

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

BY

JIRADETT KERDSRI

**A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY PROGRAM IN ENGINEERING AND
TECHNOLOGY
SIRINDHORN INTERNATIONAL INSTITUTE OF TECHNOLOGY
THAMMASAT UNIVERSITY
ACADEMIC YEAR 2014**

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

A Thesis Presented

By
JIRADETT KERDSRI

Submitted to
Sirindhorn International Institute of Technology
Thammasat University

In partial fulfillment of the requirement for the degree of
DOCTOR OF PHILOSOPHY PROGRAM IN ENGINEERING AND TECHNOLOGY

Approved as to style and content by

Advisor and Chairperson of Thesis Committee	<hr/> Assoc. Prof. Komwut Wipusitwarakun, Ph.D.
--	---

Committee Member and Chairperson of Examination Committee	<hr/> Assoc. Prof. Steven Gordon, Ph.D.
--	---

Committee Member	<hr/> Asst. Prof. Prapun Suksompong, Ph.D.
------------------	--

Committee Member	<hr/> Asst. Prof. Somsak Kittipiyakul, Ph.D.
------------------	--

External Examiner:	Prof. xx xxxx, Ph.D.
--------------------	----------------------

DECEMBER 2014

Acknowledgments

This thesis is the end of my long journey obtaining a doctorate degree in Engineering and Technology. I can honestly state that it would not have been possible without the support from several people.

First of all, I would like to express my sincere gratitude to my advisor Assoc. Prof. Komwut Wipusitwarakun for his continuous support of my Ph.D. study and research, for his patience, motivation, enthusiasm, and immense knowledge. At every step of my thesis, he guided me with his profound knowledge, insight and wisdom. I would like to express my deep gratitude to him for being such a great advisor.

Besides my advisor, I would like to thank the rest of my thesis committee: Assoc. Prof. Steven Gordon, Asst. Prof. Prapun Sukompong and Asst. Prof. Somsak Kittipiyakul, for their encouragement, insightful comments, and hard questions. I also would like to express my appreciation to my external examiner, Prof. xxx xxxx, for his useful suggestions and helpful comments. I am thankful for all faculty members in the school of Information and Computer Technology, SIIT, for their support, valuable comments and suggestions on the research.

I also would like to thank to my colleague in Information Technology of SIIT and Defence Technology Institute (DTI), for stimulating discussions and all the fun we had studying together. I appreciate their efforts in helping me solving several problems I faced through this thesis work. Thanks for their concern, mind power and encouragement all the time. Especially my supervisor at DTI, Asst. Prof. Tawiwat Veeraklaew, who inspires me and also recommended me to pursue my Ph.D. at SIIT.

Finally, my deep gratitude goes to my family, my mother and sister. I am very grateful to them for standing by me in everything I have done and giving me whatever they can. They have always provided me continuous support, encouragement and their love. I believe that nothing would be possible without the presence of them and the peaceful family environment they provided me during my life. Even though my father already passed away but he had always been my greatest teacher who inspire me about higher education. I would like to dedicate this thesis to them.

Abstract

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

by

Jiradett Kerd Sri

Bachelor of Civil Engineering, Royal Thai Air Force Academy, 1999

Master of Science in Computer, Naval Postgraduate School, 2003

Master of Geographic Information Technology, University of Melbourne, 2009

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 holding 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.

Table of Contents

Chapter Title	Page
Signature Page	i
Acknowledgments	ii
Abstract	iii
Table of Contents	iv
List of Figures	v
List of Tables	vi
List of Listings	vii
List of Acronyms	viii
1 Introduction	1
1.1 Problem Statement	1
1.2 Objective and Scope	1
1.3 Proposed Approaches	2
1.4 Our Contributions	2
2 Background and Related Work	3
2.1 Delay Tolerant Networks	3
2.2 Opportunistic Networks	4
3 Data-wise Opportunistic Routing with Spatial Information	10
3.1 Data-wise Routing	10
3.2 Simulation Model and Results	10
3.3 Summary of Contributions	10
4 Dynamic Rendezvous based Routing Algorithm on Sparse Opportunistic Network Environment	11
4.1 Rendezvous Place	11
4.2 Simulation Model and Results	11
4.3 Summary of Contributions	11
5 Conclusion and Future Work	12
5.1 Discussion	12
5.2 Conclusion	12
5.3 Future Work	12
References	13
Appendix A: List of Publications	17

List of Figures

Figure	Page
2.1 Types of DTN	4
2.2 Classification of Opportunistic Routing	6

List of Tables

Table	Page
-------	------

List of Listings

Listing

Page

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 [28]. 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 [19]. 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 [1, 34] 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 [20]. In order to handle ICNs, the Internet Engineering Task Force (IETF) [6] 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 [20]. 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 [24]. Therefore, the timer and acknowledgement mechanisms of the traditional TCP/IP protocol definitely fail in such circumstances [9]. 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 [5].

