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SPECIAL ISSUE PAPER

Cross-layer design of outage optimum routing metric for wireless ad hoc networks

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ABSTRACT

A new routing metric for multihop wireless ad hoc networks is presented. The proposed metric is based on the computation of signal-to-noise ratio and path minimization of wireless ad hoc network outage probability in a fading environment. This metric improves the quality of service by reducing the number of dropped packets. Further, by modeling the network with a Trellis diagram and then using Viterbi algorithm to select the best routing path, we reduce the routing complexity of our approach. The performance of the proposed metric is compared with other commonly used routing metrics such as minimum hop count, expected transmission count, and two other signal-to-noise ratio-based metrics in both mobile and stationary networks. Simulation results demonstrate the improvement achieved by this new metric. Copyright © 2011 John Wiley & Sons, Ltd.

KEYWORDS
mobile ad hoc networks; routing protocols; outage probability; quality of service; signal-to-noise ratio; Viterbi algorithm

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1. INTRODUCTION

With recent enhancements of high-speed wireless communication networks, the next challenging step is to transmit real-time audio and video data. For these types of applications, connection failure is not acceptable to the end user. Therefore, stability of wireless links is essential. For multihop wireless ad hoc networks, providing route stability is even more challenging. In these networks, a single-link drop may result in an overall route failure. Therefore, the stability of each link in a path is a critical factor. In these networks, where there are multiple paths between source and destination, finding and selecting the most reliable path is very crucial for the overall performance of the network. This goal can be achieved by implementing an appropriate routing scheme.

The network routing process involves two steps: first, assigning cost metrics to links and paths and second, distributing the routing information in the network [1]. Many route dissemination techniques [2,3] have been proposed to address the second step. Proactive protocols, such as Destination Sequenced Distance Vector [4], and reactive protocols, such as Dynamic Source Routing (DSR) [5] and Ad hoc On Demand Distance Vector [6], are proposed. Most of these proposed routing techniques consider the number of hops in a route called *minimum hop count (MinHop)* as their cost metric to find the desired route [2]. Although MinHop offers simplicity and low communication delay, it may not provide a good quality of service. In a wireless network, this metric tends to find paths with long and less stable links that will result in lower network capacity and reliability.

Lower stability and capacity as two critical disadvantages of MinHop metric motivated researchers to find better performing cost metrics. These efforts resulted in proposing new routing metrics that are mostly taking the quality of wireless channel into account [7–14]. There has been some study to compare the performance of these proposed routing techniques. It is shown that no single technique can consistently perform better than others for different network scenarios, such as stationary or mobile networks [12]. The main reason for this inconsistency is that most of these proposed routing metrics are based on intuitive ideas rather than on systematic approaches to calculate an optimum cost metric.

In this paper, we use analytical calculation of outage probability in wireless networks to find an optimum routing metric for these networks. This signal-to-noise ratio (SNR)-based routing metric finds the most stable end-to-end route for wireless data transmission. In order to reduce the search complexity, we model the network as a Trellis diagram and implement the Viterbi algorithm for routing search. This Trellis modeling for routing provides a new framework to design other less complex suboptimal routing protocols in the future.

Finally, we provide simulation results to verify our theoretical findings. Our simulations show that our metric provides better delivery performance compared with MinHop [5], *expected transmission count (ETX)* [7,15], *MaxMinSNR* metric [9,13], and *Average SNR* metric [14] for both stationary and mobile network scenarios with different traffic configurations.

2. RELATED WORK

In [7], a routing metric (ETX) is proposed for wireless networks on the basis of the expected number of transmissions (including retransmissions) necessary to transmit a packet. Each node estimates the forward delivery ratio to each of its neighbors and also receives the corresponding estimate of the reverse direction. This is carried out by sending a probe packet over an initialization time interval before the actual data transmission. Then, the ETX metric is calculated on the basis of the inverse of these delivery ratios. It is shown that ETX outperforms MinHop for stationary fading wireless networks [12]. One of the problems with ETX, though, is its performance in mobile networks. Because probing is completed before the actual data transmission, ETX may not be an accurate indicator of the current channel quality [15] and will result in performance deterioration in mobile networks [12]. As opposed to ETX, where the metric is calculated before the real data transmission, our technique will update the routing metric in a real-time manner taking the SNR of the actual data packets into account. Also, ETX performance in network scenarios with multiple simultaneous flows is not as good as in the single flow case [16]. This is also a consequence of having separate metric calculation probing period where the network traffic and packet sizes are different than the actual data transmission.

In [10], a routing metric based on average round trip time (RTT) is proposed. With this protocol, the routing is carried out by sending probe packets over each channel and by measuring the RTT of the probes. After receiving the packet, each neighbor responds with an acknowledgment containing a timestamp to calculate the RTT. RTT metric is designed to avoid using highly loaded or lossy links. The major drawback of this technique is self-interference, that is, route instability due to load dependence. When a node has low load, the RTT metric for the links toward that node is low. Therefore, more paths tend to select that node as part of their route. This results in higher load on that node and higher RTT metric, which leads to oscillations and instability in route selection.

In [12], *PktPair* protocol is proposed as a modified version of RTT protocol. This metric is based on measuring the delay between a pair of back-to-back probes to a neighboring node. PktPair protocol addresses some of RTT issues (mainly the self-interference problem), but the performance is poor as a result of high overhead. In [12], the performance of ETX [7], RTT [10], PktPair [12], and MinHop are compared. It is shown that ETX has the best performance in a stationary wireless network, whereas MinHop demonstrates a better performance than ETX in mobile cases. Considering these results, we only select ETX and MinHop among the aforementioned four metrics as part of our performance baseline for our simulations.

