Multi-rate Combination of Opportunistic Routing and Network Coding: An Optimization Perspective

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Abstract— **Recently, wireless communication methods that exploit the broadcast nature of the wireless medium have been attracting growing attention. Among these methods, opportunistic routing and network coding are regarded as the most promising techniques. While there have been some attempts to combine opportunistic routing with network coding to capture the advantages of both techniques, none of these attempts has considered bit-rate selection for data transmission in multi-rate wireless networks. In this paper, we study the potential benefits of the combination of opportunistic routing and network coding with the bit-rate selection mechanism from an optimization perspective. We develop a theoretical model and algorithm for finding the optimal forwarding scheme for a multi-rate combination of opportunistic routing and network coding in a given network. MIT Roofnet trace-based simulations show that considering bit-rate selection in combination with opportunistic routing and network coding has substantial benefits in terms of the expected transmission time compared to multi-rate opportunistic routing, multi-rate network coding, and a fixed-rate combination approach.**

Keywords-Opportunistic routing, Network coding, Coding-aware opportunistic routing, Dynamic bit-rate selection

I. INTRODUCTION

Since the introduction of broadcast-based transmissions in wireless networks, it has been possible for all neighbors of a transmitting node to overhear a node's transmission. Recent research papers have proposed several opportunistic routing and network coding protocols for improving the throughput in wireless networks by exploiting the broadcast nature of wireless networks.

Opportunistic routing exploits the broadcast nature of the wireless medium. While traditional routing determines a next-hop with a fixed routing path, opportunistic routing does not explicitly select a next-hop. Instead, a sender broadcasts its data. Then, among the nodes that can overhear the transmission, the closest one to the destination is selected to forward the data. In this way, opportunistic routing utilizes transmissions that have reached unexpectedly far or near to increase the network throughput.

The concept of network coding originally comes from information theory, and original works are targeted at the multicast issue in wired networks. Based on this concept, network coding protocols for wireless networks have been proposed. In network coding, data packets from different flows are mixed at an intermediate node, thereby allowing a single transmission to hold the contents of two or more packets for different receivers. This can improve the capacity of wireless networks, which eventually increases the throughput in wireless networks.

While both approaches exploit the broadcast nature of the wireless medium, they target different network conditions. Opportunistic routing targets a low-quality wireless environment that has error-prone channels. In contrast, network coding shows the best performance in the error-free channel with multiple simultaneous flows. We can naturally raise the question of whether the combination of both techniques can improve the performance of practical wireless networks that have both low-quality links and multiple simultaneous flows. There have been a few studies on the combination of opportunistic routing and network coding [4-6]. They have the following limitations: they assumed a fixed bit-rate and they do not consider the effect of bit-rate selection, which affects the performance of protocols.

If a sender transmits a packet at a low bit-rate, the packet may be heard by some distant nodes. However, it will occupy the wireless channel for a long period. Conversely, if the sender transmits a packet at a higher bit-rate, the packet loss probability will be high and the number of potential receivers might be low. However, the channel will be occupied for a short period. Therefore, the bit-rate used for transmitting packets significantly affects the throughput of any routing protocol in wireless networks.

In this paper, we evaluate the multi-rate combination of opportunistic routing and network coding from an optimization perspective. The main contributions of this study are as follows. First, we develop a theoretical model of a multi-rate combination of opportunistic routing and network coding to derive the expected transmission time in a given network topology. Second, we define finding the optimal forwarding scheme for the combination as a minimization problem and develop an algorithm for finding the optimal solution for the problem. MIT Roofnet [11] trace-based simulation results show that multi-rate combination outperforms separate multi-rate network coding and multi-rate opportunistic routing. The proposed multi-rate combination also shows better performance than the fixed-rate combination of network coding and opportunistic routing protocols.

