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

BY

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Abstract

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Opportunistic Network (OppNet) is a challenge 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 holing node such as source or neighbor node can carry the data and finds an opportunity to forward data by discovering its nearest neighbor node and uses it to forward messages toward the destination node. However, the performance of opportunistic routing algorithm largely depends on several factors such as limited knowledge of contact behavior or the density of mobile nodes. The problems arise in sparse network environment with limited delivery deadline results in low delivery ratio. Several researches attempted to address the sparseness problem by a special node such as data mules or message ferries. Nevertheless, proposed solutions impractical under some application environments especially with limited power constraints.

In order to improve the delivery ratio in such sparse network while maintaining the energy consumption, we proposed a novel Dynamic Rendezvous based Routing Algorithm on Sparse Opportunistic Network Environment where the rendezvous concept is implemented to address the problem of routing in sparse environment. In addition, we proposed DORSI: Data-wise Opportunistic Routing with Spatial Information where the significant of data content is accounted for the forwarding algorithm of the nodes. This DORSI can improve the delivery ratio for the important messages thus increase the delivery ratio if the weight of each class is accounted. In those algorithms, our common objective is to increase the network performance such as delivery ratio or composite matrices under given circumstances. We also present intensive simulation results regarding the performance comparison of the proposed algorithms with the tradition OppNet routing algorithms.

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List of Acronyms

DTNs   Delay/Disruptive Tolerant Networks
ICNs   Intermittently Connected Networks
IETF   Internet Engineering Task Force
MANET   Mobile Ad-Hoc Network
OppNets   Opportunistic Networks
OR   Opportunistic Routing

Chapter 1

Introduction

Opportunistic networks are one of the most interesting evolutions of multi-hop wireless network especially in Mobile Ad-hoc Networks (MANETs). In this network scheme, mobile nodes are enabled to communicate with each other even without connected route and prior network topology knowledge [54]. Several concepts behind opportunistic network come from the studies on DTN that led to the specification of its architecture. Source and destination nodes might never be fully connected at the same time in opportunistic network, so the forwarding algorithms in such networks follow a store-carry-forward paradigm. Typical algorithms differ based on their decisions as how to forwards the data, at what time the data is forwarded and to whom the data is sent [34]. However, the decision algorithms of what the data to sent has never fully implemented. Messages are en route between the sender and the destination on the routes that dynamically built, and any possible node can opportunistically be used as next hop, provided it is likely to bring the message closer to the final destination.

1.1 Problem Statement

In this store-carry-forward paradigm, the network suffers the decreasing of performance in the insufficient collaborating nodes environment [4, 64] Since the node holding the data requires next-hop neighbor nodes to forward the data to, the sparse network environment is normally unable to satisfy opportunistic routing. As a result, there is a need for an innovative protocol design to address this deficiency of OppNets.

In addition, none of the traditional routings in OppNets concern about the data content of the messages. If the significance of data is considered as the performance matrix, the network effectiveness of OppNets also drops in sparse network. In several environments, it is essential that the important messages from source to the destination nodes should be specially treated in order to guarantee deliverable. Therefore, it is crucial to implement a new protocol to increase the delivery ratio of important data for critical data network such as military tactical network or disaster relief network.

In this thesis, we study the algorithms to address the perform deficiency in sparse opportunistic network environment. In each approach, we use different routing techniques and work on different OppNets scenarios, however our common aim is to increase the performance in sparse network.

1.2 Objective and Scope

Objective of this research is to increase the network performance in OppNets especially the delivery ratio and other key composite matrices performance index in different schemes.

The scope of this research is based on the assumption of mobile nodes and environment in different network schemes that elaborate in each proposed approaches.

1.3 Proposed Approaches

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

- We proposed a protocol to classify the messages based on the information sensitivity concept along with nodes prioritization technique corresponding to the their delivery probability computed by spatial data. This protocol classifies the messages according to their significant level, security level and deadline relative to the sensitivity level of data. In addition we 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: (1) effective delivery ratio and (2) effective replication ratio remarkably improve over the traditional Epidemic routing.

- In order to address the problem in sparse network, we proposed the use of Rendezvous based concept in order to maintain the messages in one place as long as the messages are delivered. By injected a special node N_{rv} into the network, the gap between time and space domain of mobile nodes are bridge. 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 rendezvous node. The results clearly show that the delivery ratio of Rendezvous based protocol significant improve over Epidemic protocol especially in the sparse environment.

1.4 Our Contributions

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 are provided. Chapter 3 describes our message prioritization technique to differentiate the routing based on the significant level of messages. The details of proposed method, simulation model, and performance evaluation are included in this chapter. Chapter 4 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 5 includes the discussion, the conclusion and the recommendations for future studies.

Chapter 2

Background and Related Work

Recently, wireless networking are witnessing several deployments in various extreme environments where they usually suffer from different levels of link disruptions depending on the severity of the operations. Commonly, these networks are known as Intermittently Connected Networks (ICNs). An ICNs, also known as a Challenged Network, is an infrastructure-less wireless network that supports the proper functionality of the wireless applications operating in stressful environments, where excessive delays and no existence of end-to-end path(s) between any arbitrary source-destination pair, result from highly repetitive link disruptions [39]. In order to handle ICNs, the Internet Engineering Task Force (IETF) [14] 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 an aim to operate over the protocol stacks of the ICNs and enable gateway functionality between them through the use of storage capacity, a variety of protocol techniques, replication and parallel forwarding, forward error correction and many other techniques for overcoming the impairments of communication [39]. DTNs enable the transferring of data in extremely challenging environments where networks are assumed to experience frequent, long-duration partitioning and may have no end-to-end connectivity between source and destination [46]. Therefore, the timer and acknowledgement mechanisms of the traditional TCP/IP protocol definitely fail in such circumstances [19]. In addition, the routing algorithms designed for Mobile Ad hoc NETworks (MANETs) can not perform effectively under aforementioned constraints as well, since the availability of contemporaneous end-to-end connectivity is essential for conventional routing algorithms [12].

Basically the types of DTNs can be classified in 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 disruptive environments such as Interplanetary Internet (IPN) [9] where the contact time is not completely random but in periodic interval. In the thesis, we study in the most extreme case of DTNs which is the opportunistic networks where the contact time is undetermined along with stochastic movements.
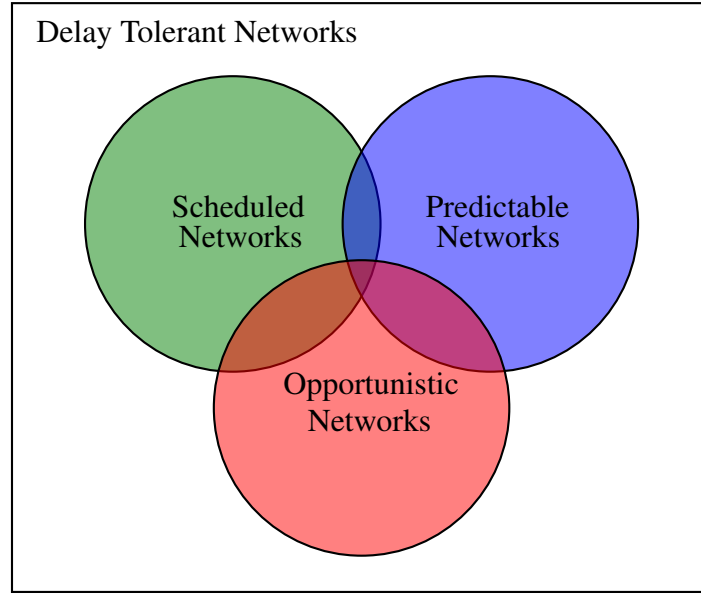
Figure 2.1: Types of DTN

2.2 Opportunistic Networks

In fact, Opportunistic networks focus on mobile ad-hoc DTNs, where tolerant delayed routes between the source and 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 storage and mobility, called *Store-Carry-Forward paradigm* [25]. In essential, there are three common steps of routing in OppNet [24]:

- Broadcast the messages to candicate relayed nodes.

- Select the best candidate node.

- Forward the messages.