In addition to the previously mentioned metrics, there are some other proposed routing metrics based on SNR. Incorporating SNR calculations in the routing metric derivation is a promising cross-layer approach, as it addresses the difficulty of defining good and bad links in wireless networks. Thus, the accurate level of link quality can be expressed by the SNR. In [9], a routing strategy is proposed to find the most stable path in the network, the one with the minimum end-to-end outage probability. It is assumed that the bottleneck link, that is, the link with the minimum SNR, limits the throughput of a path and path outage most likely happens because of a drop in this bottleneck link. The main drawback of this strategy is that the derived metric is not *composable*, that is, it does not take into account the performance of all links in the path but only the weakest one. Nevertheless, failures can also happen in other links. This is more likely when there are multiple links in a path with SNR close to the minimum SNR. "Being composable" is an important property of a routing metric so that the end-to-end path cost can be directly derived from the individual link metrics along the path. The metric we propose in this paper is a composable metric (similar to ETX and RTT) and takes into account the performance of all links to determine path performance. Our simulation results demonstrate that this strategy provides performance improvement compared with other approaches.

In [13], a very similar cross-layer approach to [9] is proposed. In this paper, traditional DSR technique is modified so that the source node selects the route on the basis of the value of the best-of-the-worst link SNR and received power among all possible routes. The general performance of this proposed technique is expected to be similar to [9]. Therefore, we take [9] as another performance comparison baseline for our simulations to represent these two references.

In [14], MinHop and link quality are considered sequentially as measures for route selection. First, the path(s) with the minimum number of hops are extracted. If more than one path is found, then the path with stronger links, in terms of average SNR, is selected. If the number of hops is different, no SNR calculation is carried out, and the path with minimum number of hops will be selected. Therefore, these techniques give a higher priority to the number of hops than SNR and do not allow the comparison of paths with different number of hops. On the contrary, our new metric allows comparison of multiple paths with different number of hops; thus, it is a more general comparison that allows us to achieve higher throughput.

The outage probability model for a network that suffers from fading was also exploited in [17]. The authors developed a probabilistic model and studied the relationship among link reliability, distances among nodes, and the transmission power. Algorithms to find the optimal link were developed by taking advantage of route diversity. The emphasis of this work is on the trade-off between reliability and end-to-end power consumption, whereas we use similar outage model for the computation of the best path with minimum outage probability for our routing technique.

3. METRIC DERIVATION

This paper considers maximizing path reliability as the main criterion in route selection for wireless ad hoc networks. Our goal is to find a routing cost metric to minimize the outage probability. In addition, this cost metric should be simple and composable to be implementable for practical applications.

We first start by calculating the link outage probability. In a Rayleigh fading environment, the channel gain can be modeled as a complex Gaussian random variable with zero mean and variance σ_m^2 per complex dimension [18]. Note that for any two Gaussian random variables X and Y, $Z = \sqrt{X^2 + Y^2}$ and Z^2 are Rayleigh and exponentially distributed, respectively.

The transmit power is constant. As a result, the received signal power will be exponentially distributed with mean σ_m^2. Further, an additive white Gaussian noise with variance $N_0/2$ per complex dimension is added to the received signal. With a finite bandwidth of B Hz and transmit power of P_T, the average received SNR, $\bar{\gamma}_m$, including path loss and shadowing is

$$\bar{\gamma}_m = \sigma_m^2 \frac{P_T}{BN_0} \tag{1}$$

The outage probability of link m in path i can be calculated as

$$P_{\mathrm{out},m}^i = P(\gamma_m^i < \gamma_{\mathrm{th}}) = 1 - P(\gamma_m^i \geq \gamma_{\mathrm{th}}) \tag{2}$$

where γ_{th} is the SNR threshold required to support system desired data rate. We will explain in Section 4 how this SNR threshold is used for link qualification purposes. For an exponentially distributed received SNR, this probability is given by

$$P_{\mathrm{out},m}^i = 1 - \exp\left(-\frac{\gamma_{\mathrm{th}}}{\gamma_m^i}\right) \tag{3}$$

Equation (3) shows link outage probability as a function of SNR.

The next step is to calculate path outage probability. Assuming link independence in a path, outage probability of path i with M_i hops is given by

$$\begin{aligned} P_{\mathrm{out}}^i &= 1 - \prod_{m=1}^{M_i} (1 - P_{\mathrm{out},m}^i) \\ &= 1 - \exp\left(\sum_{m=1}^{M_i} \ln(1 - P_{\mathrm{out},m}^i)\right) \end{aligned}$$

The path with optimal outage, i_{opt}, can be computed as

$$\begin{aligned} i_{\mathrm{opt}} &= \arg\min_{\forall i} \left\{1 - \exp\left(\sum_{m=1}^{M_i} \ln\left(1 - P_{\mathrm{out},m}^i\right)\right)\right\} \\ &= \arg\max_{\forall i} \left\{\sum_{m=1}^{M_i} \ln(1 - P_{\mathrm{out},m}^i)\right\} \\ &= \arg\min_{\forall i} \left\{\sum_{m=1}^{M_i} - \ln(1 - P_{\mathrm{out},m}^i)\right\} \end{aligned} \tag{4}$$

Replacing link outage probability from Equation (3) into Equation (4), we arrive at

$$i_{\mathrm{opt}} = \arg\min_{\forall i} \left\{\sum_{m=1}^{M_i} \frac{\gamma_{\mathrm{th}}}{\gamma_m^i}\right\} \tag{5}$$

Note that γ_{th} is fixed for all links and can be eliminated from this equation.

$$i_{\mathrm{opt}} = \arg\min_{\forall i} \left(\sum_{m=1}^{M} \frac{1}{\gamma_m^i}\right) \tag{6}$$

Equation (6) suggests that the path metric is equivalent to the summation of inverse SNR of all the links in the path. This metric finds the outage optimum path and has two important properties of a good routing metric. It is simple and composable. By calculating the inverse SNR metric for all possible paths from source to destination and finding the path with minimum cost metric, we can find the most stable and reliable path, that is, the one with the minimum outage probability.