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) [3] 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.

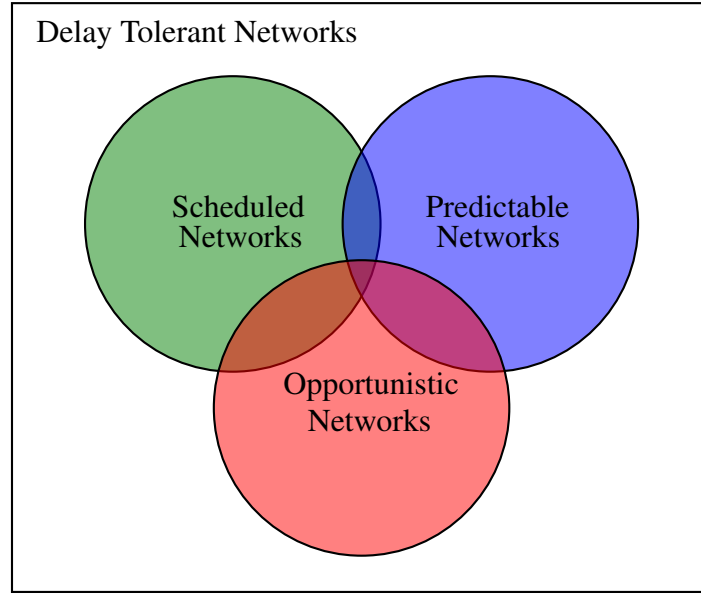


Figure 2.1: Types of DTN

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* [13]. In essential, there are three common steps of routing in OppNet [12]:

- Broadcast the messages to candidate 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 [29] :

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

- Next hop forwarder selection: Data holding nodes need to find a helper node that can forward the messages to the destination as soon as possible.

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 [30] 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 [32]. However, this scheme produces significantly long delays since the delivery delay is unbounded for this direct transmission routing [10].

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 [14]. 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 [36] is proposed utilizing epidemic algorithm to send each message to all nodes in the network. Even though the Epidemic routing can guarantee all nodes will eventually receive all messages, it incurs significant demand on both bandwidth and buffer.
- Controlled: Undoubtedly, uncontrolled flooding consumes network resources which can seriously degrade the performance if the resources are scarce [35]. 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 [11] 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 [33] 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

