FOMR: Fair Opportunistic Multicast Routing Scheme for Wireless Mesh Networks

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Abstract. Opportunistic routing has recently attracted much attention as it is considered to be a promising direction for improving the performance of wireless adhoc and sensor networks. It exploits the broadcast nature of the wireless network. Multicast is an important communication paradigm in wireless networks. The availability of multiple destinations in a multicast tree can make the selection of forwarder candidates, distributed coordination among them and related prioritization complicated. Thus far, little work has been done in this area. Selection of an appropriate metric is very important for designing the opportunistic routing scheme.In this paper, we propose an efficient multicast scheme based on opportunistic routing and network coding that uses STR as a metric. The mathematical analysis shows that STR based FOMR scheme always outperforms ETX based OM.

Keywords: Opportunistic routing, multicast, network coding, metric.

1 Introduction

Wireless Mesh Networks (WMNs) are designed to provide resilient, robust and high-throughput data delivery to wireless subscribers. They are widely deployed in many scenarios such as campus networking, community networking and so on. Previous works on traditional routing protocols mainly focus on providing robust routing by selecting the best route according to different routing metrics. In such protocols the approach to routing traffic is to select a best path for each source- destination pair(according to some metric) and send the traffic along the predetermined path. Most of the existing protocols such as DSR[11], AODV[12], DSDV[14], and ZRP[10] fall into this category. Recent studies have shown that this strategy doesn't adapt well to the dynamic wireless environment where transmission failures occur frequently, which would trigger excessive link level retransmissions, waste of network resources or even system breakdown.

Opportunistic Routing (OR) is a new class of wireless technology that exploits the broadcast nature of the wireless medium and defers route selection after packet transmission. Here any node overhearing a transmission is allowed to participate in the packet forwarding thereby increasing the reliability of the transmission. It is able

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to combine multiple weak links into a stronger link. A forwarder set is maintained for each flow. Any packet in the flow may use all the nodes in the forwarding list and the nodes in the list are prioritized with some metric.

Each node only forwards the packets which have not been received by any high priority node. So this needs multiple forwarding nodes to coordinate among themselves when only one of them actually forwards the packets. Network coding seminally proposed by Ahlswede et al[3] can fully utilize the opportunistic listening and creates an encoded packet, so it is complementary to OR.

Multicasting is a method of communication by which an identical message is sent to multiple receivers. Its main applications are videoconferencing, teleconferencing, content distribution, remote teaching and so on. Till date, the protocols proposed for opportunistic multicasting such as Opportunistic Multicast (OM) protocol have used ETX as their metric[8]. ETX being an unfair metric doesn't consider multiple links information for each forwarder so it doesn't always make good decision. This results in non-optimal forwarder set selection that directly causes many duplicate transmissions. On the contrary, STR exploits multiple links and is calculated from the destination to the source node so it offers an optimal forwarder set that minimizes the average number of transmissions required to send a packet and the number of duplicate packets received by the destination thus increasing the throughput.

The rest of the paper is organized as follows. In section 2, we survey the related work and motivate opportunistic routing. Section 3 presents our proposed FOMR scheme. In section 4 we have given the mathematical proof to support our proposed work. Finally we conclude our work in section 5.

2 Related Work

Opportunistic routing was introduced by Biswas and Morris, whose paper explains the potential throughput increase and proposes the Ex-OR protocol as a means to achieve it[1]. Since then several protocols have been proposed that exploits the concept of OR for communication in wireless networks [2, 6, 9, 15, 16]. For opportunistic multicasting, researchers have already adopted an approach in which network coding is combined with opportunistic routing to support multicast traffic. But since the metric they have used is an unfair metric, it increases duplication and thus reduces throughput. Our work builds on this foundation but adopts a fundamentally different approach. It uses a fair metric Successful Transmission Rate (STR) instead of an unfair metric Expected Transmission Rate(ETX) to increase the throughput of the transmission. The resulting protocol is practical, allows spatial reuse and supports both unicast and multicast traffic.

