Performance Evaluation of Opportunistic Routing Protocols: A Framework-based Approach using OMNeT++

Zhongliang Zhao
Institute of Computer Science
and Applied Mathematics
University of Bern
Neubrückstrasse 10
3012 Bern, Switzerland
zhao@iam.unibe.ch

Björn Mosler
Institute of Computer Science
and Applied Mathematics
University of Bern
Neubrückstrasse 10
3012 Bern, Switzerland
bjoern@students.unibe.ch

Torsten Braun
Institute of Computer Science
and Applied Mathematics
University of Bern
Neubrückstrasse 10
3012 Bern, Switzerland
braun@iam.unibe.ch

ABSTRACT

Opportunistic routing may achieve significant performance gain under lossy wireless links or in scenarios of mobile ad hoc networks, where end-to-end connectivity is not always available. Instead of deterministically choosing one node to forward a packet to, the network layer selects a set of candidate nodes and then only one of them will be chosen dynamically as the actual forwarder based on the instantaneous channel conditions and node availability at the moment of transmission. Many protocols have been proposed and most of them are studied in specific simulation environments or real-world testbeds, and no systematic analysis has been given about the integrative performance of different protocols.

In our previous work, we have shown that different opportunistic routing protocols share many common functions and these general functions could be abstracted and decoupled into a framework of functional components, which might facilitate the development and evaluation of opportunistic routing protocols. In this paper, we extend our work and present initial evaluation results of the ExOR and MORE protocols using our simulation framework in OMNeT++. Our simulation results justify scenarios where opportunistic routing may perform better than traditional MANET routing.

Categories and Subject Descriptors

I.6 [**Simulations and Modelings**]: Miscellaneous

General Terms

Simulation, Performance evaluation, Experimentation

Keywords

Opportunistic routing, Protocol comparison, Framework, OMNeT++, INETMANET

LANC'12, October 4-5, 2012, Medellín, Colombia

1. INTRODUCTION

A multi-hop wireless network is a network of nodes (e.g. computers, sensors) connected by wireless communication links. Due to limited radio transmission range, many pairs of nodes in the network may not be able to communicate directly; hence they need other intermediate nodes that forward packets for them. In a wireless network, when a packet is unicast to a specific next-hop of the sender, all the neighbor nodes in the effective communication range of the sender may have received the packet correctly while the designated next-hop node did not. Based on this observation, a new routing paradigm, known as opportunistic routing has been proposed.

Opportunistic routing exploits the broadcast nature and spatial diversity of the wireless medium to improve the performance of wireless communications by enhancing packet forwarding reliability in multi-hop environments. It targets to combat unreliable wireless links by involving multiple neighbor nodes (potential forwarders) for packet relay. Traditional routing protocols for multi-hop wireless networks have followed the idea of routing packets in wired networks by abstracting the wireless link as wired one, and finding the shortest, least cost, or highest throughput path between a source and destination pair. Most protocols rely on the consistent and stable behavior of individual links, so the intermittent behavior of wireless links can result in poor performance such as low packet delivery ratio, high control overhead or long end-to-end delay. However, node mobility, topology sparseness and channel link quality variation could all lead to situations, where the network is disconnected. Then, traditional MANET routing protocols are unable to operate or may not perform well. In opportunistic routing, instead of selecting only one hop to act as the forwarding node a priori, relay nodes are determined after the data packet has been received by multiple potential forwarding nodes. This decision is carried out for each data packet, so the instantaneous radio condition and available neighbor nodes will be considered to select the best suitable relaying node. Opportunistic routing protocols broadcast packets to multiple nodes with just one transmission. Then, the receivers of the packet will coordinate to elect one of them as the next forwarder of this packet, the others just discard the packet.

In this paper, we perform a systematic performance analysis of representative opportunistic routing protocols, ExOR and MORE, by taking into account different channel transmission rates, network node densities, route numbers from a source to a destination and channel quality. Their performance are compared with a well-known proactive link-state routing protocol, OLSR. The metrics we use are transmission delay of packets, throughput and number of collisions encountered at different nodes. The evaluation is based on an OMNeT++ framework for implementing opportunistic routing protocols that we developed in a previous work.

The rest of the paper is organized as follows. Section 2 describes the related work of opportunistic routing protocols and simulator environments that are often used to perform opportunistic routing simulation. Section 3 briefly reviews the details of ExOR, MORE and OLSR protocols. Section 4 gives the details of the simulation framework architecture and setup of the simulation experiment. The results are presented in section 5. Finally, section 6 concludes the paper.

2. RELATED WORK

Opportunistic routing protocols make use of the broadcast nature of wireless communications during data forwarding by taking advantage of the transient nature of channel and node availability. This design principle seems to be a countermeasure for the situation of mobile ad hoc networks, where nodes are highly mobile and wireless propagation is inherently instable, making network topology changes frequently. Typical MANET routing protocols may not perform optimally in those scenarios.