2.2.1 Opportunistic Routing

In this opportunistic routing, the nodes can exchange data in a spontaneous manner whenever they come in close. 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 2 factors to facilitate the opportunistic routing [56] :

- Destination path finding: Intermediate nodes are used to form paths dynamically since there is no fixed path from source to destination nodes.

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- 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.

2.2.2 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 2.2

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 [60] 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 [62]. However, this scheme produces significantly long delays since the delivery delay is unbounded for this direct transmission routing [21].

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 [26]. 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 restricted to any limited. Epidemic routing [66] is proposed utilizing epidemic algorithm to send each message to all nodes in the network. Even tough the Epidemic routing can guarantees 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 [65]. Therefore, there is a need to control the flooding by limit 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 [22] 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 incurring 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 [63] 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 message. In the *spray* phase, a number of L messages are
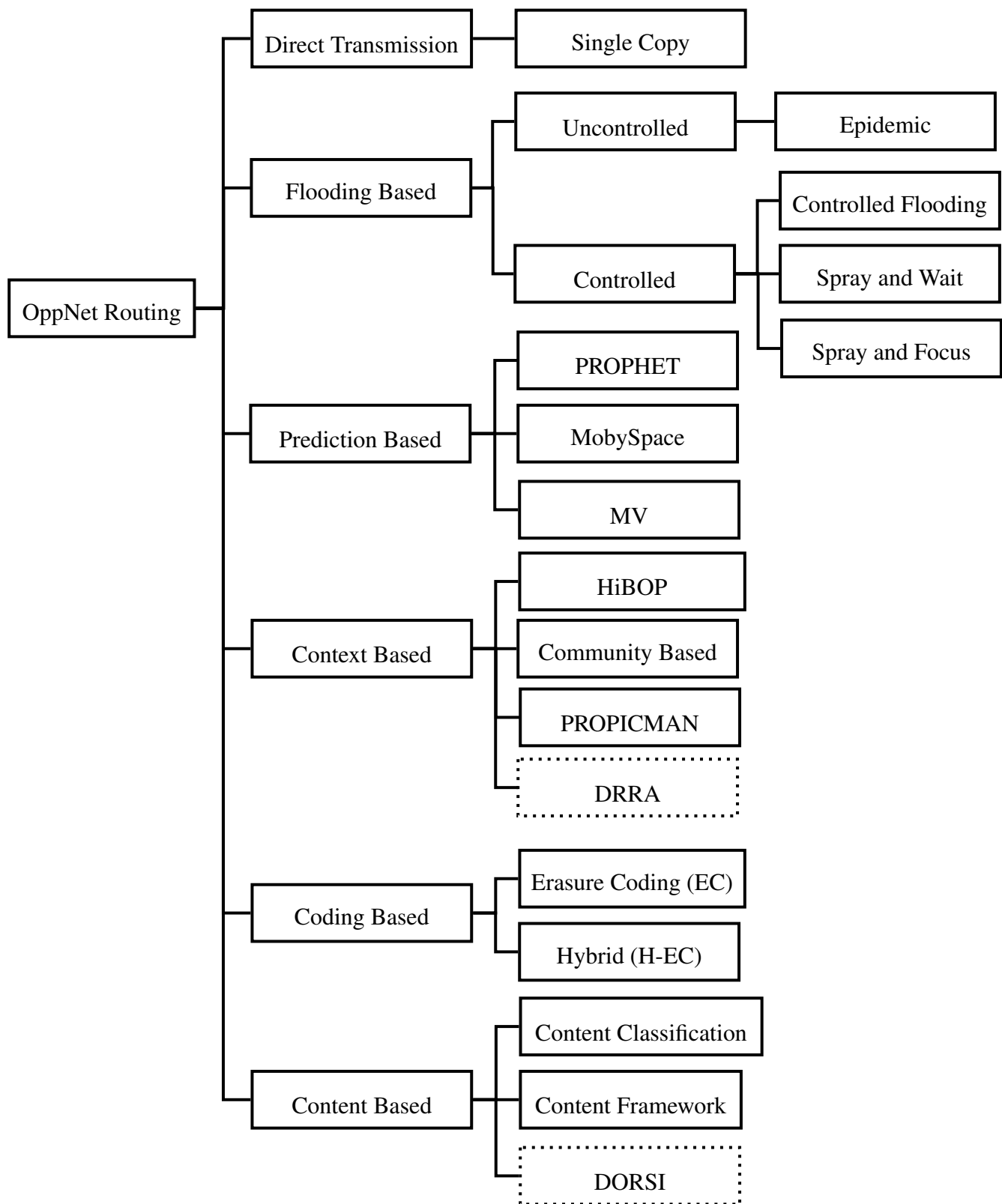
Figure 2.2: Classification of Opportunistic Routing

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 [61] 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 creating at source node. The different 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 [62].

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 [44] 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 local node to the destination. Two nodes can exchange both a summary vector containing delivery probability vector 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 predictability 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 [41, 42] proposed a MobySpace: Mobility Pattern Space Routing for DTNs which using 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 bundles 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 [10] 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 of meetings 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 achieving delivery rates closer to the true optimal rate.

Context Based

Nevertheless, the predication based routing failed in several scenarios with the reduction in delivery rates comparing 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 [51], 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 routings exploiting the mobility pattern and places that nodes are 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 [7] 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 [52] 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 Hi-BOp is the exploiting decision trees to select the next hop [18]. This method exploits the mobility as well as reduces the number of nodes involving in the forwarding process, which results in the low overhead comparing to the other dissemination-oriented routing algorithms, such as Epidemic or PROPHET [29].

- 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 [53] 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 [72] proposed a distributed optimal Community-Aware Opportunistic Routing (CAOR) algorithm by modeling an MSN into overlap-

ping 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 Bubbl rap [27], this algorithm can achieve the optimal routing performance with a very low maintenance cost.

Coding Based

The coding based routing is proposed to address the transmission issues in very poor 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 [69] is converting 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 [17]. Due to the additional information embedded in the code blocks, coding based schemes are less efficient when the network is well connected [28].

- Hybrid (H-EC): Chen et al [15] 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 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

Because of the Store-Carry-Forward paradigm requires a node to store and carry the messages in order to find the opportunity to forward the messages, the content storage can become the core service of opportunistic routing.

- Content Classification: JIAO et al [32] 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 [16] 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 tried to summarize and categorized the characteristics of routing algorithms in opportunistic networks. For more extensive researches on OppNet on the related work in the literature can also look at some surveys such as [12, 19, 56, 4, 30, 67]. 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

Opportunistic Network (OppNet) is an extreme type of Delay Tolerant Networks (DTNs) where the source and destination nodes might never be fully connected at the same time, thus there is no guarantee on the existence of a complete path between two nodes wishing to communicate [77]. This intermittent connections may result from several factors such as high node mobility, low node density, environmental interference and obstruction, short radio range and malicious attacks [57] etc. 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 assure. Example of such networks are sparse mobile ad hoc network [2], military tactical networks [58, 38] or sensor networks, such as ZebraNet [78], SWIM [59] which are wireless sensor networks in which nodes move throughout an environment working to gather and process information about their surroundings. Commonly, the key differentiating factors among those scenarios are the amount of predictability and control over the contacts between the message carriers[35]. A key concept behind Opportunistic Routing (OR) is overhearing and cooperation among relaying nodes to overcome the drawback of unreliable wireless transmission [45]. Since the mobile nodes are not always connected to each other, the forwarding algorithms in such network commonly follow a store-carry-forward (SCF) paradigm. This SCF employs storage space and node mobility to overcome the intermittent connectivity [47]. The messages sent from the source node are carried by intermediate nodes to other geographical area and transfered to adjacent nodes until the destination node receives this message. Since this fundamental SCF routing model realistically requires a certain sufficient occasion of *direct* encounter among moving nodes to exchange messages, its routing performance will highly degrade in the low-node-density sparse network [64]. Although there are several existing OppNet routing solutions [79, 26, 60, 21, 66, 38] proposed in the literature, very few proposals address the problem in this sparse network environment especially when the OppNet nodes are energy-constrained [73, 20] 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 [78, 59].