Unfair OR scheme builds a candidate forwarder set in which many forwarders are prioritized with order. The higher priority indicates that the node is closer to destination. The higher prioritized node is entitled to send the packets it received and the rest of the nodes have to wait and listen to it. So that every node only forwards the packets that have not been received by any higher priority node. Fair OR scheme also builds a candidate forwarder set but all the nodes in it are fair without any priority. The set just includes some nodes closer to the destination than the source.

OR differs from traditional routing in that it exploits the broadcast nature of wireless medium and defers route selection after packet transmission. This can cope well with unreliable and unpredictable wireless links. There are two major benefits in OR. Firstly it doesn't compromise the reliability factor over the progress made in a transmission.

A → B → C → D → E

If A sends a packet to E via B, C, D then reliability is high but the progress made is less in each step. Instead if it sends packet directly to C then progress is high but reliability goes low. However in OR the packet is broadcasted to all nodes. All the nodes coordinate among themselves to decide which node is closer to E and the rest of the nodes will then drop the packet.

Secondly it takes advantage of the multiple links. It combines multiple weak links to form a stronger link.

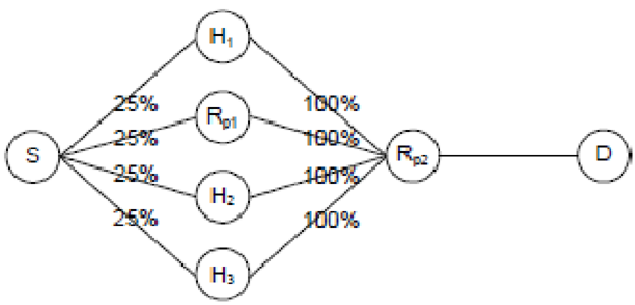


Fig. 1. Probability of sending data frames from source to Rp2

As shown in fig1 the probability of successfully delivering packets between S and the relay nodes is 0.25 and between the relay nodes and the node Rp is 1. In this case the expected number of transmissions required to send a packet from node S to Rp is equal to 5. However in OR all the four relay nodes will coordinate to deliver the packet. So the number of transmissions will reduce to (1/(1-(1-0.25)4))+1 i.e. 2.5 transmissions.

Work on network coding started with a pioneering paper by Ahlswede et al that established the value of coding in the routers and provided theoretical bounds on the capacity of such networks[3]. Besides the metric that we shall be using is STR proposed in 2009[7].It has shown that STR is a better metric when used with a fair scheme like MORE [15] or OM [8]. The paper has given that one can achieve 30% more throughput by using STR as a metric.

3 FOMR : Fair Opportunistic Multicast Routing Protocol

In this section, we will introduce a new multicasting protocol based on opportunistic routing and network coding based on STR.

3.1 Overview

FOMR scheme is based on proactive link state routing. Every node periodically measures and disseminates link quality in terms of STR. Based on this information, a multicast source selects the default multicast routing path employing the existing Steiner Tree algorithm [4,5] and a list of forwarding nodes that are eligible for forwarding the data packets. It then uses network coding to make coded packets and broadcasts them.

3.2 Steiner Tree Construction

To support opportunistic multicast routing, each node maintains a routing table consisting of three fields: multicast group, default path and the forwarder set where the default path is the average shortest cost path from the sender to the corresponding sub-group in terms of STR and forwarding list includes a list of next hop nodes that are eligible to forward the packet. We now explain how STR is computed for each node and the default multicast routing tree construction.

3.2.1 Computation of STR

STR denotes the expected Successful Transmission Rate between a certain node and the destination. Each node calculates its STR to the destination and chooses some of the neighbours with the higher STR values into its forwarder set.