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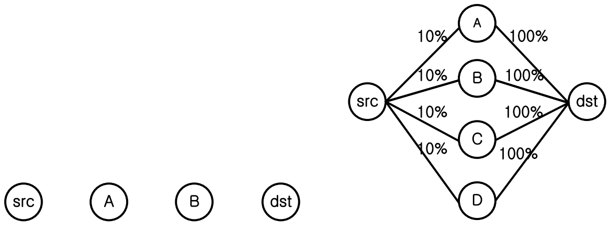


(a) Opportunistic progress (b) Independent forwarders

Fig. 1. Example of benefit of opportunistic routing

II. BACKGROUND AND RELATED WORK

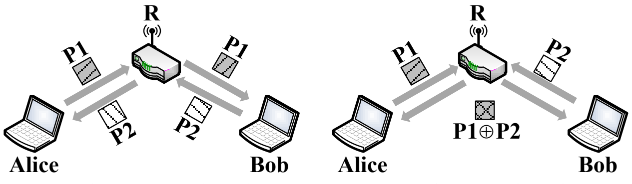
In this section, we briefly introduce the background and related work on opportunistic routing, network coding, and network coding-aware routing.

A. *Opportunistic routing*

Figure 1 shows how opportunistic routing can improve the performance in wireless networks. Consider the network shown in Figure 1(a), where *src* sends data to *dst* with intermediate nodes A and B. Assume that the packet delivery probability between two nodes decreases as the distance increases. In traditional routing, *src* must select its next-hop node among A and B. If A is used as the next-hop node and the quality of the link *src-A* is good, then the number of retransmissions required to deliver the packet to A is small, even though the progress made is small. Alternatively, if B is chosen as the next-hop node, the packet can make more progress. However, if the link quality of *src-B* is poor, multiple retransmissions may be required to deliver the packet. In contrast, opportunistic routing does not fix the next-hop node before transmission. Among the nodes that receive the packet, we choose the one closest to the destination to forward the packet toward the destination. In this way, we can exploit unexpectedly far or near transmissions, thereby achieving high throughput.

Another benefit of opportunistic routing is that each transmission may have more independent chances of being received and forwarded. Consider the scenario shown in Figure 1(b), where the number on each link represents the packet delivery probability of the link. The delivery probability from *src* to each intermediate node is 10%, and the delivery probability from each intermediate node to the destination is 100%. In traditional routing, since all data are forwarded through the same intermediate node, each packet is sent ten times on an average before being received by the intermediate node. However, in opportunistic routing, the probability of successful packet reception by any intermediate node is $1-(1-0.1)^4=0.34$. Thus, on an average, only $1/0.34=2.94$ transmissions are required for a packet to reach at least one of the four intermediate nodes.

Recently, several opportunistic routing protocols have been proposed. Extremely opportunistic routing (ExOR) [2] is a representative opportunistic routing protocol for wireless mesh networks. In ExOR, the sender selects a set of candidate forwarders before transmission. Each node in the forwarding set has a priority that is determined according to its closeness to the destination. Among the candidates that overhear a packet, the node with the highest priority forwards the packet toward the destination.



(a) Without network coding (b) With network coding

Fig. 2. Example of benefit of network coding

Reference [2] showed that ExOR increases throughput by a factor of two to four compared to traditional routing. However, ExOR does not take into account the availability of different bit-rates and hence may not select the best possible candidates. References [7] proposed a bit-rate selection mechanism for opportunistic routing protocols. Reference [7] mentioned that by considering rate selection in opportunistic routing, the proposed protocol has on an average 80% better performance than opportunistic routing with a fixed rate of 11 Mbps.

B. *Network coding*

As mentioned in Section I, network coding reduces the number of transmissions by encoding more than two packets into one packet, which increases network throughput. Figure 2 shows a simple example in which network coding outperforms traditional routing when Alice and Bob exchange packets $P1$ and $P2$ via relay node R. Without network coding, four transmissions are required for the packets to be exchanged, as shown in Figure 2(a). However, network coding can reduce the number of transmissions. R receives both packets, encodes them, and then broadcasts $P1\oplus P2$, as shown in Figure 2(b), which requires three transmissions. After receiving the coded packet, Alice and Bob can decode the packet by using the buffered packets $P1$ and $P2$, respectively.