It is important to mention that the authors in [9] have used outage probability model to find cost metric with the general assumption that path outage only happens as a result of outage in the weakest link of the path. This assumption has resulted in a different routing metric that is not optimal and is not composable. We call this metric MaxMinSNR in this paper. We will show in Section 6 that our new metric results in superior performance compared with MaxMinSNR metric for different network scenarios.

We provide an example to better illustrate the difference among the *Inverse SNR* metric proposed in this paper, MinHop metric used in [4–6], and MaxMinSNR metric proposed in [9] and [13]. Figure 1 illustrates a simple

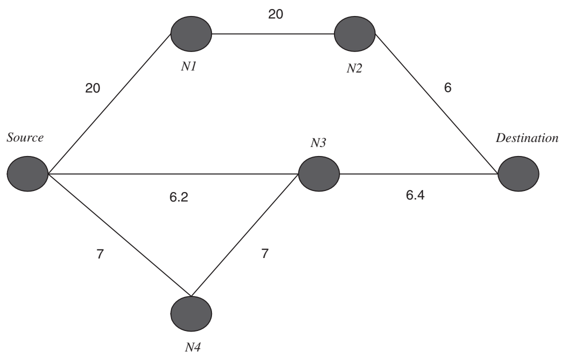

Figure 1. A simple example with three possible paths from source to destination.

network scenario. There are six nodes: one source (S), one destination (D), and four intermediate nodes. The SNR of each link is shown by a number next to it. There are three different possible routes from source to destination. Route 1 (S–N1–N2–D) and Route 3 (S–N4–N3–D) have three hops, whereas Route 2 (S–N3–D) has two hops. Therefore, MinHop routing will select Route 2 as the best route without taking link SNR into account. MaxMinSNR considers the minimum SNR of each path and will select the route with the highest minimum SNR. Therefore, MaxMinSNR will select Route 3 as the best route.

In the case of Inverse SNR routing presented in this paper, the metric for each route is the summation of inverse SNR of all the links in that route. By simply adding link metrics, the route metric for Routes 1, 2, and 3 are equal to 0.2667, 0.3175, and 0.4420, respectively. Therefore, Inverse SNR routing will select Route 1 as the best route.

This simple example shows how each of the SNR-based routing metrics may select a completely different route. In Section 6, we will provide the results and compare the performance of these routing metrics.

4. LINK QUALIFICATION AND MAINTENANCE

In a wireless network, link definition is not as straightforward as in a wired network. In a wired network, nodes have a direct link to each other if they are physically connected, but in a wireless environment, there is no physical representation for a link. Some nodes are able to communicate with each other, but their communication link may not be good enough to be considered as a link in the network topology. These links might be even able to support the low data rate required for routing application but not for the actual data transmission. Also, depending on the network application, the required data rate for the actual data transmission might be different. Therefore, network topology is practically dependent on the application rate requirements. For example, for live video transmission, this minimum required data rate will be higher than audio or data transmission. Some communication channels might be considered as a link for live audio transmission because they are able to support data rate for this application but not an appropriate link for live video transmission. Therefore, the first step is to find out which nodes are able to communicate with each other at the required data rate for targeted network applications.

Link qualification is the step that is using the required data rate for the network application to qualify links on the basis of the minimum required SNR. As previously mentioned in Section 3, this minimum SNR, which can include some additional margin, is called γ_{th}.

We need to find out which links have an average SNR higher than γ_{th}. In order to have a full qualified path, all the links in that path should have SNR higher than threshold SNR. This step not only eliminates unqualified links but also simplifies routing search by reducing the total number of possible routes. In fact, this minimum SNR qualification is an appropriate alternative for the "disk model," which is usually used to define links in other network routing techniques. Distance is the only measure for the disk model to determine which nodes are able to communicate. But in wireless fading environments, the distance among nodes cannot accurately determine the performance of the link, and SNR is a much better indicator.

For some applications such as data streaming where the minimum required data rate is not a requirement, γ_{th} can be reduced to find more links that are able to transmit data at lower rates. Therefore, γ_{th} and the link qualification step are functions of the system application.

Signal-to-noise ratio can also be utilized to prevent link drops after the routing is done and during the actual data transmission. We know that the wireless channel conditions can change because of changes in the wireless environment. A currently good performing link may not be the best candidate in the near future because of mobility or fading. Therefore, route maintenance in a wireless network can be as important as routing itself.

After the routing is done, we have one selected path that goes from source to destination and has the best performance at the current time. This path includes M links where any of them may drop in the future. Therefore, we use the SNR associated to each link to indicate if the link remains stable enough to maintain the connection. This SNR can be continuously measured and used to indicate if the link performance is improving or deteriorating. If the SNR of a link deteriorate to levels close to γ_{th}, an alert will be sent for possible link drop. As mentioned before, to add more stability to the system, γ_{th} itself can include some extra margin. For unnecessary alerts to be avoided, an exponential moving average can be used as explained in Section 6.

This alert can be used to initiate local or global search for a new path before the actual link drop happens. This search will be an addition to frequent routing searches. If the time interval is not long enough for a new routing to be completed, other link loss prevention methods such as rate adaptation techniques can be used to keep the link alive until the routing is done. In this case, the data rate will be adjusted and reduced to the level that the link can still survive until a better route is found. The common key factor here is to utilize SNR as an indicator of the link behavior to reduce the outage probability.