Various opportunistic routing protocols have been developed. ExOR [5] pioneers the concept of being opportunistic when wireless links are weak. In ExOR, the sender specifies a list of candidate nodes in the packet header. These nodes are potential forwarders of the packet. The receivers relay the packet according to their priority in the list by negotiating with the neighbor nodes. MORE [6] is the first work that introduces network coding into opportunistic routing. It is a MAC independent protocol that combines the idea of opportunistic routing and network coding to utilize spatial reuse. In contrast to ExOR's highly structured scheduler, MORE randomly mixes packets by applying network coding before forwarding them. This ensures that neighbors that hear the same transmission do not forward the same packet. As a result, MORE does not need a scheduler.

Besides, there are many other protocols proposed in the past years. OPRAH [7] is a hop-count based protocol that uses the promiscuous nature of the air interface to find an optimal path for each packet. CORE [8] is a coding-aware routing protocol that prioritizes the candidates in the forwarding set in a dynamic way according to the coding opportunities. Instead of using Expected Transmission Count(ETX), OAPF [9] proposes a new metric, Expected Any-path Transmission (EAX), to select candidates and to prioritize them. In this paper, we take ExOR and MORE as the basis for comparison, since they are the pioneering works for applying opportunistic routing and network coding to improve network performance.

Most of the proposed opportunistic routing algorithms are evaluated with specific simulators or on real testbeds. In the simulation world, ONE [13] is probably the most successful one specifically designed for evaluating Delay Tolerant Network(DTN) and opportunistic routing protocols. However, ONE focuses on the modeling of the behavior of store-carry-forward networking, and hence refrains from detailed modeling of the low layer mechanisms such as signal attenuation and congestion of the physical medium. Instead, the radio link is modeled as a communication range and a link with a certain bit-rate, which is assumed to be constant over the time of the simulation. All these limitations make ONE imperfect for simulating opportunistic routing protocols, which inherently make use of fluctuating channel conditions.

In our previous work [20], we designed a framework for simulating opportunistic routing protocols in OMNeT++ [1] with the INETMANET [2] framework. INETMANET is an open-source framework, which offers detailed modeling of radio propagation, interference estimation and implementation of various MAC and network layer protocols of wireless network. It is able to simulate the time-varying nature of the wireless medium, which makes it a better choice for simulating opportunistic routing protocols. The proposed framework adopts an abstraction of the generic functions of the most representative opportunistic routing algorithms, which include four procedures: *Forwarder Candidate Selection, Forward Selection, Forwarder Role Change Notification* and *Collision Avoidance.* In the framework, these four procedures are defined as *virtual* functions and act as implementation stubs such that different protocols could be implemented by overwriting them. Besides the core functions, some shared operations are mandatory for most opportunistic routing protocols. The framework also includes the implementation of these shared functions, which are *Neighbor Management, Packet Buffer Management and ETX/EAX Calculation and Distribution.* Protocol developers could make use of these implementation to speed up their development phases. Details can be found in Section 4.

3. PROTOCOL DESCRIPTIONS

3.1 ExOR

Extreme Opportunistic Routing (ExOR) introduces opportunistic routing in wireless mesh networks by effectively utilizing the wireless broadcast medium to increase network throughput, as compared to traditional single-path routing protocols, which do not fully exploit the wireless broadcast advantage. ExOR combines routing with MAC layer functionality.

In ExOR, nodes send broadcast packets in batches, without previous route computation. Packets are transmitted in batches to reduce protocol overhead. In addition, broadcasting data packets improves reliability because only one intermediate node is required to overhear a transmission. Nevertheless, it does not guarantee that packets will be received, because they are not acknowledged. Therefore, an additional mechanism is required to indicate correct data reception. Among the intermediate nodes that have heard the transmission, only one forwards at a time. The source node defines a forwarding list and adds it to the header of the data packet. This list contains the addresses of neighbors, ordered by forwarding priority. Nodes are classified in the forwarding list according to their proximity to the destination, computed by a metric similar to ETX. The metric used by ExOR considers only the loss rate in the forwarding direction, because there are no acknowledgements. Only those nodes that are closer to the destination than the source are included in the forwarder list. Each packet has a *BITMAP* option, which marks those packets that have been received by the relaying nodes or nodes with higher priorities. All packets are broadcast. A forwarder will relay a packet only if no forwarder with higher priority has explicitly acknowledged its reception, as indicated in the *BITMAP* position for this packet. Upon reception of a data packet, the intermediate node checks the forwarding list. If its address is listed, it waits for the reception of the whole batch of packets. It is possible, however, that a node does not receive the entire batch. To cope with this problem, the highest-priority node that has received packets forwards them and indicates to the lower-priority node the packets that were transmitted. Consequently, the lower-priority nodes transmit the remaining packets, avoiding duplicates. The transmissions are performed until 95% of the packets have reached the final destination.

3.2 MORE

The MAC-independent Opportunistic Routing and Encoding (MORE) protocol integrates opportunistic routing as well as intra-flow network coding. It is targeted for enhancing ExOR. It randomly mixes packets before forwarding them. This randomness ensures that routers that hear the same transmission do not forward the same packets. Thus, MORE does not need a special scheduler to coordinate nodes and can run directly on top of IEEE 802.11.

