Channel-Aware Routing Protocol for Wireless Ad-Hoc Networks: Generalized Multiple-Route Path Selection Diversity

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***Abstract*— Recently, [2] discussed the implementation aspects and performance evaluation of multiple path route selection (MRPS) route strategy for a specific m-path n-hop network topology over Rayleigh fading channel. MRPS is attractive because it is scalable and less sensitive to the size of the network. In this paper, we extend the analysis in [2], [3], [5] in several fronts: (i) we develop a recursive algorithm to compute the end-to-end outage probability (EOP) for MRPS in a more general network topology; (ii) our analysis is not restricted to Rayleigh fading but is applicable to a wide range of fading distributions including Rice, Nakagami-m, Nakagami-Hoyt, and Weibull fading channel models; (iii) we propose a new routing protocol MRPS-T based on selecting T best paths for forwarding the packet to the next hop. This algorithm is also scalable and can yield performance better than MPRS in terms of EOP metric. MRPS-T also admits MRPS for the special case of $T = 1$.**

I. Introduction

During the years, a large number of different MANET routing schemes have been proposed [1]. Some of these routing schemes, such as DSR and AODV, are now being standardized in IETF. However, most of these popular MANET routing protocols still simply adopted the performance metrics (e.g., hop counts) from traditional network and ignored the fact that there are fundamental differences between the links in MANETs and traditional networks. The links of the MANET are dynamic in the sense that they often experience breakage and changes as they move in the network, and link breakages severely deteriorate network throughput and routing performance. Therefore, MANET routing schemes addressing link reliability are recently gaining more and more considerations.

One way to increase the reliability of MANET routing is to use a set of redundant paths rather than only one path in traditional MANET routing protocols. In [5], the author proposed a multiple path selection algorithm, which is based on link reliability. However, [5] neither considered fading on wireless links, nor discussed how to collect the reliability information. [3] proposed the multi-route path selection (MRPS) diversity scheme, which chooses the path with the best current channel condition while forwarding packets to the next hop. However, [3] did not analyze the performance of MRPS as a function of the size of the network. In [2], the authors designed the MRPS system based on a cross-layer stack, which includes the enhancement of a conventional media access control (MAC) protocol to measure the outage probability of each link and a modification of a multiple-route protocol where multiple routes are cached and used later as alternate routes when the current route fails. However, the cases in [2] that the authors analyzed are not realistic in practical networks.

One of our contributions in this paper is that we develop a recursive algorithm to determine the EOP of MRPS routing scheme, and this algorithm is suitable for any general network topologies. Another major contributions in this paper is that we further modify MRPS by letting nodes transmit data to T next-hop neighbors whose channel conditions are the best among all the neighbors. We call this routing scheme "MRPS-T" or "generalized MRPS routing scheme". We further analyze the performance of MRPS-T versus MRPS routing scheme.

The organization of this paper is as follows. Section II briefly reviews the operation of MRPS schemes. In Section III, we analyze the performance of MRPS scheme for more general MANET network topologies. In this section, we introduce MRPS-T routing scheme and analytically evaluate its performance. The main points are summarized in Section V.

II. The Operation of MRPS Routing Scheme

MRPS was first introduced in [3]. The basic idea of MRPS is that, while forwarding the packet, the next hop is chosen to be the one that has the best current channel condition to mitigate channel fading. In nature, MRPS can be viewed as a greedy heuristic algorithm in routing decision.

Octets:	2	4	6	2	4
	Frame Control	Duration	Destination Address	CSI	Frame Checksum

Fig. 1. CTS MAC control frame.

Implementation of MRPS scheme requires modification in MAC layer so that a network node is able to gather the channel state information (CSI) of its neighbors, and the MAC layer should also have multicasting function. In [2], the authors proposed implementing MAC layer of MRPS by modifying IEEE 802.11 MAC protocol in DCF (Distributed Coordination

Function) mode and RTS/CTS mechanism, such that a network node is able to gather the channel state information (CSI) of its neighbors. [4] shows that the best CSI is obtained at the receiver side rather than at the transmitter side. Hence CSI in the MRPS MAC protocol is conveyed in CTS message, which is transmitted from the next-hop candidates back to the transmitter. Fig. 1 (adapted from [2])shows the modified CTS frame, where a new field "CSI" is added to the packet format. CSI can contain signal-to-noise ratio of the channel or the partial end-to-end outage probability. In order to receive CSI from multiple next-hop candidate nodes, a RTS/CTS protocol that has multicast function is needed. In [7], the authors proposed Batch Mode Multicast MAC (BMMM), which provides reliable multicast function in MAC layer. The authors in [2] further modified it and proposed so-called M-BMMM protocol. The operation of M-BMMM is shown in Fig. 2 with a two next-hop candidates example. Detailed operations of M-BMMM protocol can be found in [2].