5. A FRAMEWORK FOR ROUTING SEARCH

Calculating link and path metrics and searching for the best route from source to destination among all possible routes can be a very complex task in large networks. Therefore, simplicity of routing protocols is very important. In this section, we propose a general framework for mapping the Viterbi algorithm to routing search protocols. This mapping establishes a framework for the implementation of less complex Trellis-based algorithms to the routing search process.

The first step is to model a multihop wireless network with a Trellis diagram. A Trellis diagram is a finite state machine that is constructed by states, branches, and stages. In a Trellis diagram, there are finite stages from the Trellis starting point to its end point. Also, there are finite states at each stage. We consider a Trellis diagram with M stages and N states at each step (Figure 2). Each branch that starts at state x in stage m and ends at state y in stage $m+1$, has a determined weight (where x and y are less than N). There are several paths from the Trellis start point to its end point, and each path consists of M states and branches. The path weight is composable of its branch weights. As a result, each path has an associated weight, and the path with minimum weight will be selected as the final solution.

The idea is to model a network as a Trellis diagram. A multihop network has a finite number of hops and intermediate nodes that we call *relay*. Assuming a network with a maximum of M hops and N relays at each hop, each link from node x at hop m to node y at hop $m+1$ has a cost metric (both x and y are less than N) that is an indicator of the performance and quality of that link. Path metrics can be calculated from link metrics.

With this general modeling, the Trellis start and end points can be mapped to source and destination nodes in a network, and the number of stages in a Trellis diagram can be mapped to the number of hops in a network. Each state in Trellis will be similar to a node in the network, and the number of states will be equivalent to the maximum node degree in the network. Branch weight in a Trellis is similar to link metric in network routing, and the goal in both Trellis and routing is to find the path with minimum cost metric.

Table I shows in summary how we can map network components to Trellis diagram elements.

Viterbi algorithm is a dynamic programming approach used to run an optimal sequential Trellis search to minimize the error by finding the most likely sequence of states. As it is illustrated earlier, a Trellis diagram model can be implemented for a network. Because both Viterbi algorithm and network routing are dynamic programming approaches, the next step will be to show how running Viterbi algorithm for a Trellis diagram is similar to finding the best possible route from source to destination in a network.

Viterbi algorithm will perform a full search while minimizing the complexity by dynamically eliminating subpaths with lower performance originating and ending at common nodes. The Viterbi algorithm implementation will help reduce the complexity of the full Trellis search while keeping the optimal performance. This means that we can reduce the complexity without any performance degradation. More significantly, this mapping framework can be used as an initial step to implement other (already existing) suboptimal Trellis search algorithms with lower complexity into the network routing concept.

It is important to mention that the work presented in this section is only the initial step of a general framework. More details on this framework and other suboptimal schemes

Table I. Mapping network routing to Trellis diagram.

Trellis diagram	Network routing
Start point	Source node
End point	Destination node
States	Nodes
Stage	Hops
Branch	Link
Branch weight	Link metric
Survivor path	Selected route

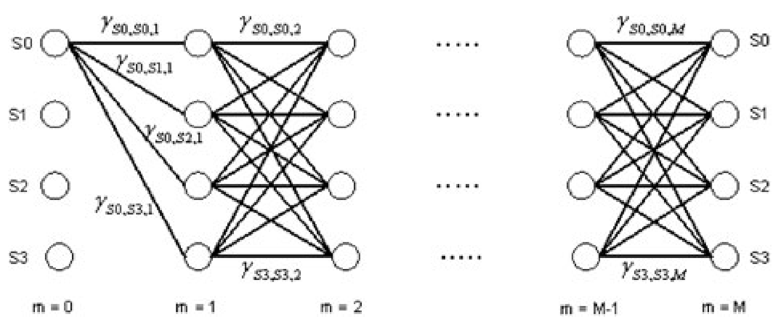

Figure 2. Four-state Trellis diagram.

are required for a more comprehensive modeling, which will be presented in future works.

6. SIMULATION

In this section, we will first explain the details of the simulation environment. Then, we will present simulation results for the Inverse SNR metric introduced in this paper and compare it with the results from other techniques.

6.1. Simulation environment

We use Qualnet [19] as the simulation environment for our experiments. We randomly distribute 30 nodes in a 1000 m×1000 m square area with Rayleigh fading channel. For the mobility scenario, each node has a random speed of 1–10 m/s. This scenario mimics an environment where people walk, run or ride bicycle.

Each node runs IEEE 802.11 as the MAC protocol and 802.11b as PHY model with a transmit power of 15 dBm. For each measurement, two nodes are randomly selected as source and destination. Constant bit rate (CBR) traffic is used to simulate the performance of generic multimedia traffic. This User Datagram Protocol-based, client–server application sends data at CBR. The source node transmits 50 000 packets of size 2048 bits with 500 packets/s CBR. The number of received packets is measured to calculate delivery ratio. Thirty measurements are carried out with different random pair of source and destination nodes and averaged to represent the performance of each technique.

Table II summarizes the important configuration parameters for our simulation.

6.2. Simulation results

We modified DSR protocol [5] to implement the Inverse SNR metric. For the Inverse SNR metric to be implemented into DSR, a new weight label is defined for each route. Whenever a packet is received by an intermediate node, it adds the inverse SNR of that link to the weight label received from the upstream neighbor and updates the weight label. Therefore, the overall route weight label is composable by adding link weight labels.