In MORE, when the source is ready to send, it keeps creating coded packets via a random linear combination of the K native packets in the current batch. The source keeps sending such coded packets out until the whole batch is acknowledged by the destination. Then, the source proceeds with the next batch. In MORE, data packets are always coded. They carry a list of forwarders and a code vector recording how the native packets have been combined. Upon receiving such a coded packet, a node in the forwarder list first checks for the innovativeness of the packet (i.e., if it is linearly independent of the packets previously received). A forwarder only stores innovative packets. Furthermore, each forwarder keeps a *TX Counter* variable, which is calculated by a distributed algorithm based on the concept of ETX. When a forwarder receives an innovative packet from an upstream node, it increments the counter by its *TX Credit*. When the MAC layer allows the node to transmit, the node checks whether the counter is positive or not. If yes, the node creates a coded packet, broadcasts it, and decrements the counter by one. If the counter is zero or negative, the node does not transmit. Once the destination receives K innovative packets, it can decode the whole batch. It then sends an ACK back to the source to allow moving to the next batch.

Different from ExOR, MORE uses the concept of *innovative packets* to judge whether a received packet brings new information instead of using *duplicate packets* as in ExOR. Moreover, it uses a *TX Counter* at each forwarder to further reduce the number of transmissions.

3.3 OLSR

Optimized Link State Routing (OLSR) [11] is a well-known proactive link-state single-path routing protocol that forwards packets over a minimum-cost path. It uses Hello and Topology Control (TC) messages to discover and then disseminate link state information through the networks before packet transmission. Each node maintains the global topology information of the network, and computes the next hop for all the other nodes in the network using shortest hop forwarding paths. To decrease the possible overhead of the network, OLSR uses Multi-point Relays (MPRs) that prevents flooding of the broadcast messages by avoiding the same broadcast message in some regions within the network. Because of the use of MPRs, OLSR is well suited for large and dense mobile networks.

We take OLSR as the comparison baseline of opportunistic routing protocols, since the advantages of OLSR over reactive routing protocols (such as AODV and DSR) is that it does not introduce route-discovery delay for a flow because the route is computed in a proactive way. This favors situations where route requests for new destinations are very frequent. The OLSR protocol is adapted to the network, which should be dense and where communication is assumed to occur frequently between a large number of nodes. On the other side, OLSR has its own drawbacks. It maintains a routing table for all the destinations at each node, which may not be necessary. When the number of nodes increases, the control overhead of the protocol also increases. By only using MPRs to flood topology information, OLSR removes some of the redundancy of the flooding process, which may be a problem in networks with weak wireless links.

4. SIMULATION FRAMEWORK AND EXPERIMENT SETUP

4.1 Framework Architecture

We developed a framework, which is based on the Opponet project [14] for simulating opportunistic routing protocols in the OMNeT++ simulator. It provides common functionalities like ETX computation and distribution, neighbor management, etc. An abstract protocol base that allows for easy implementation of further opportunistic routing protocols has been implemented. The class hierarchy is built on the assumption that all opportunistic routing protocols share certain functionalities and that the way they work can roughly be split into four procedures, which are defined as virtual functions. To implement a new protocol, one needs to inherit the abstract base class and implement the four virtual functions. These correspond to the four common steps in opportunistic routing protocols, which are:

- *Opportunistic Candidate Selection*
- *Forwarder Selection*
- *Forwarder Role Change Notification*
- *Collision Avoidance*

Opportunistic Candidate Selection is the first procedure of routing protocols. The sending node periodically polls the node factory to check the nodes within its radio range. Certain attributes (e.g., geographic region or nodes movement tendency) are adopted additionally to build the set of potential next-hop nodes. The design of these attributes should take into account that only nodes that are closer to the destination or that have a movement towards it, should be candidates.

Forwarder Selection defines rules how the actual forwarding node is picked from the candidate set. One design proposal is that the sending node broadcasts a message containing its current available channels, transmission bit-rate, and statistical movement information. Candidates that receive these packets will consider the status of these information, its remaining battery lifetime, and the pre-calculated

ETX/EAX metrics to the destination. A comprehensive utility function will be executed and each candidate will return an utility value, which is shared between neighbors. The node with the highest utility value will be the one winning the election process.

Forwarder Role Change Notification enables the winning forwarder to announce its new role and responsibility to neighboring nodes, to make them aware of the selection winner, and to stop the competition. If the winning node can successfully do this, collisions introduced by simultaneous medium access from competing nodes could be significantly reduced.

Collision Avoidance is about how the nodes that wish to access the medium at the same time coordinate with each other to avoid collisions. If a collision happens, a subsequent resolution mechanism must be applied. Contention could happen in two cases: the first case is imperfect design of the Forwarder Role Change Notification process, which leads to duplicated transmission; the second case is when two or more nodes want to send packets at the same time, which could result in packet collision.

Besides the four virtual core functions, the framework also includes some other common functionalities, which are fundamental for most opportunistic routing protocols. The implementation of these shared functions are included within the framework, which will facilitate the development of new protocols. Although there might be differences for each protocol (some protocols may not explicitly include all the four procedures), we believe that most of the protocols could be easily adapted to use the common mechanisms provided by the framework. These common functionalities include:

- *Neighbor Discovery & Management*
  Neighbor detection is essential for opportunistic routing since a well-designed neighbor detection mechanism acts as a basis for forwarder selection. The neighbor management service of INETMANET is adopted.

