. The nodes in a group are usually randomly distributed around the reference point and use their mobility model appended to that point which drives them in the direction of the group.



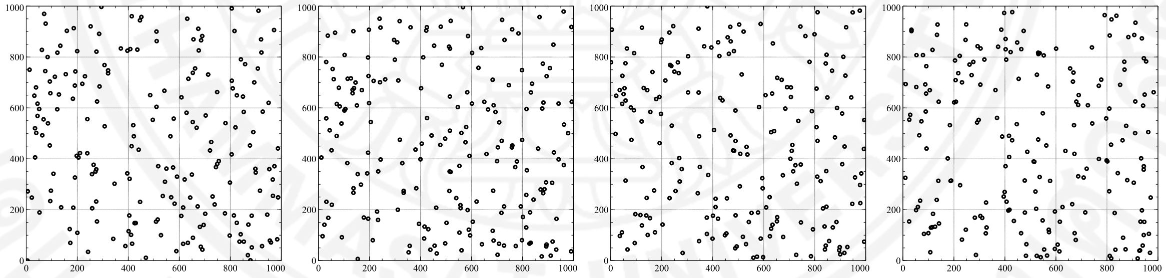
(a) 3600 s. (b) 36000 s. (c) 360000 s. (d) 3600000 s.

Figure B.17: The distribution of 200 nodes on different simulation duration



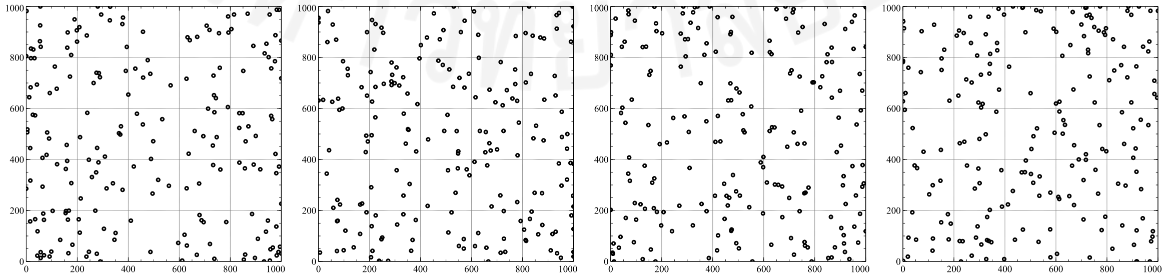
(a) 900 s. (b) 1800 s. (c) 2700 s. (d) 3600 s.

Figure B.18: The distribution of 200 nodes on the Random Waypoint model at different time



(a) 900 s. (b) 1800 s. (c) 2700 s. (d) 3600 s.

Figure B.19: The distribution of 200 nodes on the Random Walk model at different time



(a) 900 s. (b) 1800 s. (c) 2700 s. (d) 3600 s.

Figure B.20: The distribution of 200 nodes on the Random Direction model at different time

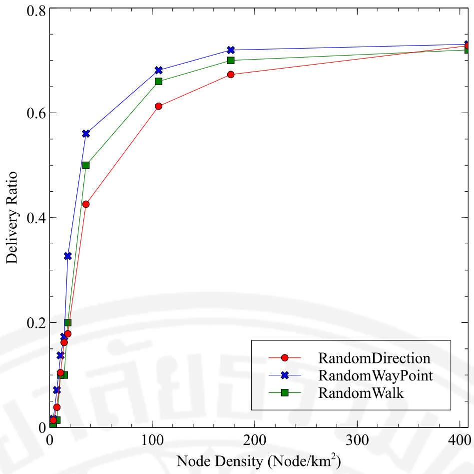
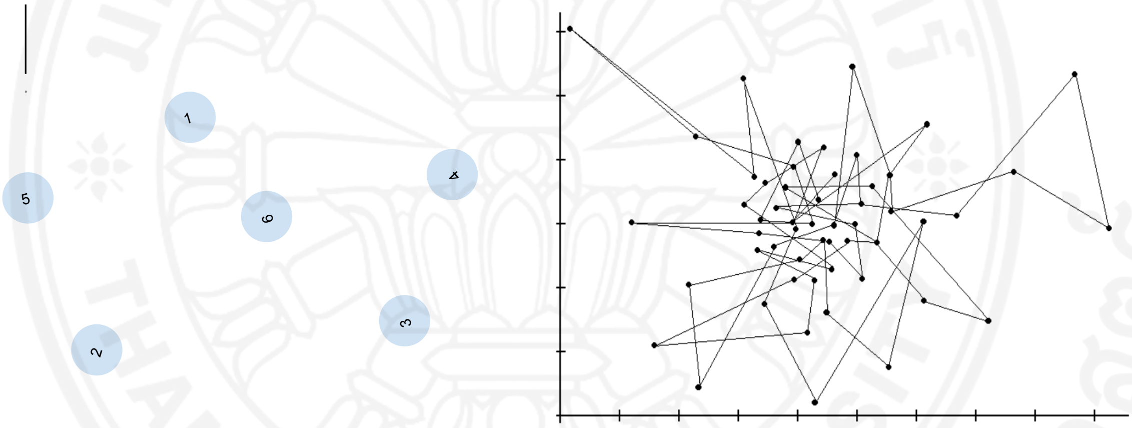
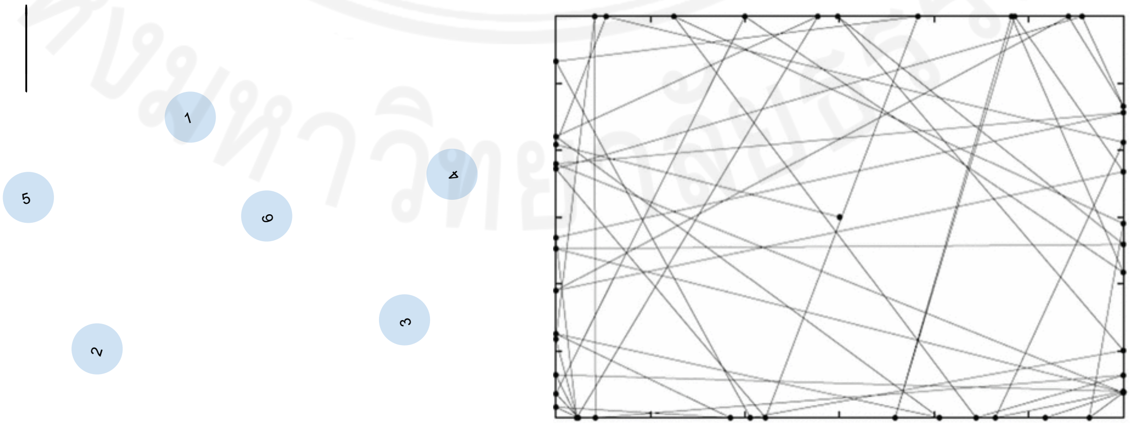


Figure B.21: Delivery Ratio on different Mobility Models



(a) Example Topography (b) Movement pattern [31]

Figure B.22: Random Walk Model



(a) Example Topography (b) Movement pattern [31]

Figure B.23: Random Direction Model