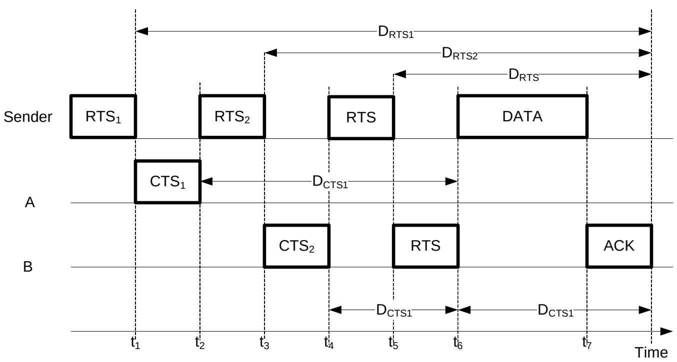

Fig. 2. Time line of M-BMMM protocol (two next-hop candidate nodes).

The authors of [2] also analyzed the performance of an m-path n-hop topology as shown in Fig. 3. However, this kind of network topology is quite unrealistic. It is unlikely in practical networks that each node has the same number of paths to the next hop, and all paths have exactly the same number of hops n. Therefore, the performance analysis on such a network topology is very restrictive. A more general ad hoc network example is shown in Fig. 4, where neither the number of paths at each node nor the number of hops of each path is fixed.

One of our contributions in this paper is that we develop a recursive algorithm to determine the EOP of MRPS routing scheme, and this algorithm is suitable for any general network topologies. Algorithm 1 is the subroutine for computing partial EOP. The EOP of MRPS is simply given by "partial_EOP(source node)". In Algorithm 1, num_path$(\cdot)$ denotes the number of paths from the current node to the next hop neighbors.

Note, however, that for general networks, it is still difficult to express the EOP of MRPS in a closed-form expression. However, we may still be able to analyze some special types of topologies. For example, a "node-disjoint" example [6] is shown in Fig. 5. In Fig. 5, there are totally m routes from the source node S to the destination node D. The distance of the

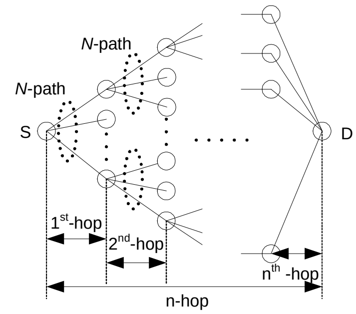

Fig. 3. A m-path n-hop network topology.

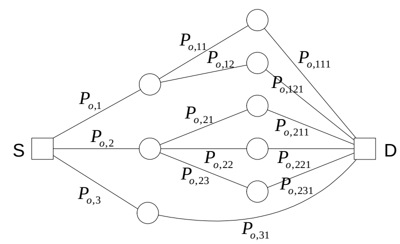

Fig. 4. An example with more general network topology.

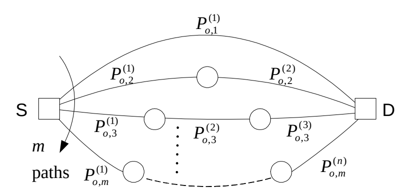

Fig. 5. An example of a node-disjoint network topology

longest route from the source to the destination has n hops. Let hop(i) denote the number of hops of the i^{th} route. Hence the partial end-to-end outage probability from the 2^{nd} hop to the last hop of the i^{th} route can be computed by $1-\prod_{j=2}^{\text{hop}(i)}[1-P_{o,i}^{(j)}]$, where $P_{o,i}^{(j)}$ corresponds to the outage probability at the j^{th} hop of the i^{th} path. Therefore, the EOP for MRPS routing

