Outage Optimum Routing for Wireless Networks

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***Abstract*—A new routing metric for multi-hop wireless ad hoc networks is presented. The proposed metric is based on the computation of Signal-to-Noise Ratio (SNR) and minimization of wireless network outage probability in a fading environment. This metric improves the Quality-of-Service by reducing 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. Simulation results demonstrate the improvement achieved by implementation of this new metric. Performance of the proposed metric is compared to other commonly used routing metrics such as Minimum Hop Count (MinHop), Expected Transmission Count (ETX) and two other SNR-based metrics in both mobile and stationary networks.**

I. Introduction

Current high speed wireless communication networks are used for real-time audio and video applications. For these types of applications, connection failure is not acceptable to the end user. Therefore, stability of wireless links is critical. For multi-hop wireless ad hoc networks, providing route stability is even more challenging. In these networks, link drop may result in overall route failure. Therefore, the stability of each link in a path can be a critical factor. In these networks, where there are multiple paths between source and destination, finding and selecting the most reliable path is very essential to the overall performance of the network.

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 (DSDV) [4], and reactive protocols, such as Dynamic Source Routing (DSR) [5] and Ad hoc On Demand Distance Vector (AODV) [6], are proposed. Most of these proposed routing techniques consider the number of hops in a route called *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 unstable links which will result in lower network capacity and reliability.

Lower stability and capacity as two critical disadvantages of *MinHop* metric motivated researchers to find cost metrics which provide better performance. These efforts resulted in proposing new routing metrics which take into account the quality of wireless channels [7]–[14]. There has been some study to compare the performance of these routing techniques. It is shown that none of these techniques 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 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 outage routing metric for network reliability. This SNR-based routing metric finds the most stable end-to-end route for wireless data transmission. In order to reduce the routing complexity, we model the network as a Trellis diagram and implement the Viterbi algorithm for routing search.

Finally, we provide simulation results to verify our theoretical findings. Our experiments show that our metric provides better delivery performance compared to *MinHop* [5], *ETX* [7], [16], *MaxMinSNR* metric proposed in [9], [13] and the *Average SNR* metric proposed in [14] for both stationary and mobile network scenarios.

II. Related work

In [7], a routing metric (*ETX*) is proposed for wireless networks based on 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 done by sending a probe packet over an initialization time interval before the actual data transmission. Then, the *ETX* metric is calculated based on 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. Since probing is completed before the actual data transmission, *ETX* may not be an accurate indicator of the current channel quality [16] 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 [17], which is also a consequence of having separate probing period for metric calculation with lower network traffic than the actual data transmission.

In [10], a routing metric based on average Round Trip Time

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(*RTT*) is proposed. In this protocol, the routing is done by sending probe packets over each channel and measuring the RTT of the probes. After receiving the packet, each neighbor responds with an acknowledgment (ACK) containing a timestamp to calculate the RTT. *RTT* is designed for highly loaded or lossy links. The major drawback of this technique is self-interference, i.e, 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 while *MinHop* demonstrates a better performance than *ETX* in mobile cases. Considering these results, we only select *ETX* and *MinHop* among the above four metrics as part of our performance baseline for simulations.

In addition to the above mentioned metrics, there are some other proposed routing metrics based on SNR. Incorporating SNR calculations in the routing metric derivation is a promising approach, as it addresses the difficulty of defining good and bad links in wireless networks. Thus, there are many separate levels of link quality that 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, i.e., the link with the minimum SNR, limits the throughput of a path and an outage can happen only due to a drop in this bottleneck link. The main drawback of their strategy is that the derived metric is not composable, i.e., 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 easily 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 to other approaches.

In [13], a very similar approach to [9] is proposed. In this paper, traditional DSR routing technique is modified so that the source node selects the route based on the value of the best of the worst link SNR and Received Power (RP) among all possible routes. The general performance of this proposed technique is expected to be similar to [9].