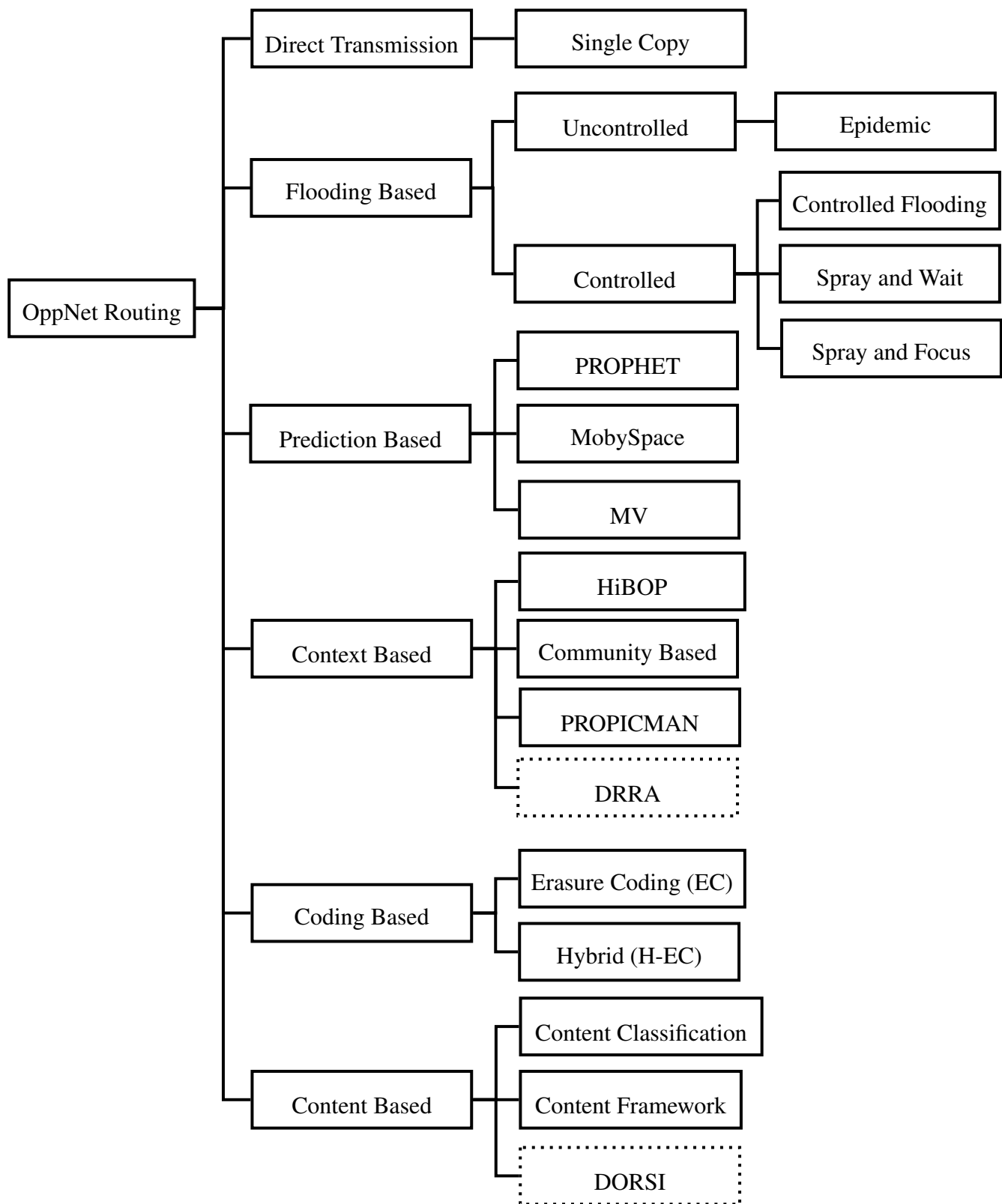


Figure 2.2: Classification of Opportunistic Routing

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 [31] 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 [32].

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 [23] 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 [21, 22] 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 [4] 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 [25], 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 [2] 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 [26] proposed the Probabilistic Routing Protocol for Intermittently Connected Mobile Ad hoc Network (PROPICMAN) in which the context information is represented by the *node profile* with evidence/value pairs upon contact opportunities to forward the messages. The main idea behind PROPICMAN is to look for the increasing matching user profiles between destination and encountered nodes, similarly to HiBoP. However, a distinctive function between PROPICMAN and HiBOp is the exploiting decision trees to select the next hop [8]. 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 [17].
- **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 [27] 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 [39] 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 [15], 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 [38] 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 $(1 + \epsilon) \cdot M/b$ erasure coded blocks while ϵ is a small constant varying by the utilizing algorithm, such as Reed-Solomon codes or Tornado codes [7]. Due to the additional information embedded in the code blocks, coding based schemes are less efficient when the network is well connected [16].
- Hybrid (H-EC):

However, coding based schemes are less efficient when the network is well connected, which is simply due to additional information embedded in the code blocks.

Content Based

- Content Classification:
- Content Framework:
- DORSI:

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 [5, 9, 29, 1, 18, 37] 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.

Chapter 3

Data-wise Opportunistic Routing with Spatial Information

3.1 Data-wise Routing

3.2 Simulation Model and Results

3.3 Summary of Contributions

Chapter 4

Dynamic Rendezvous based Routing Algorithm on Sparse Opportunistic Network Environment