Algorithm 1 partial_EOP(current node)

if (current node == destination) **then**
  EOP $= 0$;
  Return;
else
  paths $\Leftarrow$ num_path(current node);
  for $i=1$ to paths **do**
    p_EOP(i) = partial_EOP(i^{th} node next hop);
    $P_{\text{SEL}}(i) = \frac{1-P_{o,i}}{\text{paths}-\sum_{j=1}^{\text{paths}} P_{o,j}}$
  end for
  partial_EOP $= 1-(1-\prod_{i=1}^{\text{paths}} P_{o,i}) \times \left[\sum_{i=1}^{\text{paths}} P_{\text{SEL}(i)} \cdot (1-\text{p\_EOP}(i))\right]$;
  Return;
end if

scheme can be computed as

$$\text{EOP}_{\text{MRPS}} = 1 - \left(1 - \prod_{i=1}^{m} P_{o,i}^{(1)}\right) \times \left[\sum_{i=1}^{m} P_{\text{SEL}}(i) \left(1 - \prod_{j=2}^{\text{hop}(i)} \left(1 - P_{o,i}^{(j)}\right)\right)\right] \quad (1)$$

where $P_{\text{SEL}}(i)$ denotes the probability that the i^{th} route is selected, and can be determined by

$$P_{\text{SEL}}(k) = \frac{1 - P_{o,k}^{(1)}}{N - \sum_{i=1}^{N} P_{o,i}^{(1)}}, \quad (2)$$

where $k \in \{1, 2, \ldots, m\}$.

III. EOP for MRPS-T Routing Scheme

In MRPS routing scheme, a network node transmit data to the neighbors who has the best channel condition. In fact, we can further improve this routing scheme by letting the this node transmit its data to T nodes whose channel conditions are the best among all its neighbors. We call this routing scheme "MRPS-T" or "generalized MRPS routing scheme". Clearly, the EOP of MRPS-T would outperform MRPS because there are more redundant paths in MRPS-T.

Generally, it is extremely difficult to compute the EOP of MRPS-T routing scheme for general networks. However, for the special structure as shown in Fig. 3, it is still possible to analyze the EOP of MRPS-T. Before computing MRPS-T's end-to-end outage probability, we introduce the following Lemma from order statistics:

Lemma 1: Suppose at a node in the network, there are N paths to the next hop. Sort all N channel's SNR in ascending order as $\gamma_{1:N}$, $\gamma_{2:N}$, ..., $\gamma_{N:N}$, such that $\gamma_{1:N} \leq \gamma_{2:N} \leq \ldots \leq \gamma_{N:N}$. Denote the ordered outage probability of these N paths by $P_{o,1:N}$, $P_{o,2:N}$, ..., $P_{o,N:N}$ respectively. Then the outage probability of $\gamma_{k:N}$ is given by

$$P_{o,k:N} = \sum_{i=k}^{N} \sum_{z_{i,N}} \left[\prod_{l=1}^{i} P_{o,j_l}\right] \left[\prod_{l=i+1}^{N} (1 - P_{o,j_l})\right] \quad (3)$$

where the summation $\sum_{z_{i,N}}$ extends over all permutations $(j_1, j_2, \ldots, j_N)$ of $(1, 2, \ldots, N)$ for which $j_1 < j_2 < \ldots < j_i$ and $j_{i+1} < j_{i+2} < \ldots < j_N$, viz

$$\sum_{z_{i,N}} \equiv \sum_{\substack{j_i \in S_N \\ j_1 < j_2 < \ldots < j_i \\ j_{i+1} < j_{i+2} < \ldots < j_N}} \quad (4)$$

where S_N is the set of all permutations of integers 1 through N. The total number of terms in $\sum_{z_{i,N}}$ is

$$\frac{n!}{i!(n-i)!} = \binom{n}{i}. \quad (5)$$

Proof: Since

$$\begin{aligned} P_{o,j:N} &= \Pr\{\gamma_{j:N} < \gamma_{th}\} + \Pr\{\gamma_{j+1:N} < \gamma_{th}\} + \ldots \\ &\quad + \Pr\{\gamma_{N:N} < \gamma_{th}\} \\ &= \sum_{i=k}^{N} \Pr\{\gamma_{i:N} < \gamma_{th}\} \end{aligned}$$

Notice that

$$\begin{aligned} \Pr\{\gamma_{i:N} < \gamma_{th}\} &= \sum_{\substack{j_i \in S_N \\ j_1 < j_2 < \ldots < j_i \\ j_{i+1} < j_{i+2} < \ldots < j_N}} \left[\prod_{l=1}^{i} P_{o,j_l}\right] \times \left[\prod_{l=i+1}^{N} (1 - P_{o,j_l})\right] \\ &= \sum_{z_{i,N}} \left[\prod_{l=1}^{i} P_{o,j_l}\right] \left[\prod_{l=i+1}^{N} (1 - P_{o,j_l})\right] \end{aligned}$$