The exact approach used to calculate STR is:
If the node X and the destination are within one hop, the STR of node X is

$$STR_X = P_{XD}$$

If there are two hops between node X and the destination, the STR of node X is

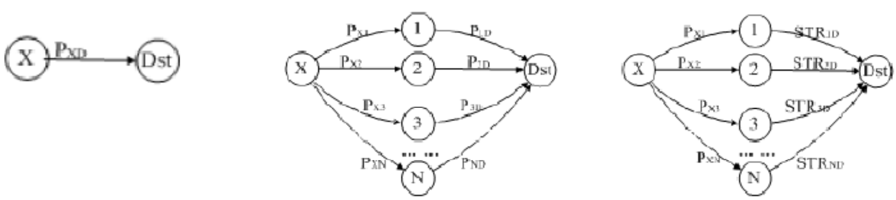
$$STR_X = P_{X1}P_{1D} + \sum_{i=1}^{N} P_{Xi}P_{iD} \prod_{j=1}^{i-1} (1-P_{Xj})$$

If there are more than two hops between node X and the destination then the STR of node X is

$$STR_X = P_{X1}\, STR_{1D} + \sum_{i=1}^{N} P_{Xi}\, STR_{iD} \prod_{j=1}^{i-1} (1-P_{Xj})$$

(the corresponding figures are shown below)

so a node needs to know its one-hop forwarder's STR values to calculate its own STR value.



3.2.2 Default Multicast Path

To construct the Steiner tree and to get the default multicast path, every node calculates STR values of the links using the formulae given in the section 3.2.1. After computing the STR values of each link of the network, a Steiner tree denoting the multicast default routing path is obtained by applying the existing Steiner tree algorithm [4]. The Steiner tree algorithm is used to find the shortest interconnect for a given set of nodes. It is similar to minimum spanning tree except that in Steiner tree, extra intermediate vertices and edges may be added to the graph in order to reduce the length of the spanning tree. The Steiner tree helps the source to know the number of number of packets it needs to multicast via the existing default delivery tree to multiple forwarding set.

3.3 Forwarder Set Selection

Forwarding node selection is critical to the performance of FOMR protocol just like other unicast opportunistic routing protocol such as ExOR, MORE and SOAR and so on. In order to leverage path diversity while avoiding duplicate transmissions, FOMR protocol relaxes the actual route that data traverses to be along or near the default delivery tree. FOMR protocol constrains the nodes involved in routing a packet to be near the default multicast distribution tree. This prevents routes from diverging and minimizes duplicate transmissions. Moreover, this forwarding node selection also simplifies coordination since all the nodes involved are close to nodes on the default delivery tree and can hear each other with a reasonably high probability. Therefore, we can use overheard transmissions to coordinate between forwarding nodes in a cheap and distributed way.

Forwarding set selection algorithm consists of two steps. First, a sender selects an initial forwarding list based on the default multicast delivery path. Then, it further limits the number of forwarding nodes to minimize duplicate transmissions. These steps are taken by a sender on each packet, allowing for the forwarding set to quickly adapt to network conditions.

When node i is on the default multicast delivery path, i selects the forwarding nodes that satisfy the following conditions:

• The forwarding node's STR to the multicast sub-group is higher than i's STR to the Multicast sub-group.

• The forwarding node's STR to i is within a threshold.

The first constraint ensures that the packet makes progress. The second constraint ensures that i hears the forwarding node's transmissions with a high probability to avoid duplicate retransmissions.

Since not only should we ensure that forwarding nodes make progress and have sufficiently good link quality from node i, but also we want the selected forwarding nodes to be adjacent to the default multicast delivery path and every pair of forwarding nodes has sufficiently good luck quality between them to avoid diverging paths. This results in the following two additional constraints in selecting forwarding nodes.

• Each forwarding node is close to at least one node on the default multicast delivery tree branch representing some multicast sub-group.

• The STR of a link between any pair of forwarding nodes in the same forwarding list is within a threshold.

These constraints ensure that forwarding nodes have good connectivity among themselves and to nodes on the default multicast delivery tree branch.

3.4 The Operation of FOMR Protocol

In this section we shall explain the working of FOMR protocol.