In this chapter, we proposed a novel Dynamic Rendezvous based Routing Algorithms (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 along the river in the wildlife monitoring application, 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
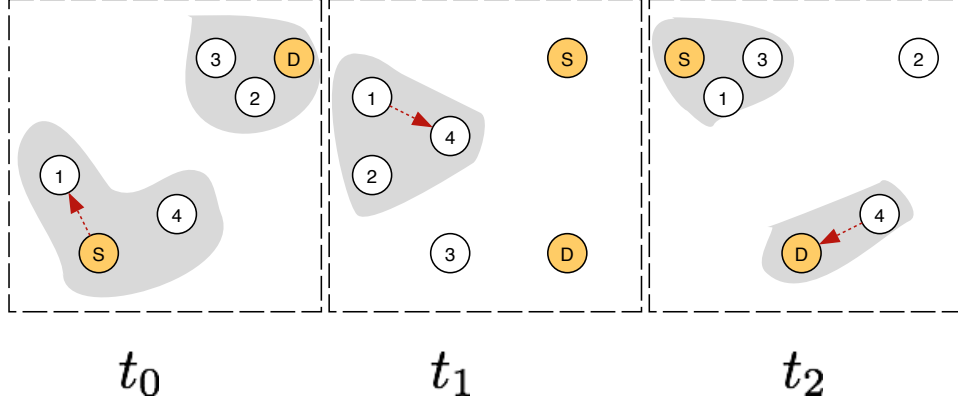
Figure 3.1: Store Carry and Forward routing model

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 The SCF routing models and existing works

In OppNet, the messages are delivered using Store-Carry-Forward routing by which the nodes can exchange data whenever they come in close. 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 as shown in Fig. 3.1. There are several existing works in the literature [66, 23, 50, 43, 11, 7, 38] with the aim for 100% delivery ratio which is quite difficult to achieve especially in sparse network with constraints in energy consumption and message delivery deadline.

Vahdat et al [66] proposed the epidemic routing using uncontrolled flooding algorithm in which the replication of source data is not restricted with any limits in order to route the message from source to destination in the intermittently connected network. However, this type of routing incurs significant demand on both bandwidth and buffer. To address the excess traffic overhead, Khaled et al [23] proposed a Controlled Flooding scheme which can limit the flooding by three parameters: Willingness probability, Time-to-Live, and Kill Time. Nevertheless, flooding based routing performance degrading has been reported in a very sparse network [50].

Lindgren et al [43] proposed a prediction based routing called PROPHET (Probabilistic Routing Protocol using History of Encounters and Transitivity) by estimating the delivery predictability to indicate the probability of success in delivering a message to the destination from the local node. In this prediction based routing category, Brun et al [11] also proposed a protocol utilizing the motion vector of mobile nodes to predict the future location of mobile nodes by using the knowledge of relative velocities of a node and its neighbor nodes to predict the closest distance between two nodes. Although the prediction based approach can reduce traffic overhead in the network, but it lacks of the aim to improve the performance in extremely low node density and failed in some certain cases which leads to the delivery ratio reduction.

To refine the prediction based routing, Boldrini et al [7] proposed the History based routing (HiBOp) which exploits current context information for data forwarding decisions. Even though, this context based routing approach can reduce the resource consumption in
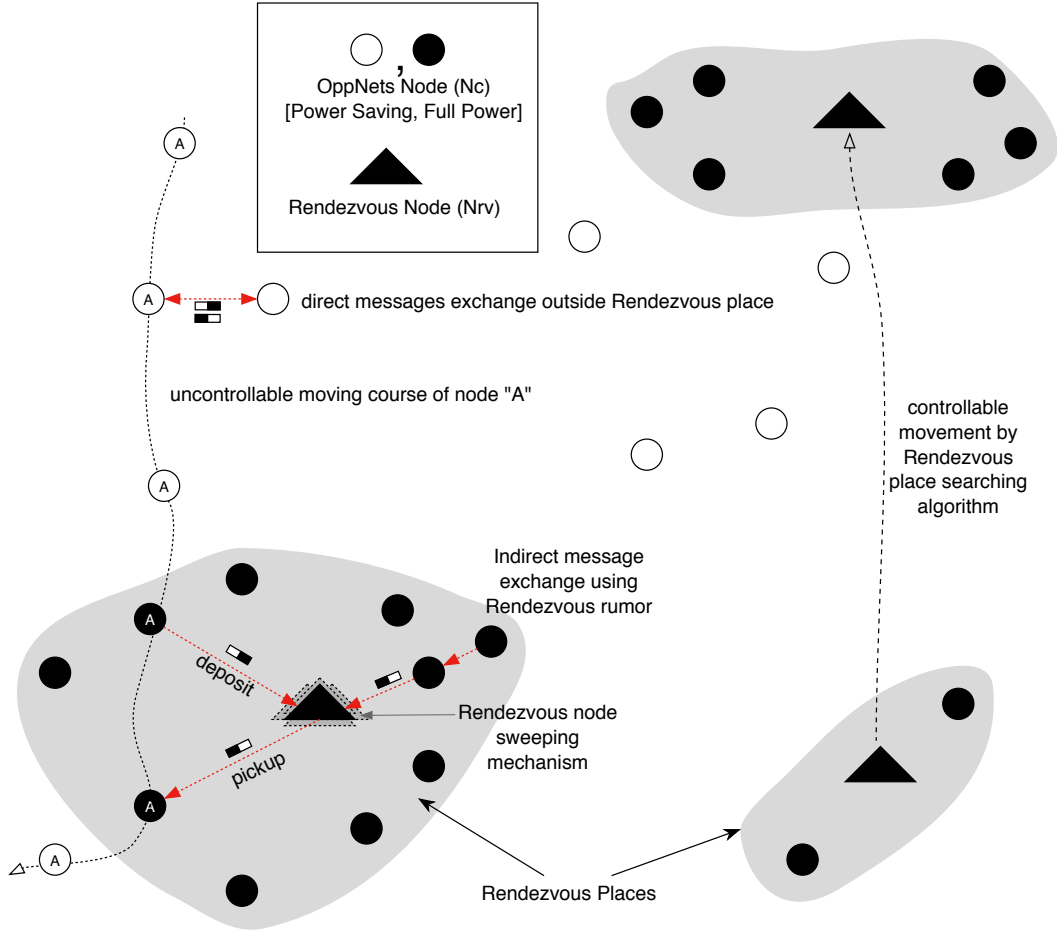
Figure 3.2: System model

terms of network traffic and storage but it increases the delay which results in significantly less efficient than Epidemic algorithm. Kerdsri et al [38] proposed DORSI protocol with the concept of content based routing which aims to classify the data in the network by messages' significance level in order to guarantee the delivery of more important data. However, the decreasing in network performance under sparse environment is not mentioned in this proposed protocol. Overall, the performance of most existing algorithms are degrading in very sparse node density and the energy consumption does not take in to the consideration which is a crucial factor in such mobile sensor devices such as in wildlife monitoring.

3.2 The proposed Rendezvous based OppNet system

3.2.1 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. 3.2, 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
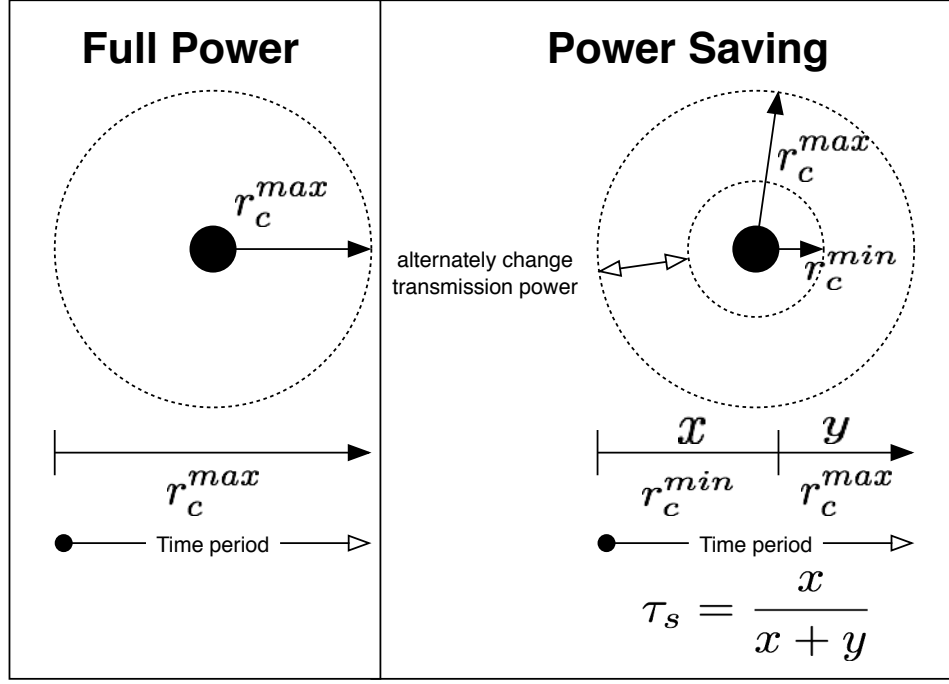
Figure 3.3: Operational modes