Therefore, we have

$$P_{o,k:N} = \sum_{i=k}^{N} \sum_{z_{i,N}} \left[\prod_{l=1}^{i} P_{o,j_l}\right] \left[\prod_{l=i+1}^{N} (1 - P_{o,j_l})\right].$$

■

Corolary 1: In Lemma 1, if the outage probabilities for all paths are independent identically distributed (i.i.d.), then the outage probability of $\gamma_{k:N}$ is given by

$$P_{o,k:N} = \sum_{i=k}^{N} \binom{n}{i} P_o^i (1 - P_o)^{N-i} \quad (6)$$

Proof: By substituting P_o into Lemma 1, the result immediately follows. ■

The following lemma shows that in MRPS-T, the outage probability from one node to its next-hop neighbors is independent of N.

Lemma 2: In MRPS-T, the outage probability from one node to its next-hop neighbors is given by

$$P_{out} = P_{o,N:N} = \prod_{l=1}^{N} P_{o,l}. \quad (7)$$

Proof: Since

$$\begin{aligned} P_{out} &= \Pr\{\text{all } T \text{ paths fail}\} \\ &= \Pr\{\gamma_{T:N} < \gamma_{th}, \gamma_{T+1:N} < \gamma_{th}, \ldots, \gamma_{N:N} < \gamma_{th}, \} \\ &= \Pr\{\gamma_{N:N} < \gamma_{th}\} \cdot \Pr\{\gamma_{T:N} < \gamma_{th}, \gamma_{T+1:N} < \gamma_{th}, \\ &\quad \ldots, \gamma_{N-1:N} < \gamma_{th} | \gamma_{N:N} < \gamma_{th}\} \\ &= \Pr\{\gamma_{N:N} < \gamma_{th}\} \cdot 1 \\ &= P_{o,N:N} = \prod_{l=1}^{N} P_{o,l}. \end{aligned}$$

Interestingly, we notice that this result is exactly the same as Selection Diversity Combining. ■

Before deriving the EOP of MRPS-T, we introduce the following notations first. $P_{(i)\to t}$ corresponds to the probability that at the ith hop, exactly t paths are success in transmitting.

$P_{\text{succ}}^{(i)}$ denotes the probability of the successful transmission at the ith hop. With Lemma 1 and Lemma 2, we are now ready to derive the EOP of MRPS-T for node-and-link-disjoint networks.

Theorem 2: MRPS-T's EOP for a N-path n-hop tree-structure network with i.i.d. link outage probability P_o can be computed as

$$\text{EOP}_{\text{MRPS-T}} = 1 - \prod_{i=1}^{n} P_{\text{succ}}^{(i)}, \tag{8}$$

where $P_{\text{succ}}^{(i)}$ denotes the probability of successful transmission at the i^{th} hop. $P_{\text{succ}}^{(i)}$ can be computed as the following:

1) for $1 \le i \le n-1$,

$$P_{\text{succ}}^{(i)} = \sum_{j=1}^{T^{i-1}} P_{(i-1)\to j}(1 - P_o^{j\cdot N}) \tag{9}$$

where notation $P_{(i)\to j}$ corresponds to exactly j paths successfully transmitting the data at the i^{th} hop. $P_{(i)\to j}$ can be inductively computed as follows:

$$\begin{aligned} P_{(i)\to j} &= \frac{P'_{(i-1)\to j}}{\sum_{j=1}^{T^{(i-1)}} P'_{(i-1)\to j}}, \\ P'_{(i)\to j} &= \sum_{k=\lceil j/T \rceil}^{T^{i-1}} P_{(i-1)\to k} \binom{kT}{j} \times \\ & \quad (1-P_o)^j \cdot P_o^{kT-j}, \\ i &= 1, 2, \ldots, n-1; \\ j &= 1, 2, \ldots, T^i; \\ P_{(0)\to 1} &= 1. \end{aligned}$$

2) for $i = n$,

$$P_{\text{succ}}^{(i)} = \sum_{j=1}^{T^{i-1}} P_{(n-1)\to j} \cdot (1 - P_o^j). \tag{10}$$

Proof: First of all, (8) is obviously true from the definition of EOP. Therefore, the computation of EOP of MRPS-T transforms to the computation of the success transmission probability at each hop. According to the operation of MRPS-T, the source node and all intermediate nodes select the best T paths among their N next hop neighbors. For a specific node, the selected T paths' transmissions could be success or failure. Hence, there could be 1, 2, ..., T successful transmissions at the first hop; 1, 2, ..., T^2 successful transmissions at the second hop, and so on. Generally, at the i^{th} hop, there could be 1, 2, ..., T^i successful transmissions.