Because link SNR can rapidly change in a mobile wireless environment, exponential moving average is used for SNR measurement smoothing as

$$SNR_t = \alpha \times SNR_{t-1} + (1-\alpha) \times SNR_{\text{ins}} \qquad (7)$$

SNR_t and SNR_{t-1} are the new and old smoothed SNR, respectively, and SNR_{ins} is the current (instantaneous) SNR value. Smaller α value gives more weight to the current measured SNR, whereas larger values give more weight to the previous average measurement. Having a small α may result in rapid change in the average SNR and frequent switching of the selected path, which is undesirable for the stability of the system. On the other hand, a large α value may result in some undesirable delay in route switching when the quality of the route deteriorates. Therefore, optimization of α value can be a determining factor in the performance of the system. For our simulation, $\alpha = 0.9$ is used for different network scenarios.

Because stability and delay are two of the most essential factors for the performance of a communication network, we present our results in terms of the number of delivered packets and average end-to-end delay. Number of delivered packets is a good metric for system stability performance. Because the transmission data rate and the total number of transmitted packets are fixed (CBR), the number of delivered packets is also a representative of the throughput. End-to-end delay is the one-way delay between the time that source sends the packet and the time that destination receives it. It is averaged over all received packets. For CBR transmission, delay can be due to the network layer queue, MAC layer delay, transmission delay, and propagation delay [19]. The propagation delay depends on the distance among nodes in a wireless network, and the transmission delay depends on the link bandwidth. Therefore, analyzing end-to-end delay will be more complicated than the number of delivered packets because the former is dependent on the route's physical length, bandwidth, and other network parameters.

We have conducted simulation results for two well-established routing metrics, MinHop [5] and ETX [7,15], as well as two recently proposed SNR-based metrics, MaxMinSNR [9,13] and Average SNR [14], all of which implemented for the DSR protocol. The DSR implementation of ETX is carried out as explained in [15], and the DSR implementation of MaxMinSNR and Average SNR is carried out similar to the process explained in [13].

We start our simulation results with a basic stationary case where there is only a single CBR flow of data transmitted through the network. Then, we look at some more complex cases such as a mobile network and multiflow

Table II. Simulation configuration.

Parameter	Value
MAC protocol	MAC 802.11
PHY model	PHY 802.11b
Carrier frequency (GHz)	2.4
Node placement	Random waypoint
Pathloss model	Two-ray
Fading model	Rayleigh
Dimension (m × m)	1000 × 1000
Packet size (bits)	2048
Transmit rate (packets/s)	500
Transmit rate (kbps)	1024
Total transmitted packets	50 000
Transmit power (dBm)	15
PHY temperature (Kelvin)	290
Antenna height (m)	1.5
Antenna model	Omnidirectional

transmission cases to show how these network configuration changes affect the performance of different routing metrics. The following text explains details of all aforementioned scenarios.

6.2.1. Stationary single flow case.

In this section, we evaluate a stationary network scenario where all 30 nodes have fixed locations during the simulation. For each metric, the simulation is carried out for 50 random node pairs, and results are averaged and displayed. We provide and compare the average number of delivered packets and average end-to-end delay as performance indicators for all five previously mentioned metrics.

As it is shown in Figure 3, Inverse SNR has the highest and MinHop has the lowest average packet delivery ratio. For this test scenario, Average SNR technique shows some improvement compared with MinHop, which is consistent with the results in [14], but the improvement is only less than 5%. The reason for this minor improvement is that Average SNR modifies the route only when there are multiple routes with the same number of hops that is not applicable to all scenarios. MaxMinSNR shows better performance compared with MinHop, which is also consistent with [13] but still has a lower delivery performance compared with ETX and Inverse SNR. As it is shown here and previously in [12], ETX performs well in single flow stationary networks; however, Inverse SNR continues to be superior. This is in line with our analytical work where it is demonstrated that Inverse SNR minimizes the outage path probability resulting in maximized delivery performance.

The average end-to-end delay comparison is shown in Figure 4. As explained before, end-to-end delay can occur as a result of network layer queue, MAC layer delay,

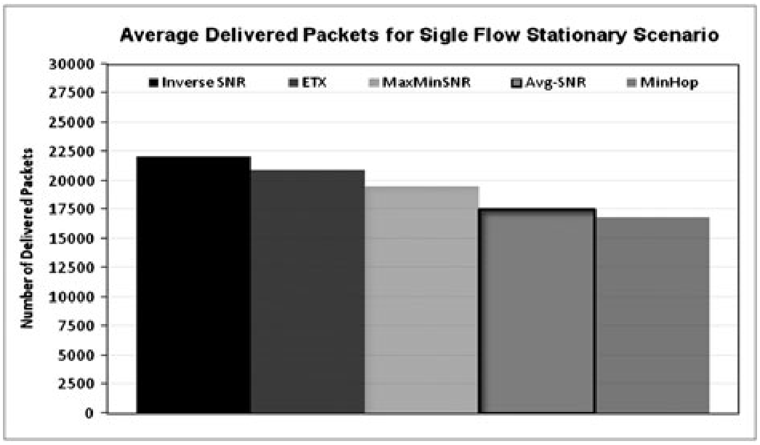

Figure 3. Inverse signal-to-noise ratio (SNR) delivers more packets on average than all the other metrics for stationary single flow scenario. ETX, expected transmission count; MinHop, minimum hop count.