Ahlswede et al. [1] published a pioneering paper that addresses the multicast capacity issue. COPE [3] is the first practical network coding protocol for wireless networks. COPE reduces the number of transmissions by allowing relay nodes to broadcast coded packets via wireless link, which increases network throughput. However, COPE's operations are independent of bit-rate selection for determining the route and transmitting packets, which limits its ability to achieve a high performance in a multi-rate scenario. To resolve this issue, a new metric called expected coded time (ECT), which considers possible gains from network coding with bit-rate selection, has been proposed [8]. ECT measures the total time needed by a node to deliver two packets to their receivers given a bit-rate for transmitting coded packets.

C. *Network coding-aware routing*

Network coding-aware routing protocols that aim at choosing paths that increase the coding opportunity have been proposed [9][10]. For instance, they modify the link metric to consider the potential coding opportunity in given traffic.

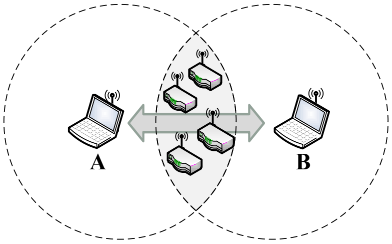


Fig. 3. Considered network model

However, they still choose a fixed routing path that limits coding chances.

To achieve more potential gain from network coding in path selection, a number of coding-aware opportunistic routing protocols that increase coding chances by choosing forwarders opportunistically have been proposed [4][5]. In [6], the authors modeled a coding-aware opportunistic forwarding scheme as an optimization problem and proposed a dynamic algorithm to solve the problem. However, it does not take into account the availability of different bit-rates, and therefore, it may not select the best possible candidate forwarders.

To the best of our knowledge, our paper is the first one to consider the combination of opportunistic routing and network coding with bit-rate selection mechanism from an optimization perspective.

III. MULTI-RATE COMBINATION OF OPPORTUNISTIC ROUTING AND NETWORK CODING

In this section, we propose a theoretical model for evaluating a multi-rate combination of opportunistic routing and network coding. Our model consists of two parts: one is the framework for the calculation of expected opportunistically coded transmission time (ExOCT), and the other is the algorithm for finding the optimal forwarding scheme to minimize ExOCT in a given topology. Before introducing the model, we briefly discuss our assumptions and the important concepts needed to understand the proposed model.

A. Network model and assumptions

We consider a network model with two wireless nodes (A and B) and K common neighbors between them, as shown in Figure 3. The dotted circles in the figure indicate the transmission ranges of nodes A and B. The two nodes continuously send fixed size packets to each other, but they cannot directly deliver packets to each other. Because of this, one or more neighbor nodes are selected as relay nodes. Let $P_{Y,X}$ denote the probability that node X in the network successfully receives or overhears a packet transmitted by node Y. We assume that in a given network, this probability is known in advance and that it is independent of different links. Further, for node X, if both $P_{A,X}$ and $P_{B,X}$ are above a certain threshold, then X is a common neighbor of A and B. There are K common neighbors and each neighbor is indicated by R_k, where $k = 1, \cdots, K$. All nodes are assumed to be stationary, like in a wireless mesh network.

TABLE I. EFFECTIVE SENDING RATE FOR 802.11B (IN MBPS)

Bit-rate	200 bits	1,000 bits	4,000 bits	12,000 bits
1 Mbps	0.5102	0.8389	0.9542	0.9843
2 Mbps	0.6849	1.445	1.825	1.938
5.5 Mbps	0.8758	2.675	4.351	5.055
11 Mbps	0.9516	3.535	7.199	9.354

In our study, we focus on 802.11b, which has a preamble time of 192 μs. Since the 802.11 physical layer preamble is transmitted at the lowest possible rate, we must take this into account when determining the effective bit-rate. Suppose that a packet size is 1,000 bits. At 1 Mbps, a duration of 1,000 μs is required to transmit the packet. However, including the 192 μs preamble, it takes a total of 1,192 μs. Thus, the effective bit-rate is 1,000 bits/1,192 μs = 0.8389 Mbps. Effective rates for 802.11b are summarized in Table I. In the paper, we use effective rates instead of original rates.

