Wireless Channel-Aware Ad Hoc Cross-Layer Protocol with Multi-Route Path Selection Diversity

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Abstract — Routing protocols for ad hoc networks have generally ignored channel fading. We propose a new routing metric, the route outage probability (ROP), which attempts to minimize packet loss due to fading. We apply ROP to a conventional single route protocol and to a protocol that uses multiple routes to minimize packet loss. More interesting, we apply ROP to a recently proposed multi-route path selection diversity (MRPS) scheme that chooses next-hop links based on current channel conditions. We propose new media access control (MAC) and network layer protocols that support ROP and our three routing schemes. We compare the three schemes analytically based on total outage probability, showing that the MRPS scheme scales to larger networks than the other schemes. We present the numerical results of the schemes over a Rayleigh fading channel. The numerical results show that the MRPS scheme outperforms the other schemes for most parameters and that it scales with network size.

I. Introduction

A variety of routing protocols have been proposed for mobile ad hoc networks communicating over unreliable wireless links [1]. However, in general, these protocols were not designed with fading of the wireless channel in mind.

Our first contribution is to propose the use of the *route outage probability* (ROP) as a metric for choosing routes. ROP is the probability that a packet will be lost due to *fading* somewhere along the route. The appeal of ROP over the conventional *hop-count* metric is clear; it is much more desirable that the packet reach its destination with high probability over additional hops than that it be lost while traversing a path with fewer hops. In [8], a multiple-route selection protocol is proposed, which uses reliability as a metric for choosing multiple routes. However, [8] does not consider fading on wireless links, nor does it propose a way to obtain the reliability information.

We can use ROP in a conventional ad hoc routing protocol to find the single route (SR) to the destination with the lowest chance of loss due to fading. Another way to increase the probability that a packet will reach its destination is to transmit it along multiple routes (MR) simultaneously. Again, ROP can serve as the metric. The disadvantage of this approach is of course that the bandwidth used to transmit the packet increases with each additional route used.

Another approach is the multi-route path selection (MRPS) diversity scheme introduced in [2]. The idea is that while forwarding the packet the next hop is chosen to be the one that has the best current channel condition to mitigate fading. This allows the packet to follow only one path, but still react to changing channel conditions. Unfortunately, [2] does not propose an implementation of this idea, nor does it analyses the performance as a function of the size of the network.

Our second contribution is a design of MRPS system based on a cross-layer protocol stack. Our design 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 in which multiple routes are cached and used later as alternate routes when the current route fails

Our final contribution is to analyze the performance of all three schemes using ROP as a routing metric. Our analytical analysis shows that the MRPS scheme outperforms both the SR and MR schemes as the size of the system increases. Our numerical results for each system confirm these results and show that the MRPS scheme can achieve qualitatively better results than the MR scheme.

The rest of the paper is organized as follows. In Section II, we propose the ROP metric and protocols for each routing scheme, as well as a new MAC. In Section III, we analyze the performance of the SR, MR and MRPS schemes. Section IV shows our numerical results, and conclusions are made in Section V.

II. Design

We propose a new routing metric, *ROP*, and show how it is used in the SR, MR and MRPS schemes. The details of the proposed MRPS system are described in some detail including the routing protocol and the new MAC.

A. Route outage probability (ROP)

ROP is the probability for a route that a packet will fail to reach its destination through that route because of fading. The motivation of ROP is to send data along the most reliable route rather than the shortest one. This is because links of ad hoc networks are wireless and thus experiences

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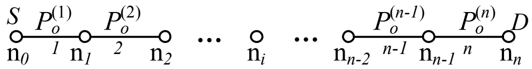


Figure.1 A n-hop route with the outage probability of each link

fading which causes transmission failure. Therefore, the cost of the wireless link should be represented by the *average received-SNR* or the *outage probability of the link*, which represents the reliability of the link, rather than just the uniform integer value of "*1*" for all the links as used in conventional ad hoc routing protocols. The outage probability of a link is the probability that the received-SNR γ at the receiver will fall below the threshold-SNR γ_T that guarantees certain level of bit error probability. For a Rayleigh fading channel with mean $\bar{\gamma}$, the outage probability P_o is derived as

$$P_o = \Pr\{\gamma < \gamma_T\} = \int_0^{\gamma_T} \frac{1}{\bar{\gamma}} \exp\left(-\frac{\gamma}{\bar{\gamma}}\right) d\gamma = 1 - \exp\left(-\frac{\gamma_T}{\bar{\gamma}}\right) \quad (1)$$

Therefore, in an ad hoc network environment, especially with fading, estimating the cost of a route using ROP, which is derived from the outage probability of all the links of the route, better represents the reliability of the route than using a conventional hop-count metric.