4.1 Rendezvous Place

4.2 Simulation Model and Results

4.3 Summary of Contributions

Chapter 5

Conclusion and Future Work

5.1 Discussion

5.2 Conclusion

5.3 Future Work

References

- [1] N. Banerjee, M. D. Corner, B. N. Levine, J. Nousiainen, Y. Cao, and Z. Sun. Routing in Delay/Disruption Tolerant Networks: A Taxonomy, Survey and Challenges. *Communications Surveys & Tutorials, IEEE*, pages 776–784, 2013.
- [2] C. Boldrini, M. Conti, J. Jacopini, and A. Passarella. Hibop: a history based routing protocol for opportunistic networks. In *World of Wireless, Mobile and Multimedia Networks, 2007. WoWMoM 2007. IEEE International Symposium on a*, pages 1–12, June 2007.
- [3] S. Burleigh, A. Hooke, L. Torgerson, K. Fall, V. Cerf, B. Durst, K. Scott, and H. Weiss. Delay-tolerant networking: an approach to interplanetary internet. *Communications Magazine, IEEE*, 41(6):128–136, June 2003.
- [4] B. Burns, O. Brock, and B. Levine. Mv routing and capacity building in disruption tolerant networks. In *INFOCOM 2005. 24th Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings IEEE*, volume 1, pages 398–408 vol. 1, March 2005.
- [5] Y. Cao and Z. Sun. Routing in delay/disruption tolerant networks: A taxonomy, survey and challenges. *Communications Surveys Tutorials, IEEE*, 15(2):654–677, Second 2013.
- [6] V. Cerf, S. Burleigh, A. Hook, L. Torgerson, R. Dust, K. Scott, K. Fall, and H. Weiss. Delay-tolerant networking architecture, ietf network working group, rfc4838, April 2007.
- [7] J.-H. Chung, S.-E. Kim, and J. Copeland. Reliable wireless multicast using fast low-density codes. In *Vehicular Technology Conference, 2003. VTC 2003-Spring. The 57th IEEE Semiannual*, volume 2, pages 1218–1222 vol.2, April 2003.
- [8] M. Conti, S. Giordano, M. May, and A. Passarella. From opportunistic networks to opportunistic computing. *Communications Magazine, IEEE*, 48(9):126–139, Sept 2010.
- [9] R. J. D’Souza and J. Jose. Routing Approaches in Delay Tolerant Networks : A Survey. *International Journal of Computer Applications*, 1(17):8–14, February 2010.
- [10] M. Grossglauser and D. Tse. Mobility increases the capacity of ad hoc wireless networks. *Networking, IEEE/ACM Transactions on*, 10(4):477–486, Aug 2002.
- [11] K. A. Harras and K. C. Almeroth. Controlled flooding in disconnected sparse mobile networks. *Wireless Communications and Mobile Computing*, 9(1):21–33, 2009.
- [12] C.-J. Hsu, H.-I. Liu, and W. K. G. Seah. Opportunistic routing - a review and the challenges ahead. *Computer Networks*, 55(15):3592–3603, 2011.

- [13] L. Hu. *Mobile Peer-to-Peer Data Dissemination over Opportunistic Wireless Networks*. PhD thesis, Technical University of Denmark, 2009.
- [14] C.-M. Huang, K. chan Lan, and C.-Z. Tsai. A survey of opportunistic networks. In *Advanced Information Networking and Applications - Workshops, 2008. AINAW 2008. 22nd International Conference on*, pages 1672–1677, March 2008.
- [15] P. Hui, J. Crowcroft, and E. Yoneki. Bubble rap: Social-based forwarding in delay-tolerant networks. *Mobile Computing, IEEE Transactions on*, 10(11):1576–1589, Nov 2011.
- [16] C. hung Yu, Y. chih Chen, and L. jyh Chen. Effective file transfer for opportunistic networks. In *IEEE INFOCOM07*, 2006.
- [17] A. A. A. V. V. Isaac Woungang, Sanjay Kumar Dhurandher. *Routing in Opportunistic Networks*, chapter Context-Based Routing Protocols for OppNets. Springer, 2013.
- [18] B. Jedari and F. Xia. A survey on routing and data dissemination in opportunistic mobile social networks. *CoRR*, abs/1311.0347, 2013.
- [19] I. Joe and S.-B. Kim. A message priority routing protocol for delay tolerant networks (dtn) in disaster areas. In T.-h. Kim, Y.-h. Lee, B.-H. Kang, and D. Izak, editors, *Future Generation Information Technology*, volume 6485 of *Lecture Notes in Computer Science*, pages 727–737. Springer Berlin Heidelberg, 2010.
- [20] M. J. Khabbaz, C. M. Assi, and W. F. Fawaz. Disruption-Tolerant Networking: A Comprehensive Survey on Recent Developments and Persisting Challenges. *IEEE Communications Surveys & Tutorials*, 14(2):607–640, 2012.
- [21] J. Leguay, T. Friedman, and V. Conan. Dtn routing in a mobility pattern space. In *Proceedings of the 2005 ACM SIGCOMM Workshop on Delay-tolerant Networking, WDTN '05*, pages 276–283, New York, NY, USA, 2005. ACM.
- [22] J. Leguay, T. Friedman, and V. Conan. Evaluating mobility pattern space routing for dtms. In *INFOCOM 2006. 25th IEEE International Conference on Computer Communications. Proceedings*, pages 1–10, April 2006.
- [23] A. Lindgren, A. Doria, and O. Scheln. Probabilistic routing in intermittently connected networks. In P. Dini, P. Lorenz, and J. de Souza, editors, *Service Assurance with Partial and Intermittent Resources*, volume 3126 of *Lecture Notes in Computer Science*, pages 239–254. Springer Berlin Heidelberg, 2004.
- [24] M. Liu, Y. Yang, and Z. Qin. A survey of routing protocols and simulations in delay-tolerant networks. In Y. Cheng, D. Eun, Z. Qin, M. Song, and K. Xing, editors, *Wireless Algorithms, Systems, and Applications*, volume 6843 of *Lecture Notes in Computer Science*, pages 243–253. Springer Berlin Heidelberg, 2011.
- [25] H. A. Nguyen and S. Giordano. Routing in Opportunistic Networks. *International Journal of Ambient Computing and Intelligence*, 1(3):19–38, 2009.