B. Network state vector and forwarding scheme

We define a node state as a set of packets a node received or overheard. In the network we are considering, the node state can be one element of $\{\phi, \{a\}, \{b\}, \{a, b\}\}$. The node state ϕ means that a node has not received any packets, and $\{a\}$ or $\{b\}$ means that a node has received packet a or packet b, respectively. The node state $\{a, b\}$ means that a node has received packets a and b individually or as a coded packet.

We also define the network state vector as a set of node states of all nodes in a network. The network state vector consists of $K + 2$ node states, and it is represented by $S = \langle S_A, S_B, S_{R_1}, \cdots, S_{R_K} \rangle$, where S_k is the node state of the node k. Moreover, $S_A \in \{\{a\}, \{a, b\}\}$, $S_B \in \{\{b\}, \{a, b\}\}$ and $S_{R_k} \in \{\phi, \{a\}, \{b\}, \{a, b\}\}$, where $k = 1, \cdots, K$. Furthermore, there are some invalid network state vectors that cannot occur in the network. For instance, the network state vector of $S_A = \{a, b\}$, $S_B = \{a, b\}$, $S_{R_1} = \phi, \cdots$, $S_{R_K} = \phi$ cannot exist since, according to our assumption, packets a and b must be relayed by some relay nodes in order to be successfully delivered to their destinations.

We also define initial state and terminated state vectors. The initial state vector, S_{init}, is the state vector for both nodes A and B before they start their transmissions, and is represented as $S_{init} = \langle \{a\}, \{b\}, \phi, \cdots, \phi \rangle$. Terminated state vectors are all state vectors with $S_A = S_B = \{a, b\}$, excluding invalid state vectors.

We modify the concept of the forwarding scheme introduced in [6], which is defined as a mapping from network state vector to a choice of node and packet for the next transmission. In addition, we add the bit-rate selection to the concept of the forwarding scheme. Moreover, the optimal forwarding scheme is defined as one that minimizes the expected total transmission time required to deliver a packet to the intended destinations. The algorithm for finding the optimal forwarding scheme will be introduced in Section III-D.

C. Expected Opportunistically Coded Transmission Time (ExOCT)

We propose a new metric called expected opportunistically coded transmission time (ExOCT), which captures the total transmission time needed to deliver a packet from a given network state vector to a terminated state vector. For example, the ExOCT of a specific state vector, say *S*, is represented as ExOCT(*S*), and it indicates the expected total transmission time required to send a packet successfully from vector *S* to a terminated state vector. ExOCT reflects not only coding decisions and opportunistic forwarding but also the selection of a proper bit-rate. This is why we select the total transmission time as our metric. Since nodes can send packets at different rates, we must normalize each value to total transmission time instead of total number of transmissions.

Hereinafter, we use the following notations in the calculation of ExOCT: *D* is the size of transmitted packet in bits, and *r* is the effective bit-rate used for transmission. Set *R* is a subset of nodes that satisfy the condition in an equation. In addition, we introduce a notation to denote the new network state vector. For instance, $\langle S_A, S_B, {}^{S_X \cup \{a\} \text{ if } X \in R}_{S_X \text{ if } X \notin R} \rangle$ denotes a new network state where {a} is added only to the state of relay nodes, *X*, in subset R, while the state of all other nodes remains unchanged.