Fig.1 shows an n-hop route. The outage probability of the i^{th} link is expressed as $P_o^{(i)}$. The probability that a packet delivery will success to its destination D can be expressed as $\prod_{k=1}^{n}(1-P_o^{(k)})$. Therefore, the ROP of the route j, ROP_j, can be expressed as

$$\mathrm{ROP}_j = 1 - \prod_{i=1}^{n}\{1 - P_{o,j}^{(i)}\} \quad (2)$$

where $P_{o,j}^{(i)}$ denotes the outage probability at the i^{th} link of the *route j*.

B. Using ROP in the SR and MR schemes

Since ROP is a metric that measures the reliability of a route that experiences fading, it can be used for any kind of routing protocols that need to choose a single route or multiple routes to the destination. We discuss a simple SR and MR scheme.

An SR scheme (such as DSR [7]) is a routing protocol that tries to find the single shortest route to the destination. In DSR, this is done in two steps. First, the source floods a route-request (RREQ) packet to find the route to the destination. Second, if the destination or the intermediate node that has route information receives the RREQ, it replies with a route-reply (RREP) packet to the source with the route information. If duplicate RREQs are received at the destination or at an intermediate node, only the first RREQ is accepted and the others that arrived later are discarded. This finds the shortest (or really the fastest) route between the two nodes. The first RREQ to reach the destination adds the newly discovered route to the source's cache of routes and transmission can begin.

Using ROP to modify DSR implies that the routing protocol is now searching for the most reliable route to the destination. One obvious way to use ROP in DSR is to compare the ROP of all the possible routes to the destination and choose the one with the lowest ROP. Before discarding the same RREQ packets that arrived later at an intermediate node by different route, it compares the ROP of the RREQ with that of the previous RREQ. If the later one has lower ROP, the node decides to re-broadcast the RREQ. Similarly, whenever the destination receives a RREQ with lower ROP, it returns a new RREP with the *route record* and the *ROP* of the new route. The source now updates its route to the destination whenever it receives the RREP with a lower ROP than the one it had before.

Route selection using ROP can be described with an example where a network that has two routes, *route x* and *route y* with the number of hops n_1 and n_2, respectively as

$$\begin{aligned} &\textit{If} \ \prod_{i=1}^{n_1}(1-P_{o,x}^{(i)}) > \prod_{j=1}^{n_2}(1-P_{o,y}^{(j)}) \\ &\textit{then} \ \{\text{Select } \textit{route x}\} \ \textit{else} \ \{\text{Select } \textit{route y}\} \end{aligned} \quad (3)$$

However, to calculate the ROP of the route, the outage probabilities of all the links of the route need to be collected at the node that makes the route selection. This is done by introducing the *partial-ROP*, which represents the outage probability of the partial route between the source (or destination) and the node at which a RREQ (or a RREP) is received. In the case of DSR, the outage probability of each link can be estimated at the node that receives a RREQ using the received power of the RREQ. As the RREQ is flooded throughout the network, the partial-ROP in the RREQ is updated to represent the corresponding outage probability of the modified partial route. For example, in the network depicted in Fig.1, the partial-ROP between n_0 and n_i can be expressed as $\{1-\prod_{k=1}^{i}(1-P_o^{(k)})\}$. When the RREQ reaches the destination, the destination obtains the ROP of the route along which the RREQ received.

The MR scheme is a routing protocol that uses fixed multiple routes to transmit data to its destination simultaneously. Details of selecting multiple routes can be found in [4], [8].

Using ROP in the MR scheme is almost the same as the SR scheme except that instead of choosing one route, MR scheme now selects m routes that have the lowest ROP among n possible routes. It then transmits the duplicate data packets along the selected routes to its destination simultaneously.

C. The proposed MRPS scheme

The two main ideas of the proposed MRPS scheme are: First, at the source and at each intermediate node, the m multiple routes with the lowest ROP are chosen using the ROP metric. Therefore, at each node, there are m next-hop candidates to the destination. Second, a node that has data to transmit to the destination first collects all the channel state information (CSI) of the links to the next-hop candidates. The data is transmitted to the next hop that has the best channel condition.