- *Packet Buffer Management*
  Nodes need to store received packets and do other manipulations. Related data structures and corresponding operations are defined to fulfill this task.

- *Transmission Reliability Control*
  INETMANET includes several channel propagation models, which provide a detailed simulation basis for transmission control. The INETMANET link layer implementation is adapted to control packet transmission.

- *Node Interface Management*
  Nodes inside the network may be equipped with more than one physical antennas to increase network throughput. The management for multiple interfaces is necessary for benefiting from more antennas, i.e., to support multichannel communication.

- *ETX/EAX Calculation and Distribution*
  Most of the “Candidate Selection” processes of opportunistic routing protocols are based on the same principle that the source node pre-determines a forwarder priority list based on ETX/EAX values. This function is implemented to calculate and distribute the ETX/EAX value of each node pair.

The adoption of INETMANET will enhance the reality of the simulation of wireless communication. As an extension of the INET[3] framework, INETMANET offers all the basic models and tools (such as propagation models, link layer protocols, mobility models, etc.) necessary for MANET protocol simulation, which provides an enriched environment to analyze opportunistic routing protocols. In particular, it includes the implementation of MANET routing protocols, such as OLSR and AODV, which will facilitate the comparison of opportunistic routing and traditional MANET routing protocols.

4.2 Simulation Setup

We implemented ExOR and MORE in OMNeT++, using the framework depicted before. The OLSR protocol implementation used for comparison is adapted from the OLSR-ETX code from INETMANET, which is an open source implementation of ETX-based OLSR protocols for the INETMANET framework of OMNeT++. In this section, we describe the simulation environment for the evaluation. The experiment results are given and discussed in Section V.

All protocols are evaluated with the same stationary topology that was used in [6], see Figure 1. The network consists of 12 static nodes, in which node 11 acted as the source and node 5 as the destination for all transmissions. Simulations were run for each batch of 32 packets, and every packet is of size of 1024 bytes. The inter-packet time equals to zero for the packets within the same batch. For each simulation run, the warm-up phase is 200s, during which some initialization work will be done, i.e. the calculation and distribution of ETX values. For each combination of those parameters, 20 simulation runs are repeated to collect statistics. We vary the channel transmission rate to 6 Mbps, 9 Mbps and 11 Mbps, to see how the channel transmission rate affects performance. Detailed simulation parameters are listed in Table 1.

Transmission Power	100mW
Propagation Model	Path-loss reception
Number of Nodes	12
Radio Sensitivity	-90dBm
Simulation Time	900s
Warm-up Phase	200s
Radio Range	25m
Network Size	120x80m
MAC Protocol	inet.linklayer.ieee80211.mac
Channel Transmission Rate	{6, 9, 11} Mbps
Node Density	{5, 10, 17, 32, 44}

Table 1: Simulation parameters

4.3 Metrics & Parameters

The following evaluation metrics are used to analyze the performance of different routing protocols:

- **Transmission delay** was the time interval between the arrival time of the first packet and the arrival time of the last packet within a batch.

- **Throughput** was measured at the destination as the ratio of the number of packets received and the time it takes to receive these packets.

- **Collision** was an interesting value to see how the coordination mechanism between multiple potential forwarders performs. Also it is an indicator of the bottleneck nodes that suffer the worst collision situation in

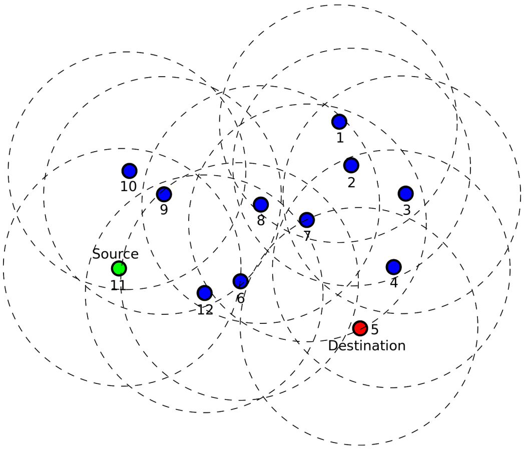

Figure 1: Simulation network topology: the circles mark the transmission ranges.

the network. It is calculated at the IEEE 802.11 MAC layer whenever an invalid packet is detected.

To investigate the influence of different system factors on the simulation results, we elaborate the following parameters to see how they affect the protocols' performance:

- **Transmission rate** to see how opportunistic routing and traditional routing behave under different physical channel transmission rates.
- **Node density** to see how large the candidate forwarder set should be to make opportunistic routing perform optimally.
- **Route number** to see whether the number of available paths to a destination has an effect on protocol performance.
- **Channel quality** to see in which channel condition opportunistic routing should be applied to show its benefit. We take *Path Loss Alpha* as the indicator of the channel condition in a wireless environment. *Path Loss Alpha* (α) is an indicator used to approximate signal attenuation in a wireless environment. Its value is normally in the range of 2 to 6 (indoor), where 2 is for a good channel, 6 is for lossy environment.