From each state vector, a transition to another vector can occur in the following five cases: when node *A* is selected and it sends packet *a* (case 1), when node *B* is selected and it sends packet *b* (case 2), and when a relay node is selected and it forwards packet *a*, *b*, or *coded packet* (cases 3, 4, and 5, respectively). For each of the five cases, we derive state transition equations. First, suppose that for vector *S*, a forwarding scheme selects node *A* to transmit its packet *a*. Then, ExOCT(*S*) can be calculated by using the following equation:

$$
\begin{aligned}
&\mathrm{ExOCT}\ (S) \\
&= \frac{1}{1 - \prod_{R_k | a \notin S_{R_k}} \left(1 - P_{A,R_k}\right)} \cdot \frac{D}{r} \\
&+ \frac{\sum_{R \in 2^{\{R_k | a \notin S_{R_k}\}}} \mathrm{ExOCT}(S') \cdot \prod_{X \in R} P_{A,X} \cdot \prod_{X \notin R} \left(1 - P_{A,X}\right)}{1 - \prod_{R_k | a \notin S_{R_k}} \left(1 - P_{A,R_k}\right)} \qquad (1) \\
&\qquad \text{where } S' = \left\langle S_A, S_B, \begin{matrix} S_X \cup \{a\} \text{ if } X \in R \\ S_X \text{ if } X \notin R \end{matrix} \right\rangle
\end{aligned}
$$

The first term in equation (1) represents the expected transmission time for transmitting a packet successfully from node *A* to at least one neighbor. Here, S' is a result vector that comes from the transmission in vector *S*. The second term represents the expected transmission time for delivering the packet in turn from result vectors, *S',* to the terminated state vector. *R* is the subset of relay nodes that have not yet received packet *a.* Thus, this recursive equation shows the expected time needed to transmit a packet from state vector *S* to any terminated state vector when node *A* is selected to transmit packet *a*. In this case, the state of nodes *A* and *B* is not changed and that of a relay node *X* that receives packet *a* is changed to $S_X \cup \{a\}$.

Similarly, case 2, in which the forwarding scheme selects node *B* to transmit packet *b,* is expressed by the following equation:

$$
\begin{aligned}
&\mathrm{ExOCT}\ (S) \\
&= \frac{\frac{D}{r} + \sum_{R \in 2^{\{R_k | b \notin S_{R_k}\}}} \mathrm{ExOCT}(S') \cdot \prod_{X \in R} P_{B,X} \cdot \prod_{X \notin R} \left(1 - P_{B,X}\right)}{1 - \prod_{R_k | b \notin S_{R_k}} \left(1 - P_{B,R_k}\right)} \\
&\qquad \text{where } S' = \left\langle S_A, S_B, \begin{matrix} S_X \cup \{b\} \text{ if } X \in R \\ S_X \text{ if } X \notin R \end{matrix} \right\rangle
\end{aligned}
$$

For case 3, in which a forwarding scheme selects relay node R_k to transmit packet *a*, we can obtain ExOCT(*S*) by using the following equation:

$$
\begin{aligned}
&\mathrm{ExOCT}\ (S) \\
&= \frac{\frac{D}{r} + \sum_{R \in 2^{\{B\} \cup \{R_i | a \notin S_{R_i}\}}} \mathrm{ExOCT}\ (S') \cdot \prod_{X \in R} P_{R_k,X} \cdot \prod_{X \notin R} \left(1 - P_{R_k,X}\right)}{1 - \prod_{X | a \notin S_X} \left(1 - P_{R_k,X}\right)} \\
&\qquad \text{where } S' = \left\langle S_A, \begin{matrix} S_B \cup \{a\} \text{ if } B \in R \\ S_B \text{ if } B \notin R \end{matrix}, \begin{matrix} S_X \cup \{a\} \text{ if } X \in R \\ S_X \text{ if } X \notin R \end{matrix} \right\rangle
\end{aligned}
$$

In the above equation, *R* indicates the subset of relay nodes and node *B* which have not yet received packet *a*. In the new state *S'*, the state of node *A* is not changed and that of node *B* and *X* that receives the packet can be changed.