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 Rendezvous Node Sweeping mechanism are used inside the Rendezvous area to let messages being exchanged more effectively without the need of direct contact between the OppNet node and the high-resource direction-controllable Rendezvous node, N_{rv}, which is act 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.*

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

The OppNet node (N_c) is a mobile node equipped with the radio interface whose transmission rage 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
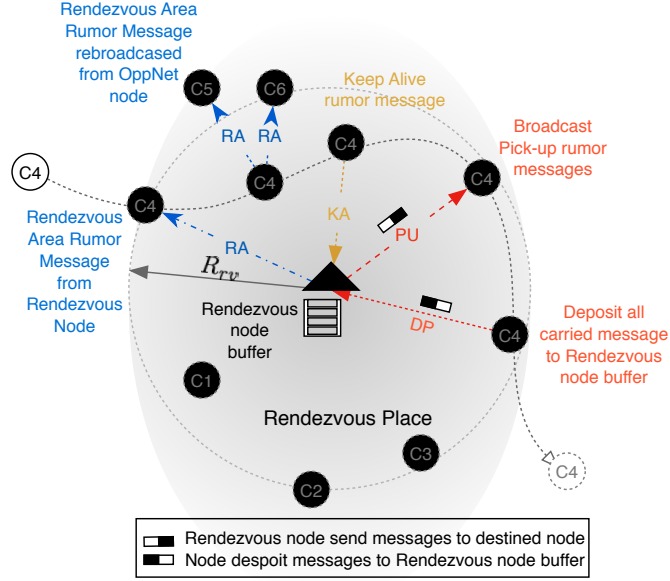
Figure 3.4: Rendezvous Place

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 it full r_c^{max} over the whole time period is a configurable parameter, τ_s, as shown in Fig. 3.3.

3.2.3 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 Rendezvous rumor protocol.

The area in 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. 3.2

When an OppNet node detects the *Rendezvous Area rumor message* (RA) broadcasted from the Rendezvous node, it learns that it enters to the Rendezvous area. Then, it will switch its operational mode to *Full Power mode* and try to rebroadcast such *Rendezvous Area* rumor message so that the other reachable nearby nodes can learn about Rendezvous place and can 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 *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 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
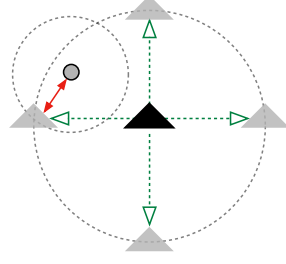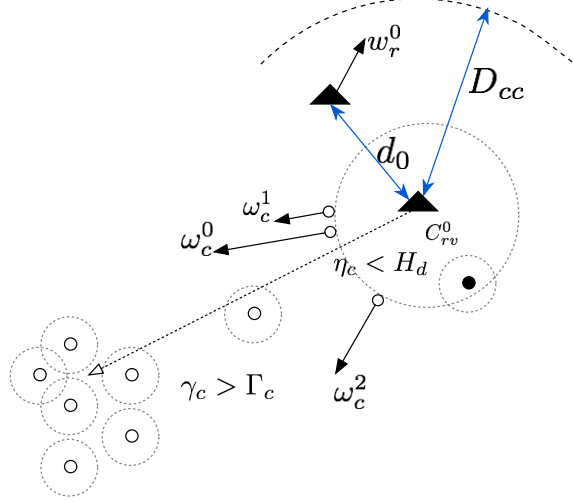
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Figure 3.5: Sweep mechanism

Figure 3.6: Rendezvous place searching

seen in Fig. 3.4.

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 directions (North, East, West, South) by the distance of its radio transmission range as shown in Fig. 3.5. 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.

3.2.4   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 node.

Predictable behavior OppNet nodes

In some applications, the movement of OppNet node is somehow predictable. Take a wildlife monitoring as an example, most animals are usually cyclically gathering in the high supplies area such as along side of the main river of some specific place at some specific time [76]. In these applications, the Rendezvous nodes can be programmed to be located at those areas at the proper time in order to maximize the effectiveness of the proposed system.

Non-Predictable behavior OppNet nodes

Without any priori knowledge about OppNet node, 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 node 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, $\vec{w}_r$ is the directional unit vector of the other Rendezvous nodes and the φ is a configurable weighting factor between group of OppNet nodes and group of other Rendezvous nodes in the area.

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

While the $\delta\left(d_j\right)$ 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 the C and R are the number of contacted OppNet nodes and the number of other Rendezvous nodes respectively.

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

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) become greater than the predefined Rendezvous place node threshold, Γ_c as shown in Fig. 3.6.

3.3 Evaluation

The objective of the evaluations is to analyze the performance of our proposed protocol 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[66] under different node density environments.

3.3.1 Simulation setup

We setup a simulation environment using ONE (Opportunistic Network Environment) [36], 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 averaging over a few hundreds independent simulation runs with different seeds. For the OppNet simulation model, the main parameter that largely effected the evaluation performance is the movement model. In our evaluation, we deploy Group movement model instead of the most commonly used, Random Way Point (RWP) model [5], to correctly capture the the actual behavior of node movements. In fact, several multi-hop wireless network scenarios are most realistically represented using Group movement model [6] 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

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Table 3.1: DRRA Simulation variables

Parameters	N_c	N_{rv}
Message Size	500 KB - 1 MB	
Maximum Radio Range	30 Meters	100 Meters
Transmission Speed	54 Mbps	
Router	DRRA — Epidemic	
Moving Speed	0.5 - 1.5 m/s	
Movement Model	Group Movement Model	

the movements in several cases are in swarm behavior, in which nodes are aggregates together and moving in some directions, such as the movement of animals 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 location of the nodes [5]. In our simulation, we fix the number of nodes while increasing and decreasing the area of operation which results in wide range of node density parameter 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 $M \times M \quad m^2$ 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.

3.3.2 Metric

Opportunistic routing protocols are commonly evaluated by delivery ratio, median latency and network overhead. However, we required specific composite metrics in order to clearly observe the performance of our proposed protocol. In our evaluation we consider the following metrics:

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 messages created from the source nodes that need to be delivered ($M_{created}$) as shown in Eq. 3.2.