5. SIMULATION RESULTS

5.1 Channel transmission rate

The physical channel transmission rate could have significant effect on the performance of routing protocols. To see how opportunistic routing and traditional routing mechanisms behave under different transmission rates, we vary the channel transmission rate (bitrate) between 6 Mbps, 9 Mbps, and 11 Mbps. The channel is configured as medium quality (path loss alpha = 3). Figure 2 gives the throughput evaluation of the three protocols OLSR, ExOR and MORE. There is no surprise that MORE and ExOR outperform OLSR at different transmission rate scenarios. This is an expected result since we know that opportunistic routing achieves better throughput than traditional routing. The performance gain mainly is twofold: First, opportunistic routing is able to exploit more packet forwarders and inherently utilizes the broadcast nature of wireless communication. Second, the ACK (acknowledge) redundancy introduced by the batch map of ExOR and MORE is removed, since both protocols do not send per-packet acknowledgements. MORE performs better than ExOR due to its support of spatial reuse, which is prevented by ExOR. ExOR forbids multiple nodes from accessing the medium simultaneously, even if two transmission flows are outside the interference range of each other.

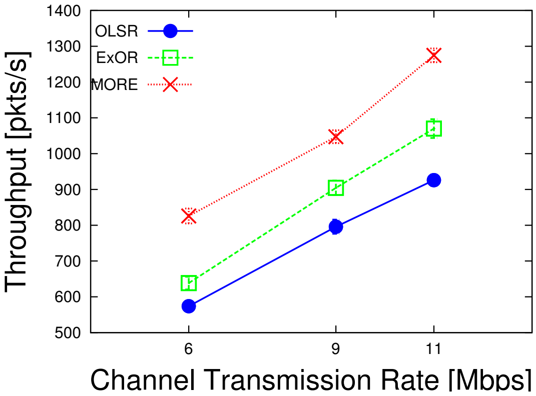

Figure 2: Throughput of MORE, ExOR and OLSR under different channel transmission rate scenarios.

5.2 Node density

Due to the integrated network coding operation of MORE, it is difficult and unfair to compare it with OLSR. From this section on, we will mainly focus on the performance comparison of ExOR and OLSR. Opportunistic routing owes its performance superiority to the adoption of multiple forwarders. It is therefore intuitive to analyze how opportunistic routing depends on the node density, basically the average number of neighbors per node. Node density should have significant influence on routing protocol performance. In general, low density may cause the network to be disconnected and high density will increase contention, resulting in low throughput. To see the performance of ExOR and OLSR for different node densities, we modify the network node number from 5, 10, 17 to 32 and 44, corresponding to 1, 3, 6, 8 and 12 neighbors per node on average, as shown in Figure 3. The channel is fixed with path loss alpha = 3, which means a fair (medium) channel condition. The result is shown in Figure 4, with default transmission rate equal to 6 Mbps. As we can expect, ExOR performs better than OLSR in all cases.

When the node density is low, the network is far from being saturated. Therefore, OLSR throughput increases when more nodes are added. After a certain point the network gets saturated and OLSR starts to degrade when the node number keeps increasing. This is probably due to the overhead of periodic control traffic, i.e., Hello and Topology Control messages in OLSR. When more nodes contend for channel access, the collision occurrence probability and interference increase. Besides, we can find out that the increased number of forwarding nodes has little influence on the throughput of ExOR, which means ExOR does not benefit from additional relay candidates. A possible reason is that adding more nodes in this topology will build joint paths between

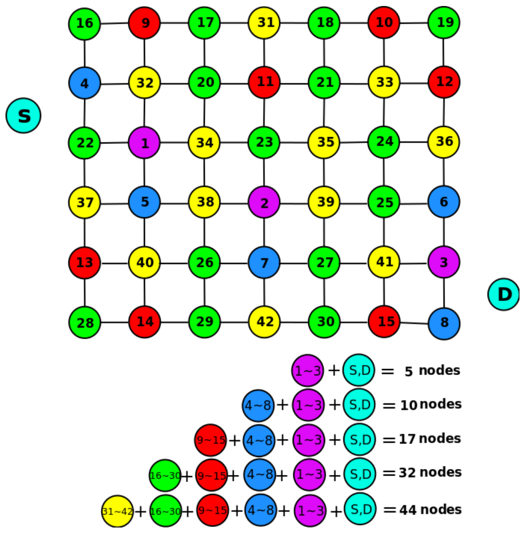

Figure 3: Network topology with different node densities.

source and destination. To further discuss the reason of this phenomenon, we next evaluate the throughput over different numbers of disjoint routes from source to destination to check whether opportunistic routing depends on the number of available disjoint routes.

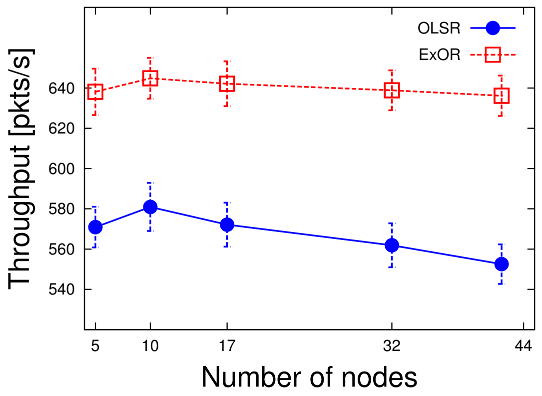

Figure 4: Throughput of ExOR and OLSR at different node density.