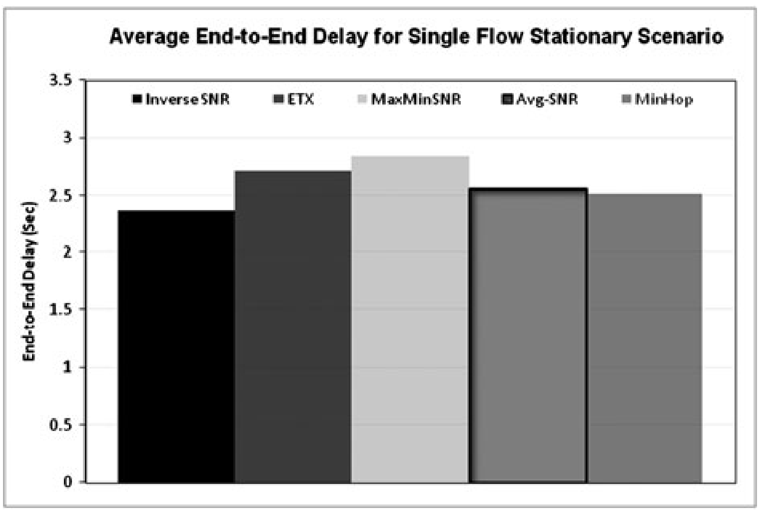

Figure 4. Inverse signal-to-noise ratio (SNR) has smaller average delay than all the other metrics for stationary single flow scenario. ETX, expected transmission count; MinHop, minimum hop count.

transmission delay, and propagation delay. Therefore, analyzing end-to-end delay for all five techniques is very complicated, but our simulation results show an overall superiority for the Inverse SNR metric. Also, as shown, MinHop demonstrates fairly good delay performance compared with other techniques, which could be attributed to a lower propagation delay and less number of packet forwarding required compared with other techniques.

6.2.2. Mobile network single flow case.

We have also conducted simulations for the mobile scenario where nodes are moving with random mobility of 1–10 m/s. This case can be a representative of the scenario when people are roaming while holding wireless transceiver-enabled devices in an office environment.

The average delivery performance for all five metrics is presented in Figure 5. Similar to the stationary cases, Inverse SNR provides the best stability (delivery ratio) and throughput performance. ETX has the worst performance compared with others because it allocates an initial probing time before the actual data transmission for link metric calculation. By the time of actual data transmission, the metrics calculated during probing may change, resulting in an inaccurate evaluation of the link performance. Therefore, ETX provides performance improvement compared with MinHop only for stationary cases, which is consistent to the findings in [12].

Average end-to-end delay comparison for mobile cases is shown in Figure 6. For this scenario, MinHop and Average SNR, which are both calculating the route on the basis of minimum number of hops, provide slightly better

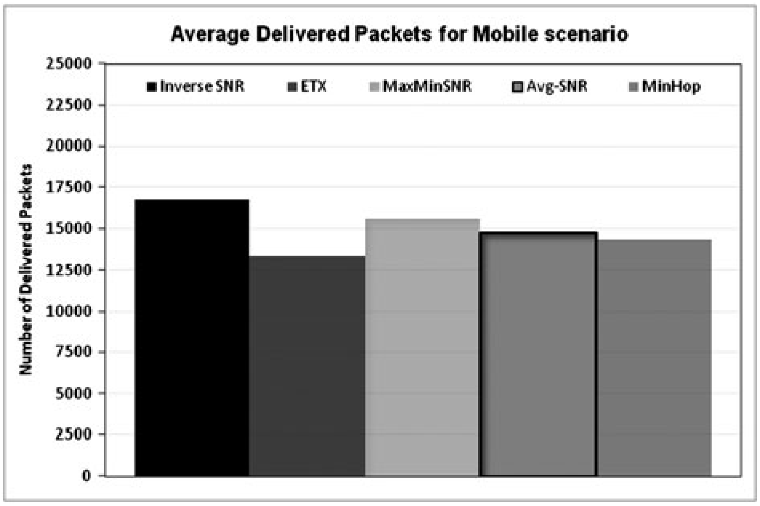

Figure 5. Inverse signal-to-ratio (SNR) has the highest throughput among all metrics for the mobile scenario. ETX, expected transmission count; MinHop, minimum hop count.

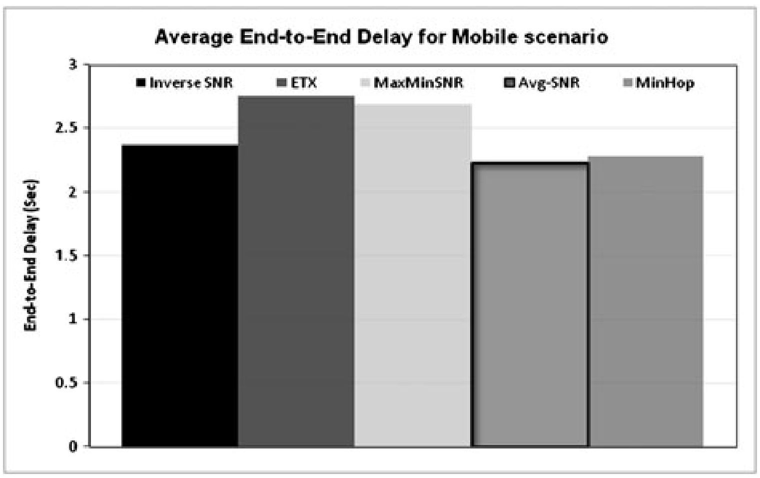

Figure 6. End-to-end delay comparison of all metrics in mobile environment. SNR, signal-to-noise ratio; ETX, expected transmission count; MinHop, minimum hop count.

performance of 6% and 4%, respectively, compared with Inverse SNR, whereas ETX and MaxMinSNR have higher average end-to-end delay. Similar to the stationary case, a detail analysis of end-to-end delay for all five techniques is complicated because it depends on various contributing factors. However, the overall delay advantage of hop counting-based techniques are related to the fact that these techniques require the least number of intermediate packet forwarding by relay nodes, which is resulting in lower queuing delay, and queuing delay is a significant factor in overall end-to-end delay.

Given the superior overall performance of Inverse SNR technique for stationary networks and better packet delivery for mobile scenarios, this approach is particularly suitable for applications that are sensitive to packet losses. Note that the delay for this technique is very close to the best techniques in our simulations.