In [14], *MinHop* and link quality are considered sequentially. 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 calculations are made and the path with *MinHop* will be selected. On the contrary, our new metric allows comparison of multiple paths with different number of hops, thus, it is more general and can achieve higher throughput.

The outage probability model for a network that suffers from fading was also exploited in [15]. The authors developed a probabilistic model and studied the relationship between link reliability, distance between nodes and the transmission power. Algorithms to find the optimal link were developed by taking advantage of route diversity. The emphasis of this work was on the trade-off between reliability and end-to-end power consumption, whereas we focus on the computation of the best path with minimum outage probability.

III. Metric Derivation

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

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 and 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

$$P^i_{out,m} = P(\gamma^i_m < \gamma_{th}) = 1 - P(\gamma^i_m \geq \gamma_{th}), \tag{2}$$

where γ_{th} is the SNR threshold required to support system desired data rate. For an exponentially distributed received SNR, this probability is given by

$$P^i_{out,m} = 1 - \exp(-\frac{\gamma_{th}}{\gamma^i_m}). \tag{3}$$

Eq. (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

$$P^i_{out} = 1 - \prod_{m=1}^{M_i} (1 - P^i_{out,m}) = 1 - \exp\left(\sum_{m=1}^{M_i} \ln(1 - P^i_{out,m})\right).$$

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

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

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

$$i_{opt} = \arg\min_{\forall i}\left\{\sum_{m=1}^{M_i}\frac{\gamma_{th}}{\gamma_m^i}\right\}. \quad (5)$$

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

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

Eq. (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, i.e., 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 which is not optimal and is not composable. We call this metric *MaxMinSNR* in this paper.

We provide an example to better illustrate the difference between 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 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 while 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 the simulation section, we will provide the results and compare the performance of these routing metrics.

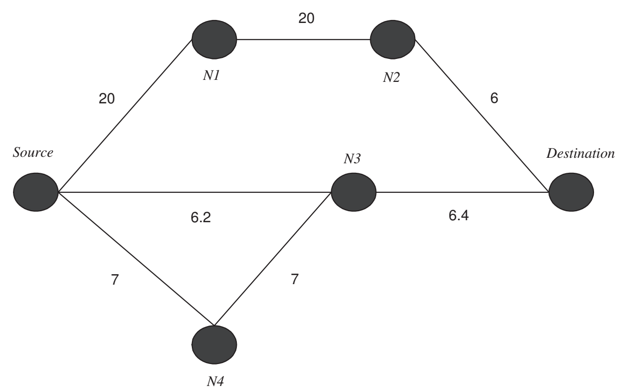

Fig. 1. A simple example with three possible paths from source to destination

IV. A Framework For Routing Search

Calculating link and path metrics to find 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.

The first step is to model a multi-hop wireless network with a Trellis diagram. A Trellis diagram is a finite state machine which 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 (Fig. 2). Each branch which 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 multi-hop network has a finite number of hops and intermediate nodes which 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) which 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

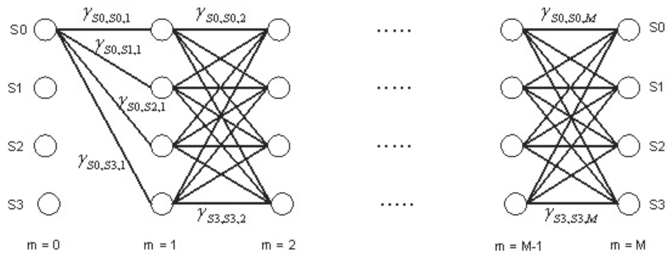

Fig. 2. 4-state Trellis Diagram

routing and the goal in both Trellis and routing is to find the path with minimum cost metric.

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 above, a Trellis diagram model can be implemented for a network. Since 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. A more comprehensive modeling will be done in future works.

Viterbi algorithm will perform a full search while minimizing the complexity by dynamically eliminating sub-paths 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 are required for a more comprehensive modeling which is beyond the scope of this paper and will be presented in future works.