3.4.1 Packet Coding and Multicasting

The source breaks up the file into batches of K packets, where *K* may vary from one batch to another. These K uncoded packets are called native packets. When the 802.11 MAC is ready to send, the source creates a random linear combination of the K native packets in the current batch. A coded packet is $p_j' = \sum i \; c_{ji} \, p_i$, where the c_{ji} 's are random coefficients picked by the node, and the p_i 's are native packets from the same batch.

We call $c_j =(c_{j1},\ldots,c_{ji}\ldots,c_{jk})$ the code vector of packet p_j' . Thus, the code vector describes how to generate the coded packet from the native packets. After the creating of encoded packet, the source multicasts the coded packet via the existing default multicast delivery tree to multiple forwarding set determined by the degree of the source. The sender keeps transmitting coded packets from the current batch until the batch is acknowledged by the farthest destination of the multicast group, at which time, the sender proceeds to the next batch.

3.4.2 Multicast Forwarding

Nodes listen to all transmissions. When a node hears a packet, it checks whether it is in the packet's forwarder list. If so, the node checks whether the packets contains new information, in which case it is called an innovative packet. Technically speaking, a packet is innovative if it is linearly independent from the packets the node has previously received from this batch. The node ignores non-innovative packets, and stores the innovative packets it receives from the the current batch. If the node is in the forwarder list, the arrival of this new packet triggers the node to broadcast a coded packet. To do so the node creates a random linear combination of the coded packets it has heard from the same batch and broadcasts it. Note that a liner combination of coded packets is also a linear combination of the corresponding native packets. Similar to the source, the forwarder forwards the multicast packet to multiple different forwarding set according to the degree of the forwarder locating at the current passion of the multicast delivery tree. That is the number of different forwarding set is determined by the number of branch of leaving the forwarder. The construction of forwarding set is formulated by the above mentioned forwarding set selection rules.

3.4.3 Acknowledgement

For each packet it receives, each destination of the multicast group checks whether the packet is innovative, i.e. it is linearly independent from previously received packets. The destination discards non-innovative packets. Once the destination receives K innovative packets, it decodes the whole batch using simple matrix inversion:

$$\begin{pmatrix} p_1 \\ \cdots \\ p_k \end{pmatrix} = \begin{pmatrix} c_{11} \cdots c_{1k} \\ \cdots\cdots\cdots \\ c_{k1} \cdots c_{kk} \end{pmatrix}^{-1} \begin{pmatrix} p_1^{'} \\ \cdots \\ p_k^{'} \end{pmatrix}$$

where, p_i is a native packet, and $p_i^{'}$ is a coded packet whose code vector is $c_i = (c_{i1}, \ldots, c_{ik})$. As soon as the farthest destination decodes the batch, it sends an acknowledgment to the source to allow it to move to the next batch. ACKs are sent using best unicast path routing and also given priority over data packets at every node.

4 Mathematical Proof

In this section we shall show the performance of STR over ETX using two different approaches.

4.1 In the first approach, we will take a network topology to show that STR based FOMRS outperform ETX based OM protocol. The parameters that we shall consider for comparison are the average number of transmissions required to send a packet from the source to the destination and the number of distinguished packets received by the destination in each case.

Consider the network topology given in fig2 where delivery probability of every link and the corresponding ETX values of the nodes are marked. S denotes the source and Dst refers to the destination. Rest of the nodes are the relay nodes that will coordinate in the transmission of a packet from S to Dst.

Let us first compute the ETX and STR values of all the nodes and figure out the forwarder set in each case.

a) Using ETX

ETX value is calculated using the delivery probability of the link :

Node	S	A	B	C	D	E	F	G	Dst
ETX	3.75	2.58	2.58	2.50	1.25	1.33	1.25	1.25	1

Now since ETX is an unfair metric, it will prioritize the nodes based on their ETX values. The node with lower ETX value will get priority over one with higher ETX value as ETX denotes the expected number of total transmissions required to send a packet. So the source will select its forwarder set as {C, A, B} or {C, B, A}. This means most of the packets will be transferred through C.

b) Using STR

STR denotes the total number of successful transmissions out of total transmissions in a packet transmission. So node with higher value of STR will get priority over the node with lower STR value.