5.3 Number of routes

To see the effect of different numbers of disjoint routes from source to destination, we define the network in Figure 6. This means that we deploy three network topologies using different numbers of intermediate nodes to make the source-destination route numbers equal to 1, 3 and 5. These three topologies include only the intermediate nodes of route 1, routes 1 & 2 & 3, and routes 1 & 2 & 3 & 4 & 5 respectively, as shown in Figure 6. Figure 5 plots the throughput of ExOR and OLSR for different source-destination route numbers, using a default channel transmission rate of 6 Mbps. From the plots we can see that for ExOR the throughput is maximized when only one route is available between source and destination. To see the possible reasons of this phenomenon, we plot the average number of packet collisions that are encountered at different nodes within the 5-routes topology. The results are shown in Figure 7, with a confidence interval of 95%. As we can see, the 5-routes topology is a symmetric deployment of nodes. The average number of collisions encountered at the different nodes are distributed symmetrically in most cases, i.e., node-pairs 8-13, 10-11, etc. Most collisions happen at the nodes that are suffering the severest medium access contention, i.e., nodes 13, 8, 11 and 10, which are concurrently within the radio range of three different neighbors. The high number of collisions encountered at nodes 13, 8, 11 and 10 might be the reason for the phenomenon that ExOR performs best when only one route is available. Nodes 13-11 and 8-10 are the bottlenecks of routes 2/4 and routes 3/5 respectively. The same explanation could be applied to the very high collision number at node 1, which is the bottleneck of route 1.

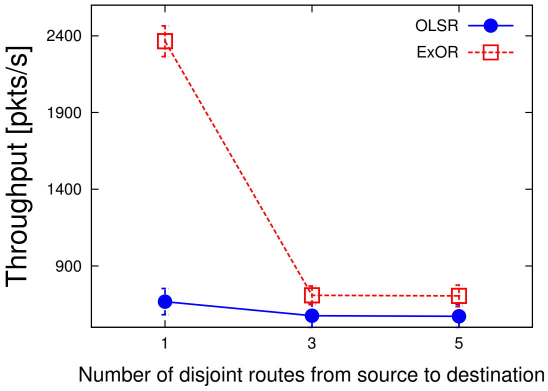

Figure 5: Throughput of ExOR and OLSR with different number of disjoint routes from source to destination in Figure 6.

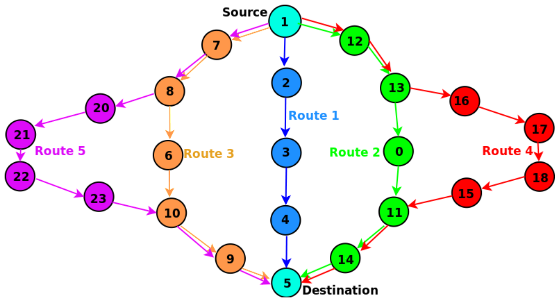

Figure 6: Network topology of different number of disjoint routes from source to destination.

As we can observe, results in Figure 4 show that the throughput of ExOR almost does not change with additional candidate nodes. However, Figure 5 reveals that network throughput drastically degrades by adding more nodes and by providing more routes from source to destination. The explanation for this observation might be as follows: when adding more nodes in Figure 3 more joint routes from source to destination are set up and there are no bottleneck nodes within the network. However, when introducing more nodes in Figure 6 to set up more disjoint routes from source to destination, bottleneck nodes will appear, i.e., node 8 and 13, which will restrict the performance of the network. For example, when the bottleneck nodes in Figure 6 suffer from high contention, the network throughput degrades significantly. Therefore, more routes may increase or decrease the throughput depending on the topology and where the bot-

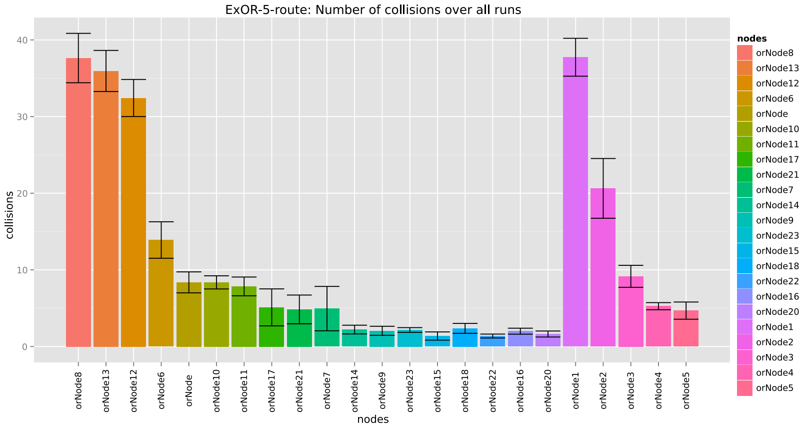

Figure 7: Average number of collisions encountered at different nodes at Figure 6 with route number = 5.