V. Simulation

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

A. Simulation Environment

We use Qualnet [19] as the simulation environment for our experiments. We randomly distribute 30 nodes in a $1000m \times 1000m$ square area with Rayleigh fading. For the stationary scenario, nodes are fixed and 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 UDP-based, client-server application sends data at a constant bit rate. The source node transmits 50000 packets of size 2048 bits with 500 packets/sec CBR. The number of received packets is measured to calculate delivery ratio. Thirty measurements are done with different random pair of source and destination nodes and averaged to represent the performance of each technique.

B. Simulation Results

We modified the reactive DSR routing protocol [5] to implement the Inverse SNR metric. When a source *S* is interested in a destination *D*, the route is set up on-demand by sending a Mesh Request (MR). The MR is replied by a Mesh Acknowledgment (MA) from the destination *D*, which is re-broadcasted by intermediate nodes toward the source. To implement the *Inverse SNR* metric into DSR, a weight label is defined for each route. Whenever a packet is received by an intermediate node, the SNR of the packet is calculated. Then the intermediate node adds the inverse of link SNR to the weight label received from the upstream neighbor to update the weight label. Therefore, the overall route weight label is composable by adding link weight labels. This process continues until we reach the source node *S*. The source node receives weight labels from all routes and selects the route with the lowest weight label (route metric).

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

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

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. For our simulation, $\alpha = 0.9$ is used for different network scenarios.

Results are presented 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. Since 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 between 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 since 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] [16], as well as two recently proposed metrics, *MaxMinSNR* [9] [13] and *Average SNR* [14], all of which implemented for the DSR routing protocol. The DSR implementation of *ETX* is done as explained in [16] and the DSR implementation of *MaxMinSNR* and *Average SNR* is done similar to the process explained in [13]. The following text explains details of stationary and mobile simulation scenarios.

1) Stationary network: In this section, we evaluate a stationary network scenario where all 30 nodes are fixed during the simulation. For each metric, the simulation is done 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 above mentioned metrics.

As it is shown in Fig. 3, *Inverse SNR* has the highest and *MinHop* has the lowest average packet delivery ratio. *Average-SNR* technique shows improvement compared to *MinHop*, which is consistent with the results in [14], but the improvement is only less than 5 percent. 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 which is not applicable to all scenarios. *MaxMinSNR* shows better performance compared to *MinHop* which is also consistent with [13] but still has a lower delivery performance compared to *ETX* and *Inverse SNR*. As it is shown here and previously in [12], *ETX* performs well in 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 Fig. 4. As explained before end-to-end delay can occur as a result of network layer queue, MAC layer delay, transmission delay and propagation delay. Therefore, analyzing details of end-to-end delay for all five techniques is complicated, but our simulation results shows the superiority of the *Inverse SNR* metric. Also as it is shown, *MinHop* demonstrates fairly good delay performance compared to other techniques which could be attributed to a lower propagation delay compared to other techniques.

2) Mobile Network: 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 Fig. 5. Similar to the stationary cases, *Inverse SNR* provides better stability (delivery ratio) and throughput performance. *ETX* has the worst performance compared to