The proposed MRPS scheme requires both new network and MAC layers. The MRPS routing protocol is based on the AOMDV (Ad hoc On-demand Multipath Distance Vector) routing protocol [4], which has the ability to find multiple loop-free and link-disjoint routes to the destination. In AOMDV, multiple routes are not used for simultaneous transmission but are cached and used later as alternate routes when the current route fails. Moreover, to collect all the CSI from the multiple next-hop candidates, a design for a MAC protocol that has multicasting is presented.

D. *MRPS routing protocol*

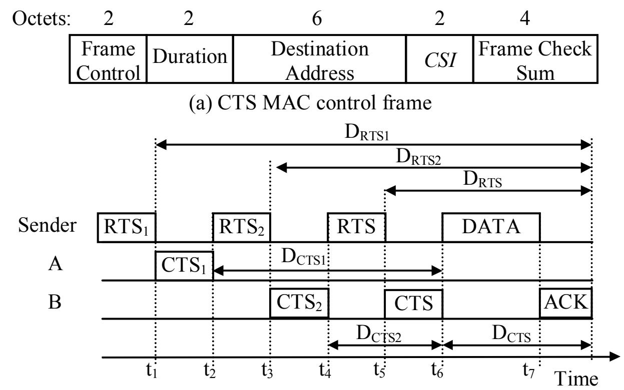
The MRPS routing protocol is based on AOMDV routing protocol using the ROP metric to find multiple routes to the destination at both the source and the intermediate nodes to gain the advantage of route diversity.

Multiple routes to the destination may be found at the source or at the intermediate nodes as described in [4], during the route discovery phase with RREQ flooding and RREPs. The ROP metric is used for choosing m multiple routes that have the lowest ROP among n possible routes to the destination. Different from the SR scheme using the ROP metric, the ROP of a route is now obtained by the use of partial-ROP in a *RREP* and updated as the RREP is forwarded along the reverse route established during the RREQ flooding. The outage probability of each link is estimated when the RREQ is received at each node and stored at the node for future partial-ROP calculation. When n multiple RREPs reach the source or an intermediate node, the m ($\leq n$) routes with the lowest ROP are selected as the candidate routes to the destination. However, since the intermediate node only forwards a single RREP with one partial-ROP, the multiple partial-ROPs received at the node are converted into one *equivalent partial-ROP*, P_o^{eq}. P_o^{eq} is calculated simply by multiplying all the received partial-ROPs. The intuition is that a route with multiple candidate routes is more preferable to one with only a single route. Before forwarding a packet, at each node, all the CSI of the m next-hop candidates are collected by the use of the MRPS MAC protocol in order to forward the packet on the one that currently has the best channel condition.

E. *MRPS MAC protocol*

The MAC layer of the proposed MRPS system uses the IEEE 802.11 MAC protocol in DCF (Distributed Coordination Function) mode [5] and the RTS/CTS (Request-to-Send/Clear-to-Send) protocol with minor modifications in the CTS MAC control packet format and the addition of a multicasting function.

The basic requirement of MRPS scheme is to have the multiple CSI from the next-hop candidates before making any path selection to the next hop. In [3], it is shown that the best CSI is obtained at the receiver side rather than at the transmitter side, and that CSI, which is obtained with a RTS/CTS exchange, is valid during a data packet transmission in a slowly varying channel. Therefore, in the proposed MRPS MAC protocol, CSI is conveyed in the CTS packets and transmitted from the multiple next-hop candidates to the transmitter. Fig.2 (a) shows the modified CTS packet format of the MRPS MAC protocol. The measured CSI is transmitted in the new field '*CSI*' of the CTS packet in the form of the average received signal-to-noise ratio (SNR) or the outage probability of the link.



(a) CTS MAC control frame

(b) Time line of M-BMMM protocol (two next-hop candidate nodes)

Figure 2. M-BMMM protocol design

To receive multiple CTS packets from the next-hop candidates, we designed a RTS/CTS protocol that has a multicasting function. In [6], the Batch Mode Multicast MAC (BMMM) protocol is proposed, which has a reliable multicasting function. However, because we only need to receive multiple CTS packets from the next-hop candidates and to send a packet to one of them, we propose a *Modified Batch Mode Multicast MAC* (M-BMMM) protocol.