- [26] H. A. Nguyen, S. Giordano, and A. Puiatti. Probabilistic routing protocol for intermittently connected mobile ad hoc network (propicman). In *World of Wireless, Mobile and Multimedia Networks, 2007. WoWMoM 2007. IEEE International Symposium on a*, pages 1–6, June 2007.
- [27] J. Niu, X. Zhou, K. Wang, and J. Ma. A data transmission scheme for community-based opportunistic networks. In *Wireless Communications, Networking and Mobile Computing, 2009. WiCom '09. 5th International Conference on*, pages 1–5, Sept 2009.
- [28] L. Pelusi, A. Passarella, and M. Conti. Opportunistic networking: data forwarding in disconnected mobile ad hoc networks. *Communications Magazine, IEEE*, 44(11):134–141, November 2006.
- [29] B. Poonguzharselvi and V. Vetrivel. Survey on routing algorithms in opportunistic networks. *2013 International Conference on Computer Communication and Informatics*, pages 1–5, Jan. 2013.
- [30] T. Spyropoulos, K. Psounis, and C. Raghavendra. Single-copy routing in intermittently connected mobile networks. In *Sensor and Ad Hoc Communications and Networks, 2004. IEEE SECON 2004. 2004 First Annual IEEE Communications Society Conference on*, pages 235–244, Oct 2004.
- [31] T. Spyropoulos, K. Psounis, and C. Raghavendra. Spray and focus: Efficient mobility-assisted routing for heterogeneous and correlated mobility. In *Pervasive Computing and Communications Workshops, 2007. PerCom Workshops '07. Fifth Annual IEEE International Conference on*, pages 79–85, March 2007.
- [32] T. Spyropoulos, K. Psounis, and C. Raghavendra. Efficient routing in intermittently connected mobile networks: The single-copy case. *Networking, IEEE/ACM Transactions on*, 16(1):63–76, Feb 2008.
- [33] T. Spyropoulos, K. Psounis, and C. S. Raghavendra. Spray and wait: An efficient routing scheme for intermittently connected mobile networks. In *Proceedings of the 2005 ACM SIGCOMM Workshop on Delay-tolerant Networking, WDTN '05*, pages 252–259, New York, NY, USA, 2005. ACM.
- [34] T. Spyropoulos, R. Rais, T. Turletti, K. Obraczka, and A. Vasilakos. Routing for disruption tolerant networks: taxonomy and design. *Wireless Networks*, 16(8):2349–2370, 2010.
- [35] O. Tonguz, N. Wisitpongphan, J. Parikh, F. Bai, P. Mudalige, and V. Sadekar. On the broadcast storm problem in ad hoc wireless networks. In *Broadband Communications, Networks and Systems, 2006. BROADNETS 2006. 3rd International Conference on*, pages 1–11, Oct 2006.
- [36] A. Vahdat and D. Becker. Epidemic Routing for Partially-Connected Ad Hoc Networks. Technical report, Technical Report CS-200006, Duke University.
- [37] A. Wahid, G. Kumar, and K. Ahmad. Opportunistic Networks : Opportunity versus Challenges-Survey. In *National Conference on Information Security Challenges (NCIC-2014)*, pages 14–24, 2014.

- [38] Y. Wang, S. Jain, M. Martonosi, and K. Fall. Erasure-coding based routing for opportunistic networks. In *Proceeding of the 2005 ACM SIGCOMM workshop on Delay-tolerant networking - WDTN '05*, pages 229–236, New York, New York, USA, 2005. ACM Press.
- [39] M. Xiao, J. Wu, and L. Huang. Community-aware opportunistic routing in mobile social networks. *Computers, IEEE Transactions on*, 63(7):1682–1695, July 2014.

Appendix A

List of Publications

International Journals

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