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

Delivery performance (D_p) is a composite metrics defined as a delivery ratio per energy consumption unit in order to clearly analyze our protocol performance. Basically, the relation between energy consumption and radio range can be determined by Eq.3.3 [74, 68].

$$E_T \quad = \quad L \cdot \varepsilon_{fs} \cdot d^\alpha \tag{3.3}$$

E_T is the amounts of transmission energy consumed at a node for transmitting an L-length message, 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. In this protocol, we approximately determine the relationship between unit of consumed energy and radio radius of node in the term of exponential equation. We assume
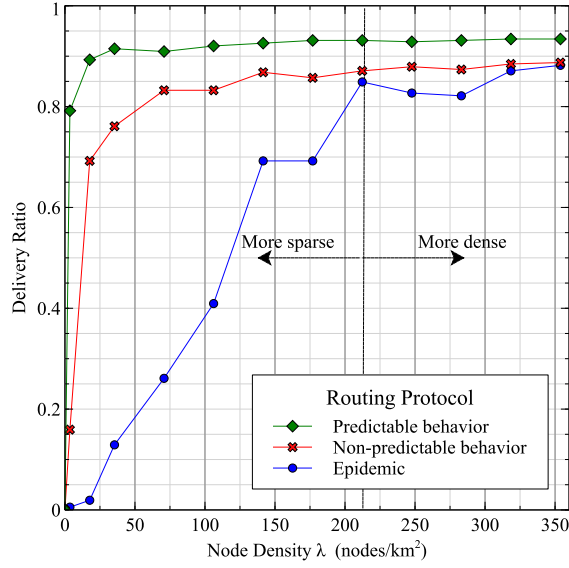
Figure 3.7: Delivery Ratio per Node Density

the simplicity of energy model by only accounting for the communication energy consumption of a wireless interface and do not consider other resources such as computation, location services or mobility. In fact, the messages generated from protocol are accounted for the delivery performance. As a result, the energy consumption can be simply derived as Eq. 3.4.

$$E_P \quad \propto \quad M_P \cdot r_P^2 \tag{3.4}$$

Therefore, the delivery performance can be calculated from Eq. 3.5.

$$D_P = \frac{D_r^P}{E_{P,B}} = \frac{D_r^P}{\left(\frac{M_P \cdot r_P^2}{M_B \cdot r_B^2}\right)} \tag{3.5}$$

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. M is the message number transmitted by OppNet nodes, excluding Rendezvous node in Rendezvous place. The average transmission radius is referred as r while α is the power consumption exponent factor [2,4] which we are using the value of 2 for our simulation.

3.3.3 Simulation Results

This section shows the results of the different simulations that have been performed evaluating the impact in the performance. The following subsections include the results of each set of simulations.

Delivery performance

Firstly, the comparison of delivery ratio is shown in Fig. 3.7 while $x-axis$ represents the node density (the number of nodes in the area of 1 km^2) and $y-axis$ shows the delivery ratio.
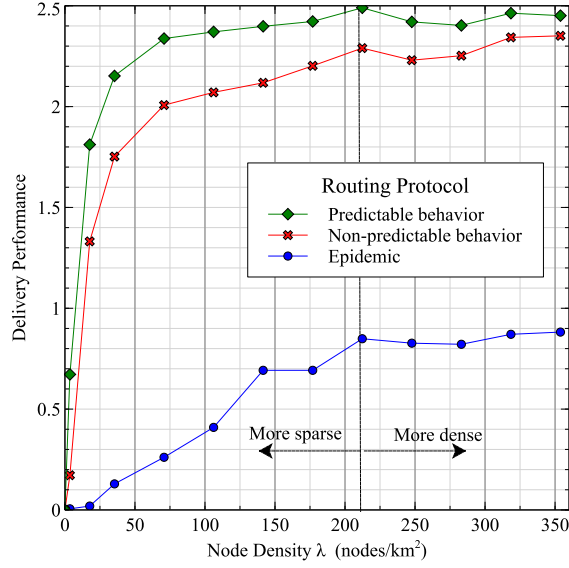
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Figure 3.8: Delivery Performance per Node Density

In our simulation, we assume the environment with 1 Rendezvous node and the ratio of time interval factor between full power and power saving, τ_s of 0.5.

Fig. 3.7 shows that our proposed protocols gain slightly better delivery ratio in the dense environment. On the other hand, the proposed protocols gain 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. Over all in average, our proposed protocols gain approximately 40% higher delivery ratio than existing traditional Epidemic routing.

The reason behind the behaviors from this result is that the Rendezvous concept can be clearly performed better when the node density becomes sparse since all nodes can effortlessly exchange messages in the dense network. However, in the sparse network, the Rendezvous nodes can help facilitating the messages exchange mechanism among OppNet nodes which resulting in much higher delivery ratio. In addition, with the knowledge of node gathering-area, the delivery ratio can be further increased especially in the extremely low node density.

Furthermore, the proposed protocols utilize less energy consumption which is a vital factor in opportunistic network because the mobile nodes in this scheme are usually equipped with limited power resources that the performance can be seen in Fig. 3.8. Similar to graph of delivery ratio, we compare the delivery performance ($y-axis$) on node density ($x-axis$), in which the D_p can be calculated from Eq. 3.5. It can be obviously seen that the proposed protocols in Fig. 3.8 can save about half of energy consumption in order to achieve the same delivery ratio in the dense environment. Nevertheless, the propose protocol use only 25% power consumption in sparse environment. The better delivery performance results from the lower messages number of our proposed protocols compare to the Epidemic counter part as can see in Fig. 3.9. Additionally, the other factor that impact the higher delivery performance is the lower average wireless transmission of our proposed protocol.
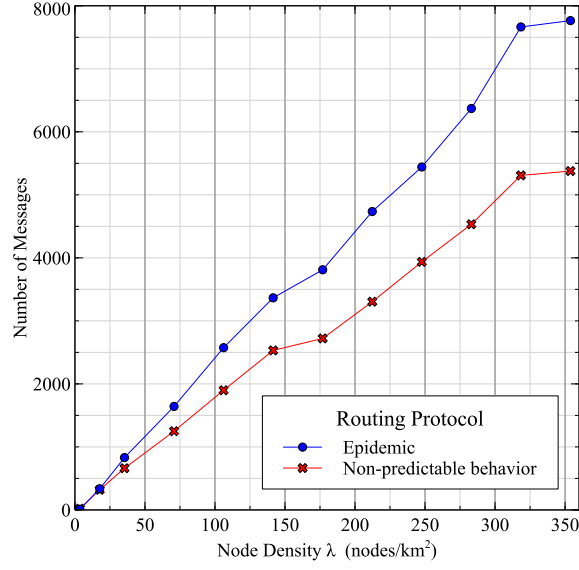
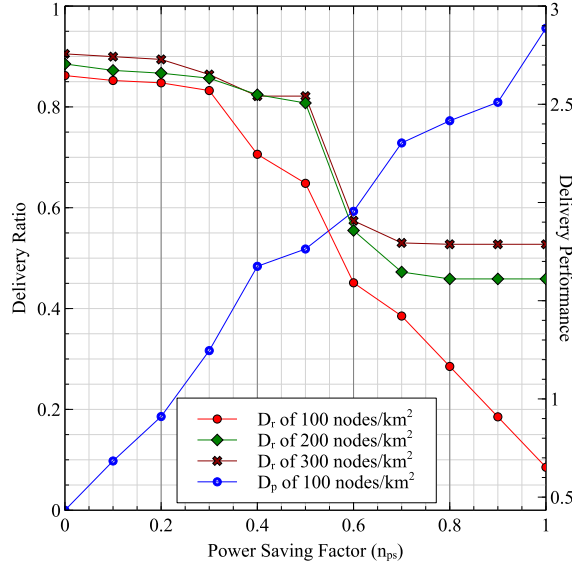Figure 3.9: Number of Created Messages per Node Density

Figure 3.10: The Optimum between Delivery Ratio and Delivery Performance

Power saving factor

In this section, we study the factors effecting the power saving and the trade-off between power consumption and delivery ratio. We define the Power Saving Factor, n_{ps} as the energy consumption parameter to analyze the power utilization of our proposed protocol which can be determined as in Eq. 3.6. In the simulation, we select the density of 100, 200 and 300 nodes to study the impact of power saving factor to the delivery ratio on different density enviornment.