Now let us calculate the successful transmission probability in i^{th} hop if there are exactly j paths succeed in the $(i-1)^{th}$ hop, for $1 \le j \le T^{i-1}$. Notice that j successful transmissions in the $(i-1)^{th}$ corresponds to j source nodes the i^{th} hop. Also notice that if there are j source nodes at a particular hop, the only possibility that this hop fails is due to all j source nodes fail. Since all links are i.i.d. and from Lemma 2, we know that the successful transmission probability with j source nodes in the i^{th} can be computed as $1 - P_o^{jN}$. Therefore, given the probability of exactly j paths succeeding in the $(i-1)^{th}$ hop, we have

$$P_{\text{succ}}^{(i)} = \sum_{j=1}^{T^{i-1}} P_{(i-1)\to j}(1 - P_o^{j\cdot N}).$$

Now it is seen that the computation of $P_{\text{succ}}^{(i)}$ boils down to determining $P_{(i)\to j}$. To better illustrate how to obtain $P_{(i)\to j}$, let us observe Table I, which illustrates the inductive relationship between $P_{(i)\to j}$ and $P_{(i-1)\to j}$. The k^{th} row in Table I enumerates alls possible numbers of successful transmissions if there exists exactly k source nodes. The last row in the table is the summation of all previous rows, and the j^{th} element in this row corresponds to exactly j paths succeeding in the i^{th} hop. Suppose that there are k sources in the i^{th} hop, from Corollary 1, the possibility of exactly j paths succeeding can be computed as follows:

$$\binom{kT}{j}(1-P_o)^j \cdot P_o^{kT-j},$$

Hence, from Table I it is clearly that

$$P_{(i)\to j} = \sum_k P_{(i-1)\to k}\binom{kT}{j}(1-P_o)^j \cdot P_o^{kT-j}.$$

However, different value of j would have different number of terms, k, in the summation. By observing Table I, we have the following relationship between the j^{th} item in the last row and the starting index involved in j^{th} item's summation.

Index j in the Last Row	The Starting Index in the Summation
$1 \le j \le T$	1
$T+1 \le j \le 2T$	2
$2T+1 \le j \le 3T$	3
$\vdots$	$\vdots$
$kT-T+1 \le j \le kT$	$\lceil j/T \rceil = k$
$\vdots$	$\vdots$
$T^i - T + 1 \le j \le T^i$	T^{i-1}

TABLE II
THE STARTING INDEX IN THE SUMMATION OF $P_{(i)\to j}$.

Notice, also, that $P_{(i)\to j}$ needs to satisfy $\sum_{j=1}^{T^{i-1}} P_{(i)\to j} = 1$. Hence $P_{(i)\to j}$ derived from the summation of $P_{(i)\to j}$ needs to be normalized. Therefore, we have the following inductive relationship of $P_{(i-1)\to j}$:

$$P_{(i)\to j} = \frac{P'_{(i-1)\to j}}{\sum_{j=1}^{T^{(i-1)}} P'_{(i-1)\to j}}$$

and

$$P'_{(i)\to j} = \sum_{k=\lceil j/T \rceil}^{T^{i-1}} P_{(i-1)\to k}\binom{kT}{j}(1-P_o)^j \cdot P_o^{kT-j}$$

Therefore, by setting $P_{(0)\to 1} = 1$, we can inductively compute all values of $P_{(i)\to j}$.