For case 4, in which a forwarding scheme selects relay node R_k to transmit packet *b*, we can use the following equation.:

$$
\begin{aligned}
&\mathrm{ExOCT}\ (S) \\
&= \frac{\frac{D}{r} + \sum_{R \in 2^{\{A\} \cup \{R_i | b \notin R_i\}}} \mathrm{ExOCT}\ (S') \cdot \prod_{X \in R} P_{R_k,X} \cdot \prod_{X \notin R} \left(1 - P_{R_k,X}\right)}{1 - \prod_{X | b \notin S_X} \left(1 - P_{R_k,X}\right)} \\
&\qquad \text{where } S' = \left\langle \begin{matrix} S_A \cup \{b\} \text{ if } A \in R \\ S_A \text{ if } A \notin R \end{matrix}, S_B, \begin{matrix} S_X \cup \{a\} \text{ if } X \in R \\ S_X \text{ if } X \notin R \end{matrix} \right\rangle
\end{aligned}
$$

For case 5 where relay R_K is selected to forward the coded packet, we can derive ExOCT(*S*) with the following equation.

$$
\begin{aligned}
&\mathrm{ExOCT}\ (S) \\
&= \frac{\frac{D}{r} + \sum_{R \in 2^{\{X | \{a,b\} \notin S_X\}}} \mathrm{ExOCT}(S') \cdot \prod_{X \in R} P_{R_k,X} \cdot \prod_{X \notin R} \left(1 - P_{R_k,X}\right)}{1 - \prod_{X | \{a,b\} \notin S_X} \left(1 - P_{R_k,X}\right)} \\
&\qquad \text{where } S' = \left\langle \begin{matrix} S_X \cup \{a, b\} \text{ if } X \in R \\ S_X \text{ if } X \notin R \end{matrix} \right\rangle
\end{aligned}
$$

Algorithm 1.
Finding the optimal forwarding scheme

```
Input : G(V,E)
OFD:=a record of forwarding decision for each round
T:= a set of visited vertices
T ← all terminated states
While (T != V)
    Find S′ such that S′ ∉T and all edges in E from S′ connected to S ∈ T
    Calculate ExOCT(S′) for all possible rates and find the smallest
    Record the forwarding decision on OFD
    T = T ∪ { S′}
End while
Return OFD
```

Here, R is the subset of nodes A, B, and all relay nodes that have not yet received the coded packet.

D. Optimal forwarding scheme

Our goal is to obtain an optimal forwarding scheme that minimizes $\mathrm{ExOCT}(S_{init})$, the expected total transmission time required for two nodes to exchange a packet from the initial state vector. First, we construct the state relationship graph in which all network state vectors become vertices and a directed edge from vertex S to S' is created if S' exists on the right-hand side of at least one of the five transition equations, $\mathrm{ExOCT}(S)$. Therefore, a directed edge from S to S' means the network state can be changed from S to S' by a forwarding scheme. This state relationship graph is a directed acyclic graph since for every directed link $S \rightarrow S'$, all elements of S' are supersets of corresponding elements of S; that is, $S_A \subseteq S'_A$, $S_B \subseteq S'_B$, $S_{R_1} \subseteq S'_{R_1}, \cdots, S_{R_K} \subseteq S'_{R_K}$, and thus S' is a strict superset of S.

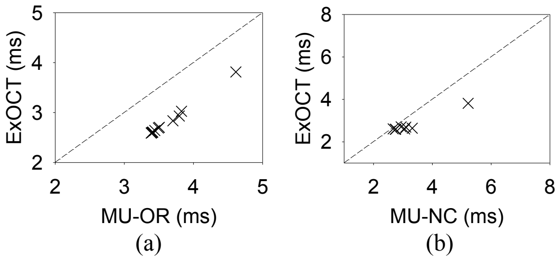
Given a state relationship graph, we can find the optimal forwarding scheme that minimizes $\mathrm{ExOCT}(\ S_{init}\ )$ with algorithm 1. The state relationship graph $\mathrm{G}(V,E)$ is given, and a set of visited vertices, T, is initialized with all terminated state vectors. That is, in the initialization step, all state vectors with $S_A = S_B = \{a, b\}$ excluding invalid state vectors become the elements of T. Note that the ExOCT values of terminated state vectors are zero. Further, the terminating condition of the loop statement in the algorithm is always guaranteed because the state relationship graph is a directed acyclic graph. By recording the selected forwarding decision on the optimal forwarding decision (OFD), including the proper node, transmitted packet, and bit-rate selection in each iteration, we can eventually obtain the OFD.