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

From Fig. 3.10, the graph presents the declining in the delivery ratio when the value of n_{ps} increases. This implies that in the attempt of saving the energy, the deliverable of
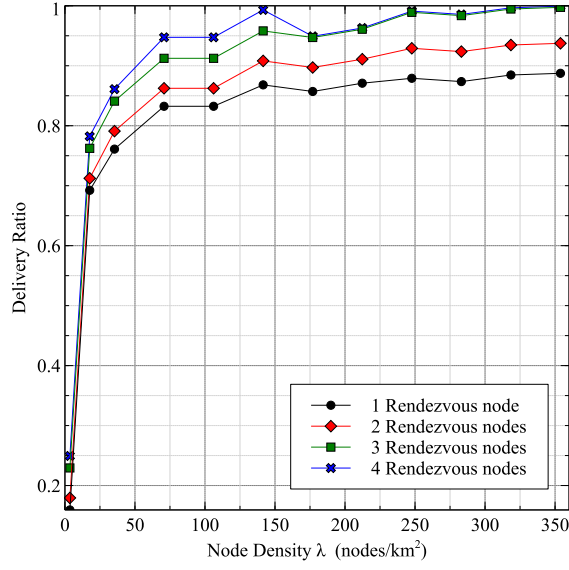
Figure 3.11: Multiple Rendezvous Nodes
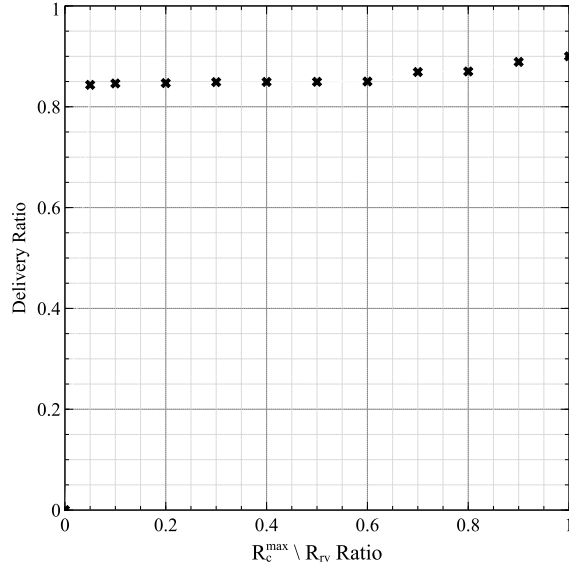
Figure 3.12: R_c^{max}/R_{rv} ratio

messages are effected from the wireless range reduction. On the other hand, the delivery performance is increasing with the value of power saving factor which shows that the higher the n_{ps}, the higher the delivery performance. Overall, the key point of Fig. 3.10 is the cross point between delivery ratio and delivery performance which can see at $n_{ps} = 0.55$ which is the optimum point of our method.

Rendezvous node factor

We investigate the main parameters effecting the environment of N_{rv} in this part. In Fig. 3.11, the number of N_{rv} are varied from one to four nodes in our simulation. The result shows similar trend of overall delivery ratio which slightly declining when the node density decreases. Nevertheless, the delivery ratio increase when more rendezvous nodes are

injected into the environment. The results suggest that more number of rendezvous node can gain higher delivery ratio. Fig. 3.12 shows the relationship between R_c^{max} and R_{rv} over the delivery ratio, starting from R_c^{max}/R_{rv} ratio of 0.1 to 1.0. This graph shows moderate incrementing in delivery ratio when the ratio of R_c^{max}/R_{rv} increases. The result suggests that the value of R_c^{max} has slightly effect on delivery ratio.

3.4 Conclusion

Opportunistic Routing techniques can be applied in plentiful variety of scenarios such as military network or wildlife monitoring. In this paper, 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 node, 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 domain. 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 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 result suggest that our protocols perform significant higher in delivery performance which is the trade off of delivery ratio per energy consumption. We can simply imply that if the location of rendezvous place can be predicted, we can achieve highest network performance. Our experiment also suggest that the OppNet node can gain higher delivery performance when the time interval of power saving mode is longer and the minimum radio range is higher. In the future work, this concept of smart node can be further extend to increase the intelligence of the node since the technologies are advanced rapidly.

Chapter 4

Data-wise Opportunistic Routing with Spatial Information

Opportunistic Network (OppNet), a subclass of Delay/Disruption-Tolerant Network (DTN), is a network paradigm that the communication contacts are intermittent. This challenged network which is also referred as Intermittently Connected Mobile Network (ICMN), is involving mobile nodes to communicate with each other without existing complete end-to-end path from source to destination. Traditional routing protocols have been exhibited ineffective in coping with unreliable and unpredictable wireless medium [75] 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 such extreme condition such as military tactical network, DTN and Mobile Ad-hoc Network (MANET) are among several promising challenged researches aiming to improve network performance. DTN protocols typically address sparse intermittently connected networks whereas MANET protocols address the fairly stable and fully connected ones. However, many intermediate situations may occur on mobility dynamics or radio link instability. In such cases, where the network frequently splits into evolving connected groups, none of the conventional routing paradigms are fully satisfactory [70]. To address the problem of intermittent links and node mobility, local forwarding are exploited in order to transfer the messages. The opportunistic routing pattern, called store-carry-forward, takes an advantage of node mobility to forward the data buffered in the carried node to the next connected node during the opportunistic contacts. Basically, the terms opportunistic networks and delay tolerant networks are occasionally used interchangeably. DTN usually computes the estimation of delivery delays in advance due to some degree of determinism of system variables. On the other hand, opportunistic link in OppNet is highly dynamic and unpredictable so routes are computed at each hop when forwarding messages [8]. This network scheme is suitable for extreme dynamic evolving network topology and limited information scenarios. The applications of opportunistic network is typically used in an environment that is tolerant of long delay and high error rate such as MANET in battlefield communication [3] or DTN for interplanetary networking [31]. 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 tradeoff 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 [48].

Even though, 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 topology information [54], especially

focusing on the dissemination algorithms and policy to control or limit flooding [55].

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. [32] 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 scheme [13], 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 [33] 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. [34] developed a DTN message priority routing protocol by modify the spray and wait [63] flooding-based routing protocol. However, these prioritizing mechanisms aim to rank the messages by defined matrices which involving network topology. In contrast, DORSI protocol 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 paper, we propose a new routing technique 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.

In this chapter, we present a routing protocol in opportunistic environment that dynamically prioritizes the candidate messages based on the content of the data. Since security is an increasing concern in military and other critical operation mission, it is vital to route data of different sensitivities differently. The most significant and sensitive data should be guaranteed its higher level of delivery and protection than common data. However, only few works have applied the well-defined information sensitivity concept such as Multi Level of Security (MLS) [40, 1] to network information such as routing information, QoS signaling and other management information [71].

In this routing scheme, 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 existing literatures. In this research, we extend our previous work [37] by generalizing information sensitivity parameters and involving spatial information into routing decision to improve the network efficiency. We conducted Opportunistic Network Environment (ONE) simulation [36] to evaluate the performance of DORSI protocol.

4.1 Opportunistic network model

Since opportunistic network commonly operates in multi-hop wireless ad-hoc network environment, links may be disrupted or shut down periodically when nodes move away or absent
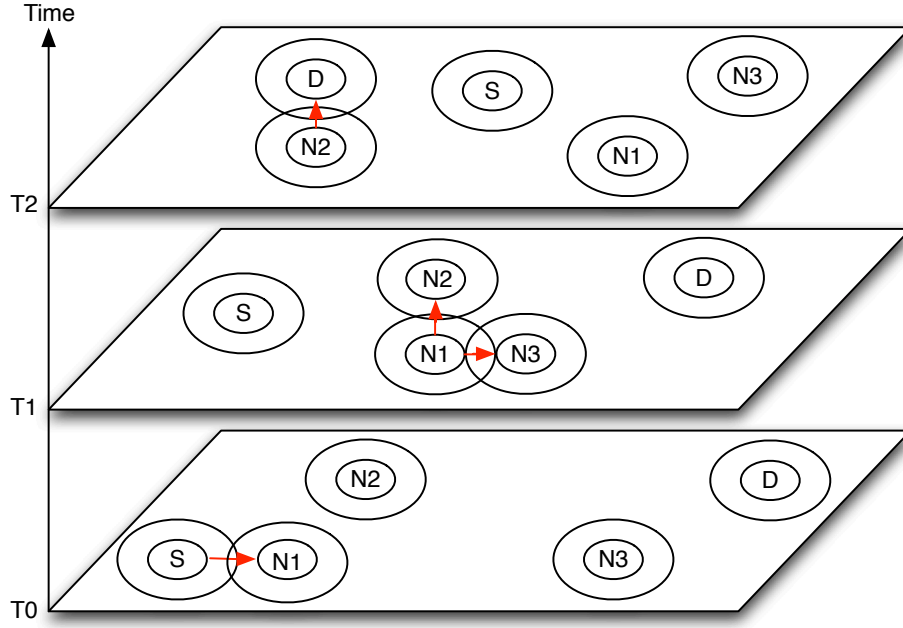
Figure 4.1: Opportunistic network model

which resulting in intermittent connectivity [49]. As a result, nodes require to communicate with each other via opportunistic contacts through store - carry - forward fashion [26]. Instead of selecting a node to act as the next hop, multiple relay nodes may be determined when a data packet is being transmitted. This decision is carried out for each data packet according to the instantaneous wireless links condition in order to select the best relaying nodes. In OppNet, a node is an entity acting as a host, router or gateway. Each node can route and exchange message (full-duplex) between nodes that move randomly among remote fragment of network within its contact period. Nevertheless, OppNet node must contain enough processing power and storage to keep the data until this node gets contact with intermediate carrier or destination node. Within this disruptive environments, the contact period is extremely dynamic since contact may appear arbitrarily without prior information and this transmission link can be absent at any time.