STR values can be computed using the formulae given in section 3.2.1 so

node	S	A	B	C	D	E	F	G
STR(%)	70.84	74	60	64	80	75	80	80

So using the algorithm of forwarder set selection with STR metric[7] , the forwarder set of S comes out to be {A, B, C}.

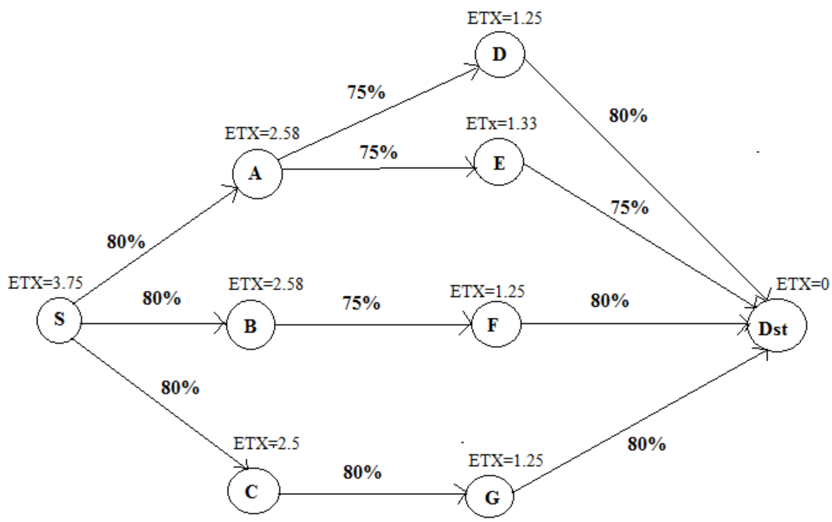


Fig. 2. Network topology with ETX values marked

Analysis:

We will now compare the two forwarder set selected on the basis of:

a) Distinguished packets

Using the STR concept, we found that the number of distinguished packets received by the destination through A are 74 while the number of distinguished packets received through C are 64 only. This gives an increment of about 10.68%.

This means A can forward more packets (Distinguished) than C. So our STR based FOMRS will have more throughput than ETX based OM protocol.

b) Average number of transmissions required

Average number of transmissions required to send a packet from source to destination through A will be 3.368.

Average number of transmissions required to send a packet from source to destination through C will be 3.75.

As is clear from the values above the average number of transmissions required to send a packet using STR is less than ETX based forwarder set.

4.2 In the second approach, we consider a set V of $n = |V|$ wireless nodes deployed in a given area. Each node has a unique identifier $vi \in \{v1, v2, \ldots, vn\}$ and has an omnidirectional antenna. We model the network with a probabilistic direct graph: $G = (V,L,D)$ in which a vertex $vi \in V$ denotes a node and an edge $li,j \in L$ represents a communication link from node vi to node vj Each link li,j is characterized by a delivery ratio $di,j \in D$, which measures the probability that a packet is correctly received in a single transmission along such a link. Clearly, we have that $di,i = 1$.

Let $s, d \in V$ be the source and the destination of a packet transmission respectively, and let $f : V \times V \rightarrow R$ be the priority function2, i.e. the function that measures the routing progress of a packet toward the destination. We define the ordered set of the allowed relays $r_i \in V$ for the packet sent by s toward d as:

$\mathbf{R_{s,d}} = \{S=r_0,r_1,\ldots\ldots r_N,r_{N+1=d}\}$ for all i <= j

$P_{ri,rj}=\{d_{ri,rj} \prod_{k=j+1}^{N+1} (1-d_{ri,rj})\}$ for all i<=j … .(A)

$P_{ri,rj}=0$ for all i>j .....(B)

R is the relay node set and $P_{ri,rj}$ represents the probability with which node j will receive the packet from I to forward it further.

