Wireless Channel-Aware Ad Hoc Routing Protocol with Multi-route Diversity

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Abstract

A mobile Ad hoc network has become great interest due to the increasing use of wireless devices to access the network. However, the channel quality of the wireless link is unfavorable than that of the wired network. Moreover, the quality of a wireless link changes in time. In this paper, we analyze the performance gain that could be obtained from the use of the channel information of the link at the network layer and propose a system model that could enable the use of physical layer information at the network layer routing protocol. To mitigate the fading channel, the routing protocol of the proposed system employs multi-route diversity scheme that selects the link to the next hop that has the best channel condition. The implementation of the proposed system is possible with a little modification of the IEEE 802.11 standard [8], MAC (Media Access Control) layer protocol and the AODV (Ad hoc On-demand Distance Vector) routing protocol [2] of the network layer. The performance of the system is measured with the outage power probability over the Rayleigh fading channel and the simulation results are compared with 1) the system that does not uses multi-route diversity and 2) that uses multi-route diversity but sends the same packet through all available routes to the destination. The simulation results show that the proposed system outperforms the system that doesn't use the multi-route diversity scheme. Moreover, for a large size of Ad hoc network, the proposed system even outperforms the system that uses multi-route diversity, which sends the same packet through all available routes to the destination

1. Introduction

The Ad hoc network consists of a number of mobile nodes that communicates with each other over unreliable wireless links. Since there is no control node that could coordinate the communication between any two nodes, all the nodes in the network participates as a router when it needs to relay a data between two nodes. Various routing protocols, such as AODV (Ad hoc On-demand Distance Vector) [2] and DSR (Dynamic Source Routing) [3] have been proposed for the Ad hoc network routing protocols during past several years. However, they only use the hop count of the links as the information for route selection, which is only effective in the wired networks. Because the wireless communication between the two nodes experiences multipath fading channel, which is due to multipath and mobility of the nodes, to achieve the reliable transmission, we need to employ a diversity scheme. At the physical layer, many diversity and coding schemes are proposed to improve the performance of the system over the fading channel [10]. If the nodes in the multi-hop network are dense enough so that there are multiple routes to the destination, we can employ the multi-route diversity that sends packets over multiple routes from source node to the destination. Multi-route (multi-path) diversity schemes have been investigated by a number of papers [4,5,6]. They have shown that the multi-route routing protocols have a number of advantages such as the network throughput increase, the reliable connection time between two nodes increase and the network load balance. However, previous works have not proposed a practical system model that uses the physical layer information at the network layer protocols and have not analyzed the performance of the multi-route routing protocol related to the number of hops from the source to the destination.

In this paper, we design a multi-layer protocol stack that could utilize the wireless channel information at the routing protocol of the network layer, by modifying the existing IEEE 802.11 standard and the AODV routing protocol. The rest of the paper is organized as follows. In section 2, we propose a multi-layer protocol stack that utilizes the wireless channel information at the network layer. In section 3, we analyze the system performance based on outage power probability and compare with the two other conventional systems that do not use the channel information. Section 4 describes the simulation result of the proposed system and compares the performance with the conventional systems. The conclusions are made in section 5 with some interesting results.

2. System Model

The system model can be divided into two layers, MAC layer and network layer. The wireless channel information is transmitted by a MAC layer control frame, and the routing protocol utilizes the instantaneous channel information to select the link to the next-hop. The details of the protocols are described in the following subsections.

A. MAC (Media Access Control) layer protocol for the multi-route diversity

The MAC layer of the proposed system uses the modified IEEE 802.11 standard in DCF (Distributed Coordination Function) mode [8]. The basic DCF mode is generally used for Ad hoc networks. It uses special MAC control packets, RTS (Ready to Send)/CTS (Clear to Send) packets, to prevent a collision with other nodes. A sender sends out the RTS packet to announce that there are data packets to send to the destination. If the destination is able to receive the packet, the receiver sends the CTS packet to the sender. During the RTS/CTS packet exchange, the other nodes that overheard those communications defer their transmission. After the data packet is transmitted to the destination, the destination replies with ACK (Acknowledgement) packet to the sender to confirm the correct reception of the data packet. In [1], a rate-adaptive MAC protocol is proposed. The appropriate transmission rate is estimated based on the channel information measured at the receiver and the rate information is exchanged on per-packet basis during RTS/CTS packet exchange. Since we are interested in the channel condition at the receiver, using the channel information that is transmitted from the receiver by the CTS control packet provides more timely and complete channel information to the source. Moreover, the paper shows that the proposed method successively tracks time varying channel using the RTS/CTS control packets. If a node is moving with speed less than 2m/sec, i.e., walking speed, communicating at 2Mbps over a 2.4GHz channel, change of the channel occurs slowly enough in time domain. Therefore, we can assume that the channel is constant during the packet exchange [1]. For faster node speed, the paper shows that the protocol tracks fast enough to gain performance improvement. In [1], the MAC protocol is modified such that the duration field in the RTS/CTS control packet is replaced to rate field and data length field to negotiate the transmission rate between sender and the receiver.