Fig. 4.1 presents the model of OppNet routing exploiting their node mobility and contacts for data delivery. A node can exchange message with other intermediate nodes inside its wireless coverage area until the message reach the destination. From Fig. 4.1, all node can move with time (T0 - T2 as an example). At T0, The source node transmit the data to the next node within its radio coverage. This receptors at T1 now can act as a relay node and replicate message to the other nodes in its wireless link radius until this message reach the final destination at T3. Therefore, OppNet leads to a load balancing while it increases the robustness of the multi-hop wireless network as multiple receptors are potential relays.

4.2 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
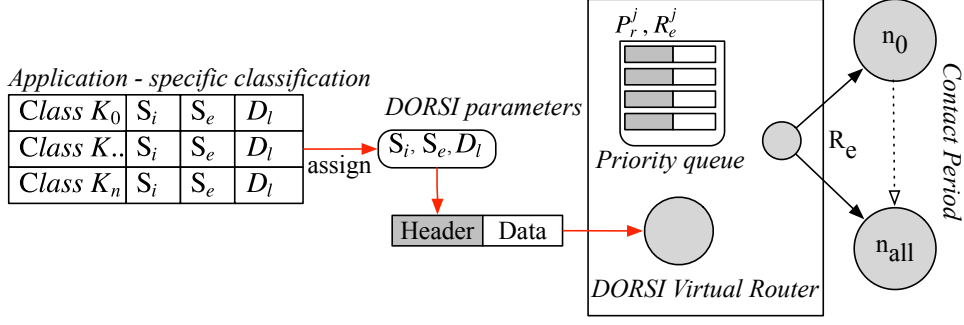
Figure 4.2: DORSI system model

number of message replica in this network according with information sensitivity concept [40, 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. 4.2 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 [71]. 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 routing 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 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

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countable message lifetime, τ_{max} and τ_{min}, in the system. The message with the residual life-time $\tau_t = \tau_{max}$ 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 any 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.

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

The replication probability value, in range of $[R_{min}, 1]$, is based on the concept that a message with more priority, P_r^j, should be disseminated more in order to increase delivery ratio while the message with more 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 application requirement. In 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, , is calculated according to its departure probability representing the relative chance to move away from the DORSI router node, r.

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

It can be estimated as the difference in distance between the current DORSI router, r, and the contacting node n, after they moves further one unit distance 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 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.

4.3 Evaluation

4.3.1 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 scheme can be integrated into this
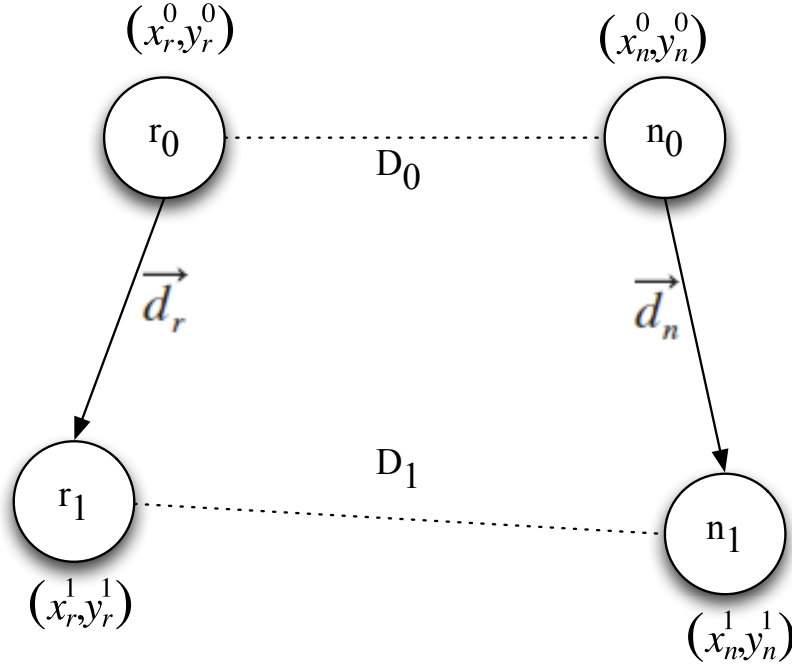
Figure 4.3: Node ranking model

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	
Moving Speed	0.5 - 1.5 m/s	
Movement Model	Random Waypoint	
Wait Time	0 - 180 Seconds	
Number of classes	5	

Table 4.1: DORSI Simulation variables

tactical network to aid significant and secure operations. In addition we employ MLS [71] 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) [36]. 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 [66]. 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 message 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. In random way point movement (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.

4.3.2 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.

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

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.

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

4.3.3 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
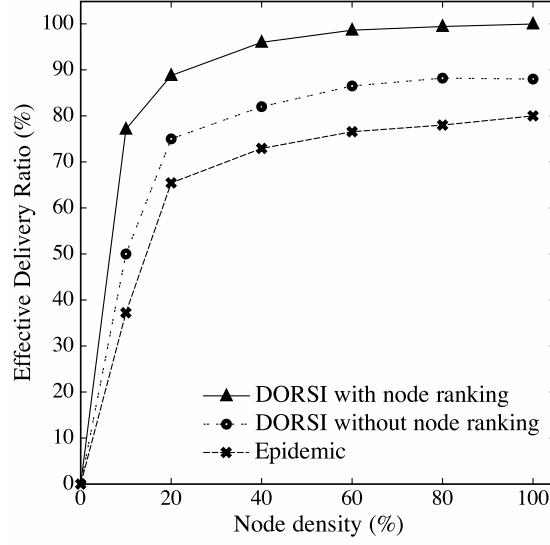
Figure 4.4: Effective Delivery Ratio comparison

important data. Figure 4.4 presents the relationship between effective delivery ratio and node density comparing DORSI to 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 even though all resource is 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.
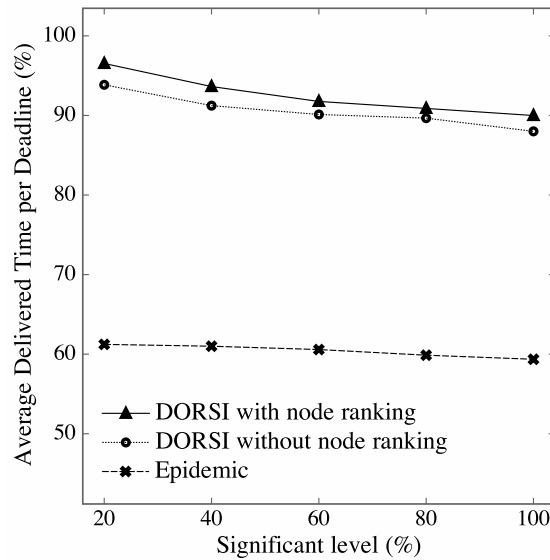

Figure 4.5: Average Delivered Time per Deadline on Significant Level

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 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 deadline.
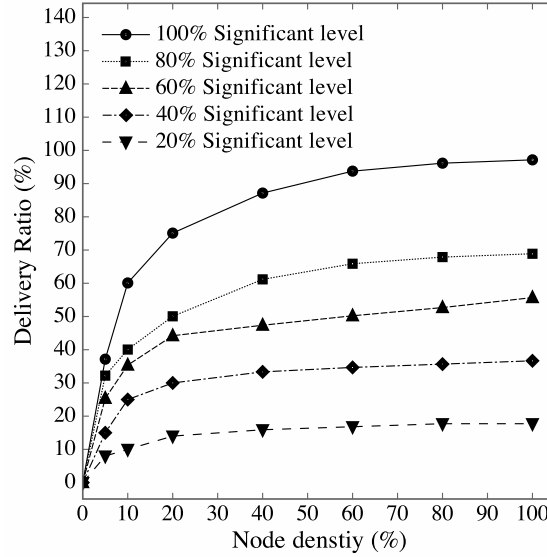

Figure 4.6: DORSI Delivery Ratio on each class

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 to 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 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.