6.2.3. Multiflow transmission case.

For this case, similar to the first case, the network is stationary, but there are multiple concurrent CBR flows for the actual data transmission as opposed to a single CBR flow for previous cases. In this section, we show the results for two different traffic cases, three and five concurrent CBR flows. Comparing these results with the results from single flow scenario illustrates the impact of network traffic increase on the performance of all five examined metrics.

Figure 7 shows the average packet delivery comparison for all five metrics with three simultaneous flows of data in the network. As it was the case for all previous scenarios, the Inverse SNR metric provides the best delivery performance. Average SNR, MaxMinSNR, and MinHop provide lower delivered packets by less than 10%, whereas ETX's performance deteriorates significantly

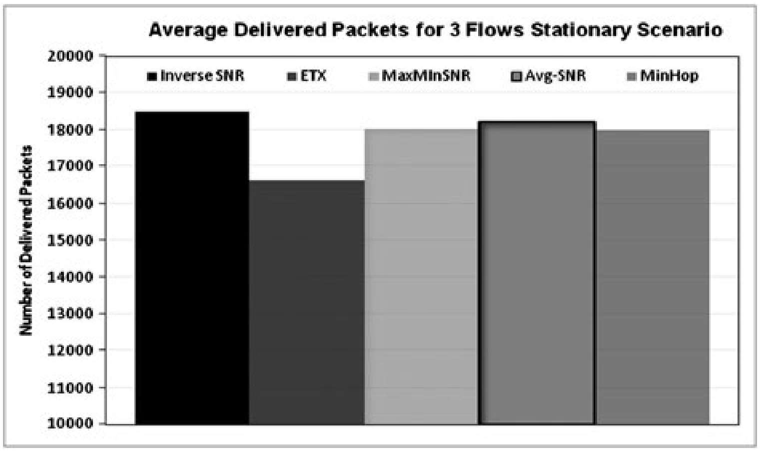

Figure 7. Inverse signal-to-noise ratio (SNR) has the highest throughput in three flows scenario. ETX, expected transmission count; MinHop, minimum hop count.

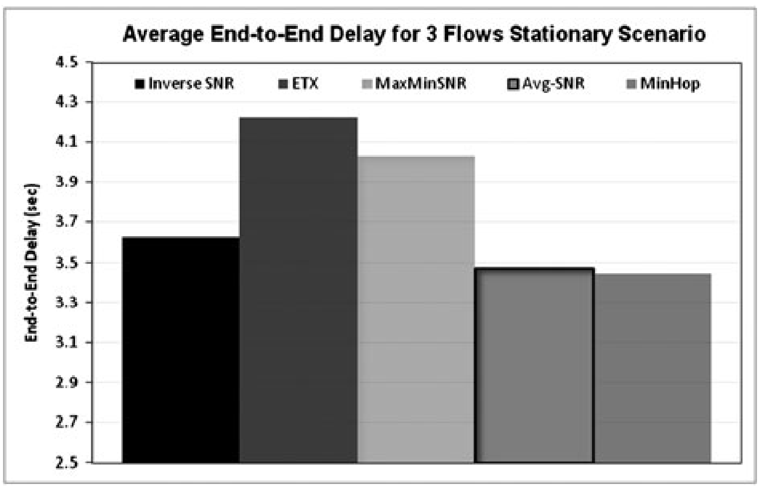

Figure 8. End-to-end delay comparison of all metrics in three flows scenario. SNR, signal-to-noise ratio; ETX, expected transmission count; MinHop, minimum hop count.

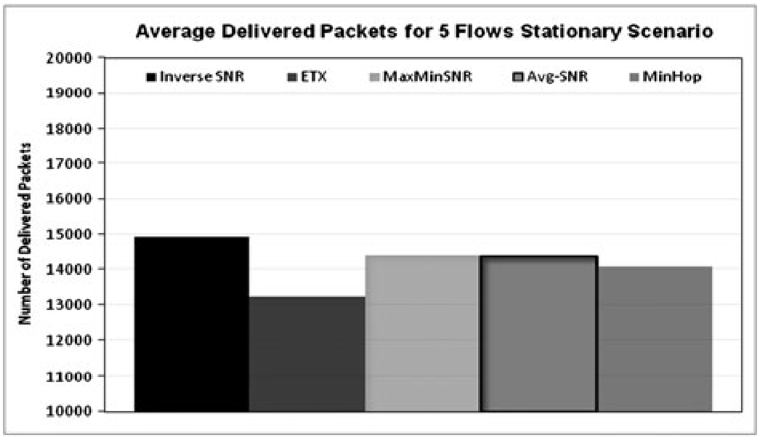

Figure 9. Inverse signal-to-noise ratio (SNR) has the highest throughput in five flows scenario. ETX, expected transmission count; MinHop, minimum hop count.

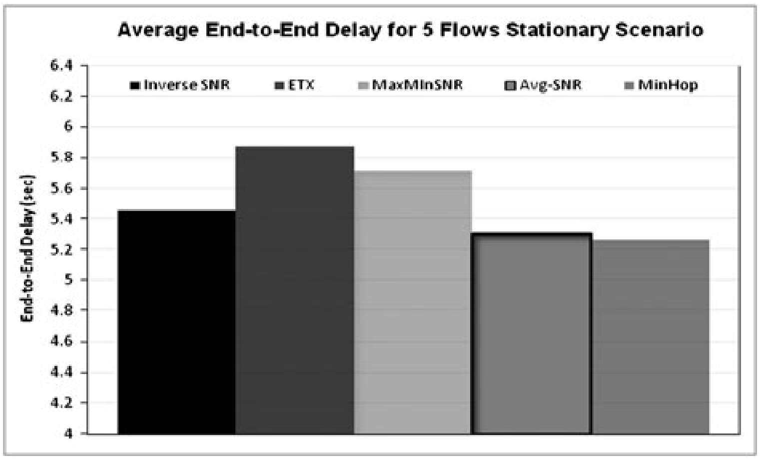

Figure 10. End-to-end delay comparison of all metrics in five flows scenario. SNR, signal-to-noise ratio; ETX, expected transmission count; MinHop, minimum hop count.

for multiflow scenario, which is consistent with results previously reported in [16].