The basic operation of M-BMMM protocol is shown in Fig.2 (b) with a two next-hop candidates example. The sender S first transmits RTS_1 to the first receiver A with the destination address of A. A sends back CTS_1 with its estimated CSI. S transmits RTS_2 to B with the destination address of B. Even though B has heard CTS_1, in M-BMMM, if the source address of RTS_2 and the destination address of CTS_1 are same, B sends CTS_2 to S. After collecting all the CSI, the MAC protocol hands the collected CSI to the MRPS routing protocol. A data packet is forwarded to the link with the lowest outage probability. In this example, if the CSI of B is better than that of A, B is selected as the next hop. Now S follows the conventional RTS/CTS protocol to transmit DATA. Notice that the duration information D_{CTS1} and D_{CTS2} of CTS_1 and CTS_2 are only the time until the end of CTS transmission as depicted in Fig.2 (b). This makes the neighboring nodes of A, which heard CTS_1, able to communicate with other nodes, if necessary.

III. PERFORMANCE ANALYSIS

We analyze the performance of the all three schemes in terms of the *total outage probability* (TOP), which is defined as the probability that a packet fails to reach its destination. For simplicity, the analysis is first performed with a simple four-node network shown in Fig.3 (a). Then the result is extended to a general *m-path n-hop* network, which is shown in Fig.3 (b).

A. *Simple two-path two-hop network*

In Fig.3 (a), the source node S has two paths to the next-hop candidates A and B, and the distance between S and the destination D is two hops.

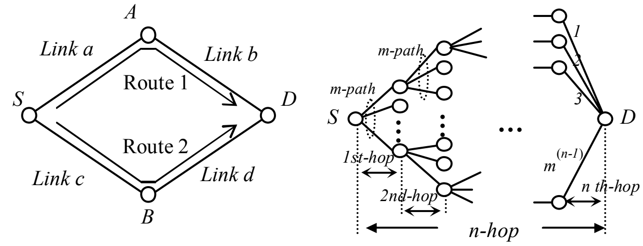


Figure 3. (a) A *two-path two-hop* and (b) a *m-path n-hop* networks

The SR system uses a fixed single route. The TOP of the SR system, P_{o_SR}, is the probability that at least one of the links that is part of the selected *route* fails to deliver a packet to the destination *D*. Therefore, if we assume that the selected route to the destination is *route 1*, P_{o_SR} can be expressed as

$$P_{o\_SR}=1-P_{S,1}^{(a)}\cdot P_{S,1}^{(b)}=1-(1-P_{o,1}^{(a)})(1-P_{o,1}^{(b)}) \qquad (4)$$

where, $P^{(i)}_{S,j}$ denotes the probability that a packet is successively transmitted through the i^{th} *link* of the j^{th} *route*.

The MR system has two routes, *route 1* and *route 2*, to the destination as shown in Fig.3 (a). The probability that a packet fails to reach *D* is the probability that both routes fail. Therefore, the TOP of MR system, P_{o_MR}, is derived as

$$\begin{aligned}P_{o\_MR}&=P_{F,1}\cdot P_{F,2}\\&=\{1-(1-P_{o,1}^{(a)})(1-P_{o,1}^{(b)})\}\{1-(1-P_{o,2}^{(c)})(1-P_{o,2}^{(d)})\}\end{aligned} \qquad (5)$$

where, $P_{F,j}$ denotes the probability that a packet transmission fails at j^{th} route.

Finally, we derive the TOP of the MRPS system, P_{o_MRPS}. Since *S* selects the next-hop destination *A* or *B* based on the CSI of *link a* and *link c*, if at least one of the links has good channel condition with which a packet can be delivered to the next-hop without error, the packet will reach the next-hop destination successfully with only a single packet transmission on the selected path. The last hop to *D* from *A* or *B* can be reached from only a single path. Therefore, we have no advantage of multi-path diversity at the last hop. The probability that the packet will be transmitted through *link b* or link *d* depends on whether the source node *S* selects node *A* or *B* as the next-hop destination. Successful packet delivery at the last hop is possible when the received-SNR γ of the last hop is higher than the threshold-SNR γ_T. Therefore, P_{o_MRPS} is derived as

$$\begin{aligned}P_{o\_MRPS}&=1-P_S(1st\ hop)\cdot P_S(2nd\ hop)\\&=1-(1-P_{o,1}^{(a)}\cdot P_{o,2}^{(c)})\times\\&\quad\{(1-P_{o,1}^{(b)})P_{SEL}(b)+(1-P_{o,2}^{(d)})P_{SEL}(d)\}\end{aligned} \qquad (6)$$

where, P_S (i^{th} hop) denotes the probability that a packet transmission will success at i^{th}-hop and P_{SEL}(k) denotes the probability that the link selected at the last hop is the link *k*.