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.

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 Epidemic. This result proves our design concept of security risk and aids in the optimum network bandwidth utilization.
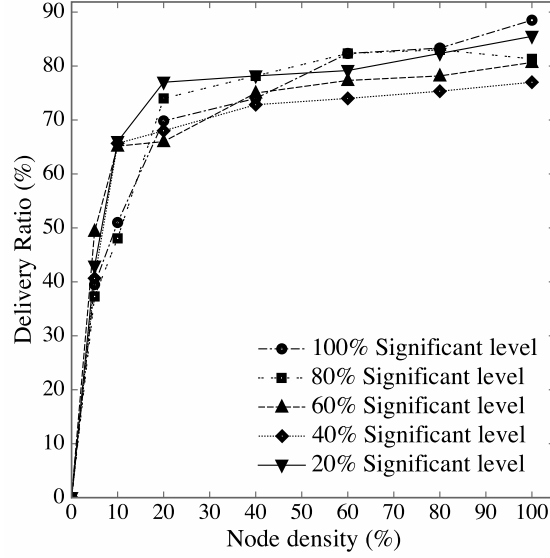
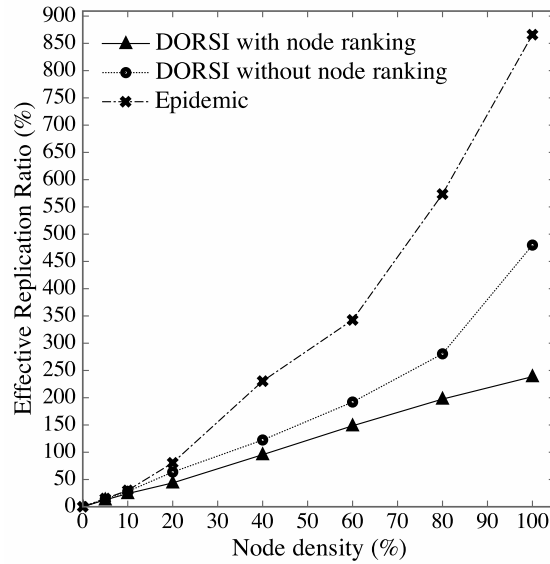Figure 4.7: Epidemic Delivery Ratio on each class

Figure 4.8: Effective Replication Ratio Comparison

To study the behavior of our protocol, we analyze the result of various number of classes as well. In our scenario, we divide the data class 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 class of data, we simulate the data with different scale 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 node amount to process the node ranking mechanism. This result proves that the classification technique can be deployed to various number of classes in any application.
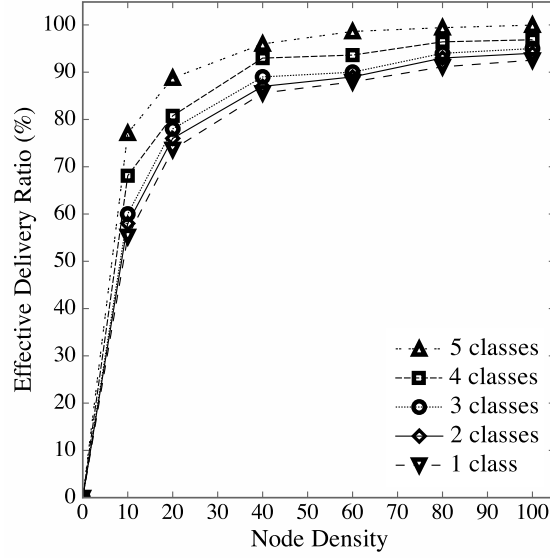
Figure 4.9: EDR on different classification scale

To study the behavior of DORSI, we select 20% node density scenario 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 increase 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 selecting the candidate nodes, resulting in more chance of reaching destination.
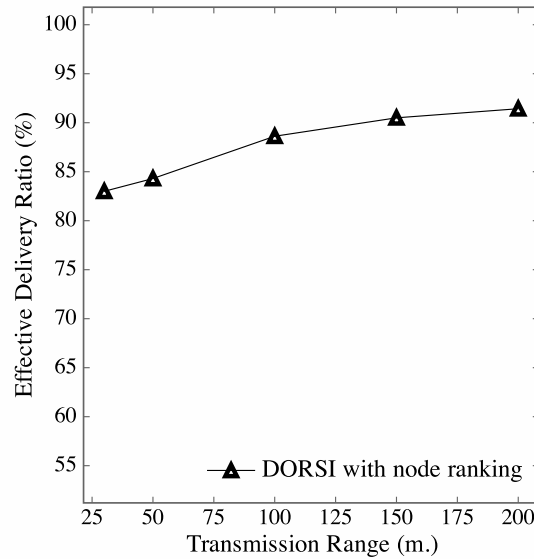
Figure 4.10: EDR comparing varied by transmission range

All in all, the key performance from simulation results confirms with our design goals. In DORSI, the value of EDR and ERR shows that we can control the message replication thus the message with higher priority can reach the destination faster to prove 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 near 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.

4.4   Conclusion

In this paper, 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 nodes prioritization technique corresponding to the their delivery probability computed by 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 paper 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 effective delivery ratio and effective replication ratio remarkably improve over the traditional Epidemic routing. Moreover, the delivery ratio of DORSI and Epidemic comparison shows notable overall enhancement of the network routing efficiency. This means that DORSI protocol can guarantee 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 deadline. In addition, this method can be applied to different scale 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. For the future work, we consider incorporating the trustworthiness degree of each router node such as the node clearance level. It might not be faster, however it would be more secure in terms of military network.

Chapter 5

Conclusions and Discussions

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

5.1 Discussion

This thesis has mode two major research contributions with several sub-routing algorithms in each major field of opportunistic routing 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.

5.1.1 Discussion about Chapter 3 on Dynamic Rendezvous based Routing Algorithm

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 by which a node can keep the receiving messages, carrying the messages with them when moving and then forwarding 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 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.

5.1.2   Discussion about Chapter 4 on the Data–wise Opportunistic Routing

Opportunistic network is a challenged networks where network contacts are intermittent and link performance is highly variable or extreme. This revolutionary network deploys store-carry-forward paradigm to deal with the occasionally partial-connectivity or node mobility in the network. The local forwarding decision of this type of network is based on the current and future connectivity information. Most of the routing in opportunistic networks consider forwarding decision based on locally collected knowledge about node behavior to predict the delivery probability of each node. However, none of these routing techniques concerns about the data content. This paper 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. 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 guarantee higher delivery ratio on data with higher priority within time limit while restricting the replicas of data with higher security level.

5.2   Conclusion

5.3   Future Work

Throughout each chapter of the thesis, we discussed the future work that we plan to do regarding the work of that specific factor. Beside these plans, we also would like to work on the following issues. First of all,

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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. x, No. xx, pp. xx-xx, 2014 (in ISI, impact factor=0.727) (To appear)

- Jiradett Kerdsri, Komwut Wipusitwarkun, "DORSI: Data-wise Opportunistic Routing with Spatial Information", *JCIT: Journal of Convergence Information Technology*, Vol. 8, No. 13, pp. 91-103, 2013 (in SCOPUS, impact factor=??)

International Conferences

- Jiradett Kerdsri, Komwut Wipusitwarkun, "Rendezvous Based Routing in Opportunistic Networks" *2014 International Telecommunications Symposium*, pp.xx-xx, 17-20 Aug. 2014 (To appear)

- 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