Now, average number of transmissions is given by equation:

$$n_{s,d}=1/1-p_{s,s} \quad [\, 1+ \sum_{k=1}^{N} p_{s,rk} \quad n_{rk,d} \,] \tag{1}$$

and,

$$n_{rk,d}= 1/1-p_{rk,rk}\ [1+ \sum_{l=k+1}^{N} p_{rk,rl}\ n_{rl,d}] \tag{2}$$

Analysis:

We will now derive an expression for average number of transmissions in both cases

a) For ETX

Average number of transmission can be derived using equations (1) and (2) as:

For ETX, delivery ratio between any two nodes is given by the expression

$d_{rk,d} = \quad 1/1-p_{rk,d}$ where

$$p_{s,s}= d_{s,s}\ (1-d_{s,r1})\ (1-d_{s,r2})\ldots\ldots\ldots (1-d_{s,rd})$$
$$= 1.\ (1-1/p_{s,r1})\ (1-(1/p_{s,r1}\ .\ 1/p_{r1,r2}))\ldots\ldots\ldots (1-ETX_{s,d})$$
$$=K_1(1-ETX_{s,d}) \quad \text{where K1 is a constant}$$
$$= K_1-K_1\ ETX_{s,d} \tag{3}$$

Similarly,

$$P_{s,rk}= K_2-K_2\ ETX_{s,d} \tag{4}$$

and similarly we have $P_{rk,rk} = K_3$

Now, substituiting the values found in eq. (3)and (4) in eq. (1) and (2), we get,

$$n_{s,d} =[\ 1/1-(K_1-k_1ETX_{s,d})][\{1+\sum_{k=1}^{N} \ (K_2-k_2ETX_{s,d})\}\ \{(1/1-k_3)(1+ \sum_{l=k+1}^{N} \ k_3\ n_{rl,d})\ \}] \tag{5}$$

$$n_{rl,d}= [1/1-p_{rl,d]}\ [1+ \sum_{k=1}^{N} \ p_{rl,k}\ n_{rk,d}]$$
$$= \ [1/1-(k_1' - k_1' ETX_{s,d})]\ [1+ \sum_{k=1}^{N} \ p_{rl,rk}\ n_{rk,d}] \tag{6}$$

On solving, we get

$$n_{s,d} = [1/1-(k_1-k_2\ ETX_{s,d})\ ]\ [\{1+ + \sum_{k=1}^{N}\ (K_2-k_2ETX_{s,d})\}\ \{(1/1-k_3)(1+ \sum_{l=k+1}^{N}\ k_3\ [1/1-(k_1' - k_1' ETX_{s,d})]\ \ [1+ \sum_{k=1}^{N}\ p_{rl,rk}\ n_{rk,d}]\ \}] \quad (7)$$

b) For STR

Equation (7) can be modified by considering formulae of STR as given in the section 3.2.1.Putting these values in equation (1) and (A) for each ETX in it, we get $P_{s,s}= 1. (P_{s,r1})(P_{r1,r2})\ldots\ldots\ (P_{r(n-1),rn}) = C$ where C= constant integer <= 1

Using above value, we get

$$n_{s,d} = C' [1+\sum_{K=1}^{N} P_{s,rk}\ n_{rk,d}\ ]$$

Where $C' = 1/1-C$

$$n_{s,d}=C'[1+\sum_{K=1}^{N}P_{s,rk}\{STR_{x-x1,\ldots..xn,d}\}] \quad (8)$$

As can be concluded by considering equation (7) and (8) average number of transmissions is more in ETX than that required by STR.

5 Conclusion

In this paper, we proposed an efficient multicast protocol based on the opportunistic routing and network coding that uses STR as a metric Mathematical analysis reveals that the performance of the STR based FOMR protocol outperforms the conventional multicast protocols based on ETX in wireless mesh networks. It can improve the network performances, in terms of throughputs and the packet transmission cost. In the future work, we will continue to investigate the opportunistic multicast routing protocols . We will try to improve upon the acknowledgement scheme and the default path selection algorithm that will increase the reliability of FOMR protocol.

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