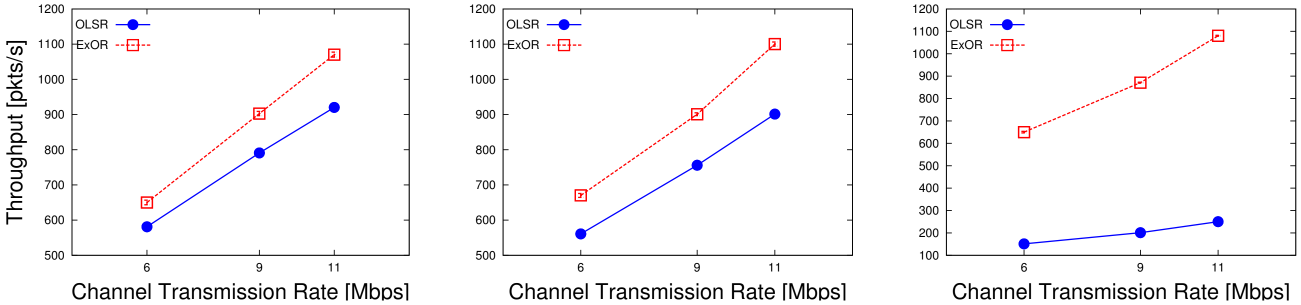

Figure 8: Throughput of ExOR and OLSR under different transmission rate scenarios with different channel quality(Left: good quality with $\alpha = 2$, Middle: medium quality with $\alpha = 3$, Right: bad quality with $\alpha = 4.5$)

tleneck nodes reside.

5.4 Channel quality

The high loss rates in wireless networks (e.g., 20-40% as observed in several deployments [21]) make traditional routing inefficient. To achieve better performance, opportunistic routing exploits communication opportunities that arise by chance due to the broadcast nature of the wireless medium. When a sender broadcasts its data, any node that hears the transmission may forward the data toward the destination. Although individual nodes may experience high loss rates, as long as there exists one forwarder that is closer to the destination and receives the transmission successfully, the date could move forward. In this way, opportunistic routing can efficiently combine multiple weak links into a strong link. To see how opportunistic routing makes use of poor channels, we need to know first what is the effect of channel quality on the performance of opportunistic and traditional routing mechanisms. To see this, the parameter of path loss alpha is varied between 2, 3, and 4.5, to represent the channels of good, medium and bad quality respectively.

We use the network topology of 17 nodes in Figure 3. We vary the channel transmission rate at the source between 6 Mbps, 9 Mbps, and 11 Mbps to see the superior performance of ExOR with different channel qualities. The results are shown in Figure 8 and Figure 9. As expected, ExOR behaves better than OLSR in all situations of 6 Mbps, 9 Mbps and 11 Mbps. An interesting observation is that the performance of OLSR significantly degrades when channel quality gets worse, while ExOR shows a stable performance under different channel conditions. The superiority of ExOR increases as the channels become worse. When the channel quality degrades, OLSR nodes suffer from an increased number of packet retransmissions and performance degrades, while the diversity of multiple neighbors in ExOR will alleviate this problem to some degree. Therefore, the performance gain of opportunistic routing will increase in a lossy wireless environment.

6. CONCLUSIONS

In this work, we have presented a framework implemented in the OMNeT++ simulator for facilitating the implementation of opportunistic routing protocols. The framework decouples opportunistic routing into four general steps and abstracts them as virtual functions. Some other functions shared by most opportunistic routing protocols are also included in the framework. Using the framework, we implemented two opportunistic routing protocols, ExOR and MORE. Detailed simulations analyze the performance of ExOR and MORE. They justify in which situations opportunistic routing may be more beneficial compared to traditional MANET routing mechanisms. Compared with the work in [22], we give a detailed comparison of the most representative opportunistic (ExOR and MORE) and proactive (OLSR) routing protocols. Their comparison is based on two general opportunistic and geographical routing protocol implementations. We can not confirm some of their original observations. They conclude that opportunistic routing makes sense under low traffic scenarios (inter-packet generation interval bigger than 1 second). This statement does not hold for ExOR and MORE, since the batch transmission mechanism they deploy will send packets continuously

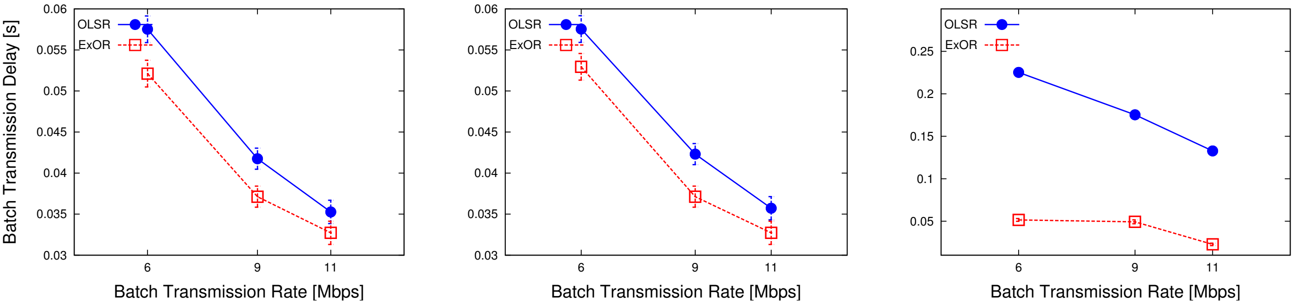

Figure 9: Batch transmission delay of ExOR and OLSR under different channel quality (Left: good quality with $\alpha = 2$, Middle: medium quality with $\alpha = 3$, Right: bad quality with $\alpha = 4.5$)

without any delay.