B. General m-path n-hop network

We extend the result derived from the *two-path two-hop network* into a general *m-path n-hop network*. Fig.3 (b) shows the network, in which each node has *m* multiple paths to the next hop, and the distance from the source to the destination is *n* hops. For simplicity and to compare the performance of the three schemes, we assume that all the links in the network have an equal outage probability, P_o.

Then, for the *m-path n-hop network* the TOP of the MR system, P_{o_MR}, is derived as

$$\begin{aligned}P_{o\_MR}&=\prod_{j=1}^{m}P_{F,j}=\prod_{j=1}^{m}\left\{1-\prod_{i=1}^{n}(1-P_{o,j}^{(i)})\right\}\\&=\{1-(1-P_o)^n\}^m\end{aligned} \qquad (7)$$

For *m*=1, (7) becomes the TOP of the SR scheme, P_{o_SR} = $\{1-(1-P_o{}^n)\}$. Clearly, the SR scheme is unfavorable for a large network because P_{o_SR} goes to 1 faster than the MR scheme as *n* gets large.

Because the MRPS scheme selects the link that has the best channel condition among *m* possible paths to the next hop, the probability that a packet transmission will succeed at the i^{th} hop, P_S(i^{th} hop) is one minus the probability that the instantaneous SNR of all the paths to the next hop falls below a given outage threshold. Again, the last hop only has one path to the destination, which limits the performance of the system to the outage probability of the last link. If we assume that P_{SEL}(k) is equally probable, the total outage probability of the MRPS system, P_{o_MRPS}, is derived as

$$\begin{aligned}P_{o\_MRPS}&=1-\prod_{i=1}^{n-1}P_S(i^{th}\text{ hop})\cdot P_S(n^{th}\text{ hop})\\&=1-\prod_{i=1}^{n-1}\left(1-\prod_{j=1}^{m}P_{o,j}^{(i)}\right)\cdot\left(\sum_{k=1}^{m^{n-1}}\left(1-P_{o,1}^{(n)}\right)P_{SEL}(k)\right)\\&=1-(1-P_o^m)^{n-1}\cdot(1-P_o)\end{aligned} \qquad (8)$$

Because of the term $P_o{}^m$ in (8), the MRPS system outperforms the other two systems in a large network. From (7) and (8), and by approximating $P_{o\_MRPS}\approx P_o$, we can find the number of hops, *n*, that satisfies $P_{o\_MR}>P_{o\_MRPS}$ as

$$n>\frac{\log(1-P_o^{m^{-1}})}{\log(1-P_o)} \qquad (9)$$

If the number of hops is greater than *n*, the MRPS system has lower TOP than the MR system, without the disadvantage of increasing the network bandwidth used. As P_o increases, the *n* that satisfies $P_{o\_MR}>P_{o\_MRPS}$ decreases which increases the region where the MRPS system outperforms the MR system.

IV. NUMERICAL RESULTS

Using the results of Section III, we obtained numerical results of the three schemes using the AT&T WaveLAN wireless LAN card model, which is implemented in the ns-2 simulator [9]. The outage threshold of the signal power at each node is set to –64.37dBm which corresponds to 250m transmission range when the transmission power at the transmitter is set to 24.5dBm [9]. We used a Rayleigh fading channel model and a *two-path n-hop* network.