	Possible Number of Successful Transmissions											
$P_{(i-1)\to 1}$	1	$\dots$	T									
$P_{(i-1)\to 2}$	1	$\dots$	T	$\dots$	$2T$							
$\vdots$	$\vdots$	$\dots$	$\vdots$	$\vdots$	$\vdots$	$\dots$						
$P_{(i-1)\to k}$	1	$\dots$	T	$\dots$	$2T$	$\dots$	$\dots$	kT				
$\vdots$	$\vdots$	$\dots$	$\vdots$	$\dots$	$\vdots$	$\dots$	$\dots$	$\vdots$	$\dots$			
$P_{(i-1)\to T^{i-1}}$	1	$\dots$	T	$\dots$	$2T$	$\dots$	$\dots$	kT	$\dots$	$\dots$	$\dots$	T^i
$\sum\downarrow$	$P_{(i)\to 1}$	$\dots$	$P_{(i)\to T}$	$\dots$	$P_{(i)\to 2T}$	$\dots$		$P_{(i)\to kT}$		$\dots$		$P_{(i)\to T^i}$

TABLE I

THE INDUCTIVE RELATIONSHIP BETWEEN $P_{(i)\to j}$ AND $P_{(i-1)\to j}$.

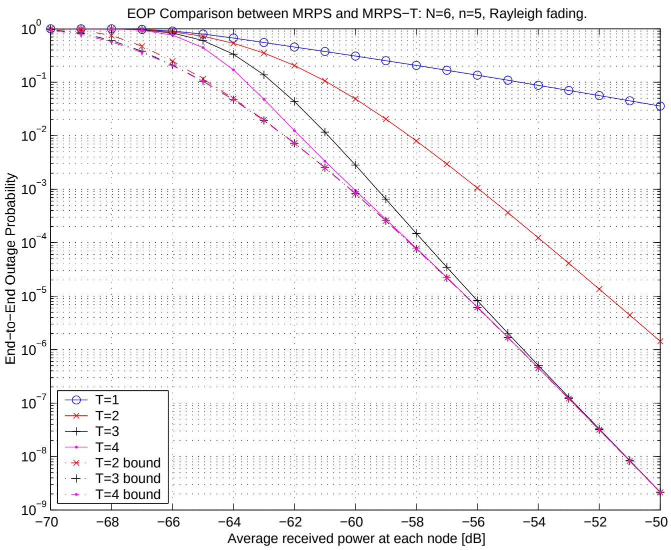

Fig. 6. EOP performance comparison between MRPS and MRPS-T.

In the last hop, each node has no routing diversity anymore. Suppose that there are j source nodes in the last hop, then there are totally j paths in the last hop. Hence, the successful transmission probability can be computed as

$$P_{\text{succ}}^{(i)} = \sum_{j=1}^{T^{i-1}} P_{(n-1)\to j} \cdot (1 - P_o^j).$$

Finally, the discussions of hops $1 \dots n-1$ and hop n complete the proof. ∎

Note that if $T = 1$, it is easy to show that $\text{EOP}_{\text{MRPS}-\text{T}}$ is exactly the same as Eq. (8) in [2]. Therefore MRPS is only a special case of MRPS-T with $T = 1$.

On the other hand, we can also get the EOP performance bounds for MRPS-T from the above derivation:

$$\text{EOP}_{\text{MRPS}-\text{T}}^{\text{bound}} = 1 - \left[\prod_{i=1}^{n-1} (1 - P_o^{m\cdot T^{i-1}})\right] (1 - P_o^{T^{n-1}}) \quad (11)$$

Suppose that $N = 6$ and $n = 5$, also assume that each link in the network is experiencing Rayleigh fading. Figure 6 shows the performance bound improvement of this change of T from 1 to 2, 3, and 4. From this example, it is theoretically seen that MRPS-T routing scheme significantly improves the EOP performance of MRPS routing scheme by simply changing T. This is due to the increased number of redundant paths in the network. Notice that when T is increased from 3 to 4, the EOP performances are approximately the same except in low SNR region. This observation shows that $T = 3$ is a good choice in terms of balance between EOP and bandwidth consumption. Notice also that if $T = 6$, then MRPS-T simply becomes MR-T [8] routing scheme. Therefore, the bigger T is, the closer that MRPS-T would perform compared to MR-T.

IV. CONCLUSION

In this paper, we first derive a recursive algorithm for computing EOP for any general network topologies. Specifically, we derive the closed form expression for EOP of "node-disjoint" networks. We further extend the simple MRPS routing scheme to a generalized MRPS routing scheme, MRPS-T, in which the node transmits packets to T neighbors whose channel conditions are the best. We theoretically analyzed the EOP performance of MRPS-T and compare it with MRPS. We show that MRPS-T performs significantly better than MRPS while maintaining the nice features of MRPS.

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