The correctness of the algorithm can be proved as follows. According to the algorithm, the ExOCT value of every state vector that has already been an element of the set T is minimal. Further, in each iteration, the algorithm finds the optimal choice, which leads to the smallest ExOCT value, for the selected state vector by examining all possible rates, and then it records the decision on OFD. Eventually, we can find an optimal forwarding scheme that minimizes $\mathrm{ExOCT}(S_{init})$ for a given network topology with algorithm 1.

IV. PERFORMANCE EVALUATION

We conducted our performance evaluation study using MIT Roofnet [11] trace data, obtained from 90 seconds broadcast transmissions from each node in a wireless mesh network consisting of 32 nodes equipped with an 802.11b network interface. The packet size was 1,500 bytes, and 1, 2, 5.5, and 11 Mbps data rates were used for transmissions. We extracted node pairs that have more than two common neighbors to create the network topology presented in Section III-A.

We conducted two experiments. First, we compared the expected transmission time of the multi-rate combination of opportunistic routing and network coding, multi-rate opportunistic routing (MU-OR), and multi-rate network coding (MU-NC). We evaluated the performance of MU-OR and MU-NC using the opportunistic routing and network coding part extracted from our model. Thus, the expected transmission times of MU-OR and MU-NC in the evaluation are also optimal. Second, we also evaluated our optimal selection by comparing it with the fixed-rate combination. For this evaluation, we extracted the combination of opportunistic routing and network coding excluding the bit-rate selection mechanism from our model.



(a) (b)

Fig. 4. Comparison with MU-OR and MU-NC in entire trace

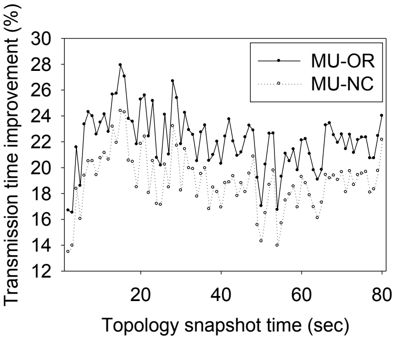
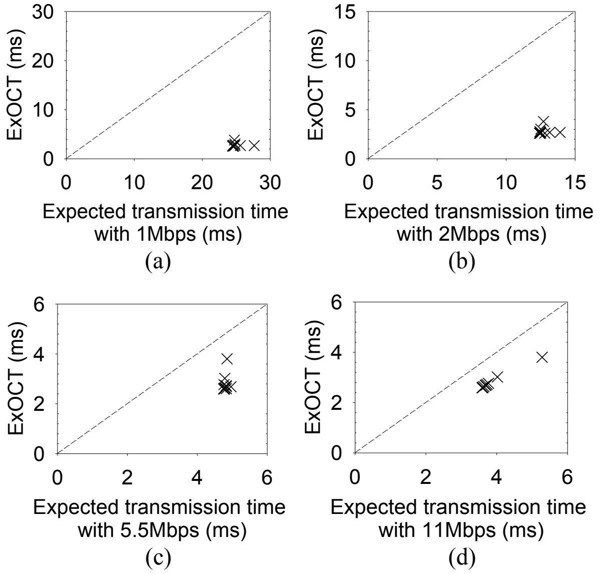


Fig. 5. Comparison with MU-OR and MU-NC in topology snapshot

A. Comparison with MU-OR and MU-NC

Our first evaluation was the comparison of the expected transmission time of multi-rate combination (ExOCT), of multi-rate opportunistic routing (MU-OR), and of multi-rate network coding (MU-NC). Figure 4 shows scatter plots of all node pairs for the comparison with MU-OR and MU-NC. Each mark in the plot shows the expected transmission time for successfully exchanging packets between two nodes in each pair. The dotted $y = x$ line is drawn as a reference. As shown in the figure, the expected transmission time of multi-rate combination is shorter than that of MU-NC and that of MU-OR. Multi-rate combination outperforms MU-NC by up to 27% and 16% on an average, and outperforms MU-OR by up to 24% and 22% on an average.