In the proposed system, the sender needs only the channel information at the receiver, i.e., the signal power level estimated at the receiver. Therefore, all the mechanism of the original IEEE 802.11 MAC protocol is valid, except there needs to be a little modification at the CTS control packet frame. That is, the channel information must be added in the CTS control packet. This will increase the packet size of CTS frame, which will result in the throughput decrease. However, the size of the channel information field depends on the accuracy required for the information. Since the resolution of the channel information doesn't need to be high, one octet (8bit) should suffice for representing the channel status information (CSI) for the routing protocol.

B. Routing Protocol for the multi-route diversity

The proposed system uses modified AODV (Ad Hoc On-demand Distance Vector) Routing protocol [2] that has added capability of using multiple path routing information. The basic operation of the modified AODV protocol is as follows. Whenever there is a data to send to the destination, it first broadcasts a RREQ (route request) message to the neighboring nodes to discover the routes to the destination. The node that received the RREQ message replies with RREP (route reply) message to the sender only if the node knows the path to the destination or it is the destination. If the node is just intermediate node between the source and the destination and it is the first time to receive the RREQ message, the node again broadcasts the RREQ message to the next neighboring nodes. During route discovery phase, the reverse paths back to the source are automatically established. When the RREQ message arrives at the destination, the destination replies with RREP message to the source. Since there are already reverse paths to the source that are made during the RREQ message flooding, in case of a symmetric channel, the RREP message doesn't need to find the path to the source again. Moreover, when RREP message traverses to the source, it establishes forward path to the destination. To use the multi-route diversity, all the multiple RREP messages with the same destination and source that is received at the node should be processed and the routing information to the destination should be stored in the routing table. After the route-discovery phase is over, the data is transmitted to the destination based on the established multiple route and the path selection algorithm which will be discussed later. In [4], AOMDV (Ad hoc On-demand Multipath Distance Vector) routing protocol is proposed. The protocol computes multiple loop-free and link-disjoint routes. However, this protocol again doesn't utilize the channel information. It only uses conventional hop-count information.

In the proposed system, the path to the next-hop selection algorithm is modified to use the channel information on each hop. In the routing protocol, the conventional hop count metric is replaced with the new received-power-level metric. Since the Ad hoc network is a wireless network, the link cost should be average power or SNR rather than the integer value of one, which represents the cost for one hop. As the RREQ and RREP traverses a route, the average power level of each hop of the route is added up and used as the metric that is used to select the best route to the destination.

This is similar to the method that increases the hop-count as the RREQ traverses the network in the conventional Ad hoc routing protocols. For a simple three-node network such as Figure 1, the basic route selection algorithm for the routes that have different cost is expressed as following.

If $(1-P_{out,a})(1-P_{out,b}) > (1-P_{out,c})$ *then {Select two-hop path with link a and b}*

else {Select one-hop path with link c}.

where the $P_{out,a}$, $P_{out,b}$ and $P_{out,c}$ denotes the outage power probability at the link *a*, *b* and *c* respectively. The above inequality could be extended to the comparison between the *n-hop* route and the *m-hop* route, where *n* is greater than *m*, as following selection algorithm.

If $\prod_{i=1}^{n}(1-P_{out,i}) > \prod_{j=1}^{m}(1-P_{out,j})$ *then {Select n-hop path} else {Select m-hop path}.*

If there are a number of routes to the destination that have the same route cost, we use the instantaneous channel information of all the links to the next-hops. This is obtained by the CTS control packets of the MAC layer protocol, and the routing algorithm selects the link to the next-hop that has the best channel condition, which leads to the destination. To obtain the channel information of all the links to the potential next-hop destinations, the routing protocol requests MAC layer protocol to send multicast RTS control packet to the potential next-hop nodes. The potential next-hop nodes that have received the RTS control packet, reply with a CTS control packets with the channel information added. The routing protocol collects all the channel information from the potential next-hop nodes, compares the obtained values, and selects the link that has the highest instantaneous power level and sends data packet through the selected link.