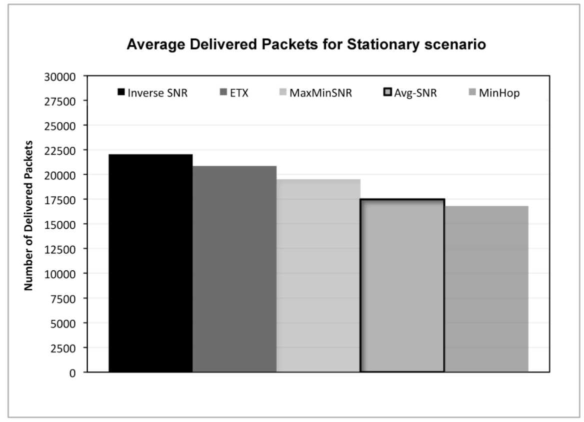

Fig. 3. Inverse SNR delivers more packets on average than all the other metrics

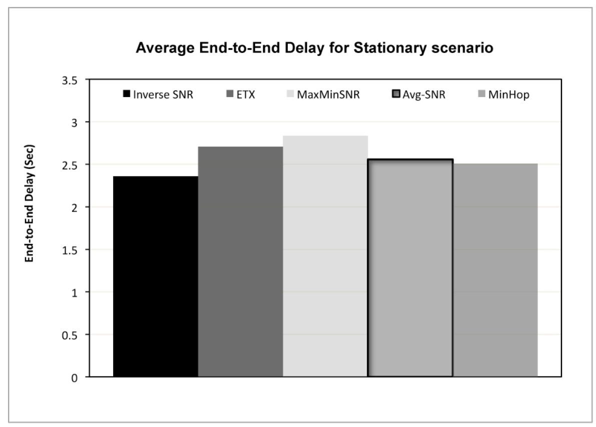

Fig. 4. Inverse SNR has smaller average delay than all the other metrics

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* only provides performance improvement for stationary cases which is consistent to findings in [12].

Average end-to-end delay comparison for mobile cases is shown in Fig. 6. For this scenario, *MinHop* and *Average SNR* provide slightly better performance of 6 and 4 percent respectively compared to *Inverse SNR* while *ETX* and *MaxMinSNR* have the highest average end-to-end delay. Similar to the stationary case, analysis of end-to-end delay for all five techniques is complicated because it depends on many different network parameters.

Given the superior performance of this technique for stationary networks and better packet delivery for mobile scenarios, this approach is particularly suitable for applications that are

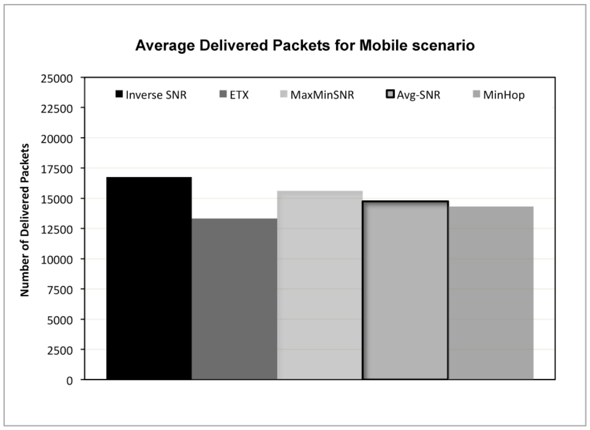

Fig. 5. Inverse SNR has the highest throughput in a mobile scenario

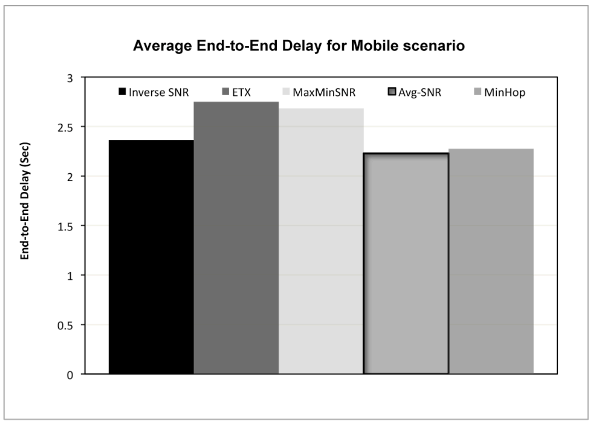

Fig. 6. End-to-End Delay Comparison of all metrics mobile environment

sensitive to packet losses. Note that the delay of this technique is very close to the best techniques in our simulations.

VI. 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 maximize the network delivery performance in fading environments. Simulation results show that this *Inverse SNR* metric has better delivery performance compared to *MaxMinSNR*, *Minhop*, *Average SNR* and *ETX* routing in both mobile and stationary wireless networks. Further, the *Inverse SNR* scheme is a composable metric which is desirable for path selection. We also demonstrated how to take advantage of Viterbi algorithm to implement *Inverse SNR* approach.

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