Average end-to-end delay comparison for three flows scenario is shown in Figure 8. It can be seen that MinHop has the lowest end-to-end delay. Inverse SNR has slightly higher delay than MinHop but still performs significantly better than other SNR-based metrics. Higher Inverse SNR delay compare with MinHop for higher traffic cases is the result of traffic congestion on best-performing links. As traffic increases, more flows tend to select common high-performing links, and that causes more queuing and transmission delay.

Figure 9 shows the average delivery comparison for all five metrics with five simultaneous CBR flows of data in the network. As it was shown theoretically and seen for all previous scenarios, the Inverse SNR metric provides the best packet delivery ratio among all metrics. Average end-to-end delay comparison for this test scenario is shown in Figure 10, which is, in general, consistent with the results from three flows scenario, and same comments are applicable to this case as well.

7. CONCLUSION

This paper introduces a new routing metric based on the inverse SNR criterion for wireless networks. This metric is derived by theoretical calculations to minimize the path outage probability in a wireless network and to maximize the network delivery performance in fading environments.

Simulation results show that as far as stability, throughput, and outage performance are concerned, Inverse SNR metric dominates MaxMinSNR, MinHop, Average SNR, and ETX metrics for all test cases with different traffic and mobility configurations, which is consistent with our theoretical derivations.

Further, the Inverse SNR is a composable metric, which is a desirable characteristic for routing metrics.

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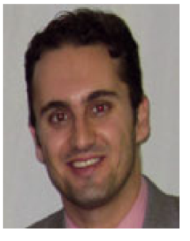
REFERENCES

1. Hossain E, Leung K. *Wireless Mesh Networks: Architectures and Protocols*. Springer Science: New York, 2007.
2. Royer EM, Toh CK. A review of current routing protocols for ad hoc mobile wireless networks. *IEEE Personal Communications* 1999; **6**(2): 46–55.
3. Abolhasan M, Wysocki T, Dutkiewicz E. A review of routing protocols for mobile ad hoc networks. *Ad Hoc Networks* 2004; **2**: 1–22.
4. Perkins CE, Bhagwat P. Highly dynamic destination sequenced distance-vector routing (DSDV) for mobile computers. In *Proceedings of the ACM SIGCOMM conference on communications architectures, protocols and applications*: London, UK, 1994; 234–244.
5. Johnson DB, Matlz DA. Dynamic source routing in ad hoc wireless networks. In *Mobile Computing Chapter 5*. Kluwer Academic Publishers, 1996; 153–181.
6. Perkins CE, Royer EM. Ad-hoc on-demand distance vector routing, In *Proceedings of the Second IEEE workshop on Mobile Computer Systems and Applications*, New Orleans, USA, 1999; 90–100.
7. Couto D, Aguayo D, Bicket J, Morris R. A high-throughput path metric for multi-hop wireless routing, In *ACM Conference on Mobile Computing and Networking (MOBICOM)*, San Diego, USA, 2003; 134–146.
8. Koksal CE, Balakrishnan H. Quality-aware routing metrics for time-varying wireless mesh networks. *IEEE Journal on Selected Areas in Communications* 2006; **24**(11): 1984–1994.
9. Gui B, Dai L, Cimini LJ. Routing strategies in multihop cooperative networks. *IEEE Transactions on Wireless Communications* 2009; **8**(2): 843–855.
10. Adya A, Bahl P, Padhye J, Wolman A, Zhou L. A multi-radio unification protocol for IEEE 802.11 wireless networks. *Technical Report MSR-TR-2003-44*, Microsoft Research, 2003.
11. Draves R, Padhye J, Zill B. Routing in multi-radio, multi-hop wireless mesh networks, In *ACM Conference on Mobile Computing and Networking (MOBICOM)*, Philadelphia, USA, 2004; 114–128.
12. Draves R, Padhye J, Zill B. Comparison of routing metrics for static multi-hop wireless networks, In *ACM conference of Special Interest Group on Data Communication (SIGCOMM)*, Portland, USA, 2004; 133–144.
13. Alnajjar F, Chen Y. SNR/RP aware routing algorithm, cross-layer design for MANETs. *International Journal of Wireless and Mobile Networks (IJWMN)* 2009; **1**(2): 127–136.
14. Zhou Y, Chung S, Yang L, Choi H. A link-quality aware routing metric for multi-hop wireless network, In *International Conference on Communication Software and Networks (ICCSN)*, Chengdu, China, 2009; 390–394.
15. DeCouto D. High-throughput routing for multi-hop wireless networks, *Ph.D. thesis*, Massachusetts Institute of Technology, 2004.
16. Ni X, Lan K, Malaney R. On the performance of expected transmission count, (ETX) for wireless mesh networks, In *Workshop on Modelling and Design of Wireless Mesh Networks (MODENETs)*, Athens, Greece, 2008.
17. Khandani AE, Abounadi J, Modiano E, Zhang L. Reliability and route diversity in wireless networks. *IEEE Transactions on Wireless Communications* 2008; **7**(12): 4772–4776.
18. Goldsmith A. *Wireless Communications*. Cambridge University Press: New York, 2005.
19. Scalable Networks. The Qualnet simulator. http://www.scalable-networks.com/products/qualnet.

AUTHORS' BIOGRAPHIES



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