Opportunistic routing may achieve significant performance gain in a lossy wireless environment, and it will reach an improvement for high channel transmission rate scenarios. The number of potential forwarders has strong influence on performance. A large number of potential forwarders may introduce collisions that will eliminate the benefits it introduces.

Acknowledgment

This work is partly supported by the Swiss National Science Foundation under grant number 200021-130211.

7. REFERENCES

[1] A. Varga. The omnet++ discrete event simulation system. *Proceeding of European Simulation Multiconference*, June 2001.

[2] Inetmanet framework for omnest/omnet++ 4.x. *https://github.com/inetmanet/inetmanet/*, 2001.

[3] Inet framework. *http://inet.omnetpp.org/*.

[4] M. Heissenbüttel, T. Braun and M. Wälchli. BLR: beacon-less routing algorithm for mobile ad hoc networks. *Elsevier's Computer Communications Journal*, 2004.

[5] S. Biswas and R. Morris. ExOR: Opportunistic routing in multi-hop wireles networks. *Proceedings of ACM SIGCOMM*, Philadelphia, Pennsylvania, August 2005.

[6] S. Chachulski. Trading structure for randomness in wireless opportunistic routing. *Proceeding of ACM SIGCOMM*, 2007.

[7] C. Westphal. Opportunistic Routing in Dynamic Ad Hoc Networks: the OPRAH protocol. *Proceeding of IEEE International Conference on Mobile Ad Hoc and Sensor Systems*, 2006.

[8] Y. Yan, B. Zhang, J. Zheng and J. Ma. CORE: A Coding-aware Opportunistic Routing Mechanism for Wireless Mesh Networks. *Journal of IEEE Wireless Communications*, 2010.

[9] Z. Zhong, J. Wang and S. Nelakuditi. Opportunistic Any-Path Forwarding in Multi-Hop Wireless Mesh Networks. *USC CSE Technical Report*, 2006.

[10] S. Katti and D. Katabi. Symbol-level network coding for wireless mesh networks *Proceeding of ACM SIGCOMM*, Seattle, WA, USA, August 2008.

[11] T. Clausen, P. Jacquet, A. Laouiti, P. Muhlethaler, a. Qayyum and L. Viennot. Simple opportunistic routing for wireless mesh networks. *Wireless Mesh Networks*, 48-54, Reston, VA, USA, 2006.

[12] A. Zubow and M. Kurth. Multi-channel opportunistic routing. *European Wireless*, 2007.

[13] A. Keränen and J. Ott and T. Kärkkäinen. The ONE Simulator for DTN Protocol Evaluation. *SIMUTools '09: Proceedings of the 2nd International Conference on Simulation Tools and Techniques*, Rome, Italy, 2009.

[14] O.R. Helgason and K.V. Jonsson. Opportunistic Networking in OMNeT++ *SIMUTools '08: Proceedings of the 1st International Conference on Simulation Tools and Techniques*, 2008.

[15] K.V. Jonsson. A Gateway for Wireless Dissemination of Delay-Tolerant Content. *Master Dissertation*, 2008.

[16] V. Kawadia, Y. Zhang and B. Gupta. System Services for Ad-Hoc Routing: Architecture, Implementation and Experiences. *MobiSys '03: Proceedings of the 1st international conference on Mobile systems, applications and services*, 2003.

[17] U. Correa, C. Montez, V. Mazzola, M. A. R Dantas. Frad-Hoc: A Framework to Routing AD-Hoc Networks. *IFIP International Federation for Information Processing*, Vol. 212, page 71-82, 2006.

[18] A. Ariza-Quintana, E. Casilari and A. TriviÃśo Cabrera. Implementation of MANET routing protocols on OMNeT++. *SIMUTools '08: Proceedings of the 1st International Conference on Simulation Tools and Techniques*, 2008.

[19] N. Gazoni, V. Angelakis, V. A. Siris and B. Raffaele. A framework for opportunistic routing in multi-hop wireless networks. *PE-WASUN '10: Proceedings of the 7th ACM workshop on Performance evaluation of wireless ad hoc, sensor, and ubiquitous networks*, 2010.

[20] Z. Zhao and T. Braun. OMNeT++ based Opportunistic Routing Protocols Simulation: A Framework. *ADHOC '11: 10th Scandinavian Workshop on Wireless Ad-hoc Networks*, 2011.

[21] D. Aguayo, J. Bicket, S. Biswas, G. Judd and R. Morris. Link-level measurements from an 802.11b mesh network *Proceeding of ACM SIGCOMM*, 2004.

[22] R.C. Shah, S. Wietholter, A. Wolisz and J.M. Rabaey. When does opportunistic routing make sense? *PERCOM '05: Proceedings of the 3rd International Conference on Pervasive Computing and Communication*, 2005.