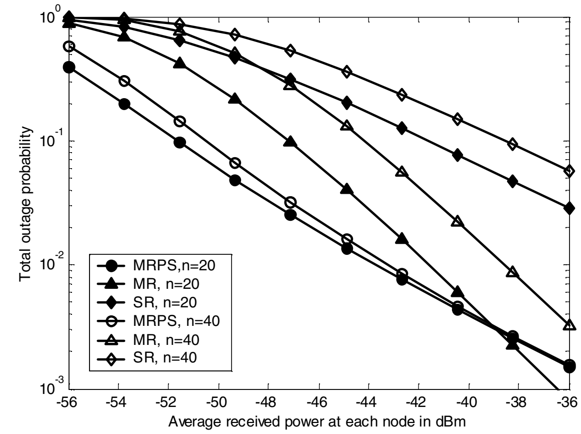


Figure 4. The outage probability of the SR, the MR and the MRPS systems. (number of hops, n = 20 (solid), 40 (dash) and number of multi-path $m = 2$)

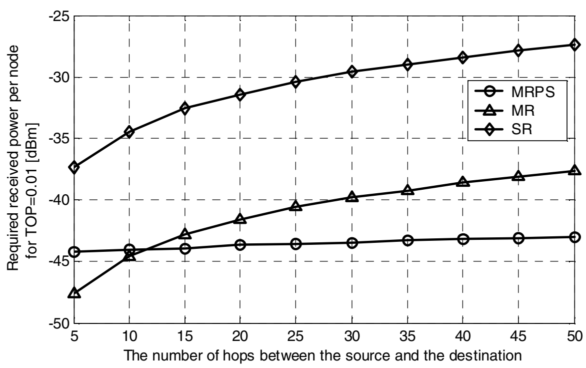


Figure 5. The required received power at each node that guarantees TOP = 0.01 for SR, MR and MRPS schemes. (number of multi-path $m = 2$)

Fig.4 shows the performance comparison between the three schemes choosing n to be both 20 and 40. We measured the TOP by varying the average received power of a node from –60 to –30 dBm. For the most part, the MRPS scheme outperforms the other two schemes. As would be expected, the MR scheme always outperforms the SR scheme. The MR scheme also outperforms the MRPS scheme at the highest simulated powers when $n = 20$ because of the increased reliability of each route to the destination. When packet loss is 1%, the MRPS system obtains 2dB to 4dB performance gain compared to the MR system. The MRPS system obtains at least a 12dB performance gain compared to the SR system for $n > 20$.

Fig.5 shows the required received-power at each node that guarantees TOP=0.01 for the *two-path n-hop* network. We measured the required power by varying the number of hops n from 5 to 50. As the number of hops increases, the required received-power for the MRPS scheme to guarantee TOP=0.01 increases approximately 1dB whereas that of the other two schemes increases approximately 10dB. The result of MRPS scheme shows a markedly smaller dependence on the number of hops n than the other two schemes, suggesting that it has a significant scaling advantage. However, for networks with few hops from the source to the destination, the MR scheme outperforms the MRPS scheme because of the increased reliability of each route to the destination.

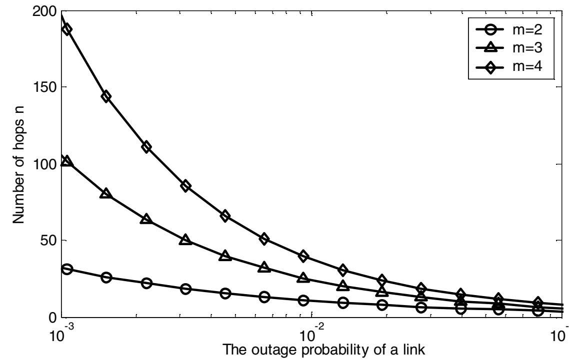


Figure 6. The number of hops n that guarantees $P_{o\_MRPS} < P_{o\_MR}$. (number of multi-path m = 2, 3 and 4)

In Fig.6, the size of the network where the MRPS scheme outperforms the MR scheme is measured by varying both the outage probability of each link and the number of multiple paths. The result shows that as the outage probability of each link gets larger the size of the network at which the MRPS scheme outperforms the MR scheme gets smaller. If we increase the number of multiple paths, which increases the reliability of the MR scheme, the region where the MRPS scheme outperforms the MR scheme (upper region of the graphs) is decreased.

V. CONCLUSION

In this paper, we proposed a new routing metric ROP and a cross-layer protocol stack using that metric and supporting the MRPS diversity scheme. The total outage probabilities for the MRPS, the MR and the SR systems were derived and the size of the network at which the MRPS system outperforms the MR system was determined. We found that the MRPS system is less sensitive to the size of the network compared to the SR and the MR systems. That is, the MRPS system scales better in size.

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