In wireless networks, signal conditions vary frequently, and the resulting changes in delivery ratios and topology may affect the optimal bit-rate. To observe this effect, we created topology snapshots by extracting delivery ratios of all links for each second. Figure 5 shows the total transmission time improvement over MU-OR and MU-NC for the snapshot for 1,500 byte packets. We can see that multi-rate combination improves the performance of both MU-OR and MU-NC, and as in the case of the previous result, the improvement over MU-OR is higher than that over MU-NC.



(a) (b)

(c) (d)

Fig. 6. Comparison with fixed-rate combination in entire trace

From the evaluation results, we can make an important observation that by combining MU-OR and MU-NC, we can significantly reduce the total communication time needed for two nodes to exchange packets.

B. Comparison with fixed-rate combination

To observe the effect of adapting a bit-rate selection mechanism on performance, we compared multi-rate combination with fixed-rate combination of opportunistic routing and network coding. Figure 6(a)–(d) shows scatter plots of all node pairs when data rates are 1, 2, 5.5, and 11 Mbps, respectively. As shown in the figure, multi-rate combination requires shorter expected transmission time than fixed-rate combination at all rates. For instance, with 5.5 Mbps, multi-rate combination outperforms fixed-rate combination by up to 45% and 42% on an average.

Moreover, to observe the effect of the signal condition over a long period, we used topology snapshots as shown in Figure 7. As in the case of the previous result, the largest improvement is made when the data rate is 1 Mbps, and when the data rate is 11 Mbps, multi-rate combination shows up to 29% better performance than fixed-rate combination (Figure 7). In summary, from the trace-based simulation, we can see that the multi-rate combination of opportunistic routing and network coding benefits from the bit-rate selection mechanism compared to fixed-rate combination.

V. CONCLUSION

In this paper, we developed a theoretical model for evaluating the potential benefit of multi-rate combination of network coding and opportunistic routing. In addition, we proposed an algorithm for multi-rate combination to obtain the optimal forwarding scheme that minimizes the expected total transmission time. With the MIT Roofnet trace-based simulation, we can see that in terms of the expected transmission time, the multi-rate combination of network coding and opportunistic routing outperforms the separate multi-rate opportunistic routing and multi-rate network coding approaches. Furthermore, the benefit of adapting the bit-rate selection mechanism was proved by comparing it with a fixed-rate combination approach.

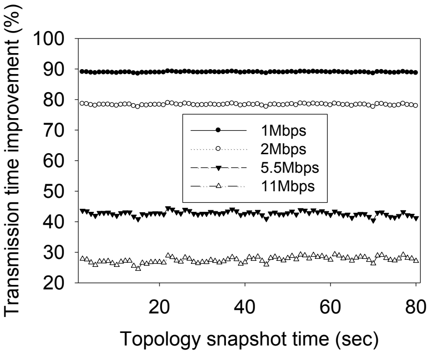


Fig. 7. Comparison with fixed-rate combination in topology snapshot

ACKNOWLEDGEMENTS

This research was supported by World Class University program funded by the Ministry of Education, Science and Technology through the National Research Foundation (NRF) of Korea (R31-10100), by Basic Science Research Program through the NRF of Korea funded by the Ministry of Education, Science and Technology (2011-0026371), and by the Ministry of Knowledge Economy, Korea, under the Information Technology Research Center (ITRC) support program supervised by the National IT Industry Promotion Agency (NIPA) (NIPA-2012-C1090-1231-0009).

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