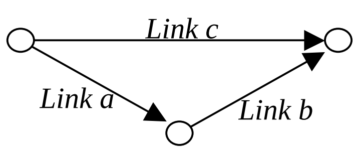

Figure 1. Simple three-node network

3. Performance analysis

The performance analysis of the proposed system is based on the simplified wireless network model. The performance of the system is measured with the outage power probability that is generally used to analyze the wireless system performance. The performance of two other conventional systems with different routing protocols are analyzed and compared with the performance of the proposed system. The conventional systems are 1) the system that does not use multi-route diversity which sends data through only one route, and 2) the system that utilizes the multi-route diversity but by sending the same data through all available routes to the destination, which will increase the bandwidth consumption in the network.

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

At first, the performance analysis is done for a simple two-path two-hop network that consists of only four nodes as depicted in Figure 2(a). The source node has two paths to the next-hop destination and the distance from the source node to the destination node is two hops.

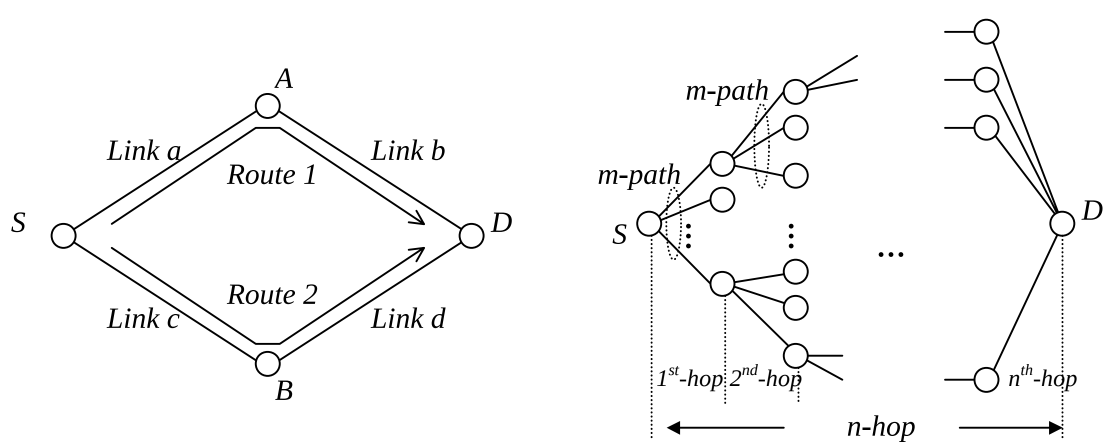

Figure 2 a) *two-path two-hop* network and b) general *m-path n-hop* network

Lets assume that all the links have the same distance between connected (within the RF range) nodes for simplicity and all the links are experiencing independent Rayleigh fading channel which is general characteristic of outdoor wireless channel [9]. By this assumption, all the nodes have the same average receiving power per hop. Since all the nodes have the same wireless interface with same hardware performance, we can assume that the outage power threshold is same for all the nodes. With these assumptions, the outage power probability of all the links $P_{out,a}$, $P_{out,b}$, $P_{out,c}$ and $P_{out,d}$ will have the same value P_{out}. For the two-path two-hop system, there are two distinct routes from the source node *S* to the destination node *D*. The total outage probability, P_{out_total}, denotes the probability that a packet will be dropped during the transmission between the node *S* and the node *D*, and can be computed as following for the proposed system and the two other conventional systems with different routing protocols:

1. *The system without multi-route diversity (conventional routing protocol):*

$$\begin{aligned} P_{out\_total} &= 1 - \Pr(\text{a packet not dropped on } \textit{link } a) \cdot \Pr(\text{a packet not dropped on } \textit{link } b) \\ &= 1 - (1 - P_{out,a})(1 - P_{out,b}) \\ &= 1 - (1 - P_{out})^2 \end{aligned}$$

2. *The system with multi-route diversity sending data through all available paths:*

$$\begin{aligned} P_{out\_total} &= \Pr(\text{a packet dropped on the } \textit{route } 1) \cdot \Pr(\text{a packet dropped on the } \textit{route } 2) \\ &= \{1 - (1 - P_{out,a})(1 - P_{out,b})\}\{1 - (1 - P_{out,c})(1 - P_{out,d})\} \\ &= \{1 - (1 - P_{out})^2\}^2 \end{aligned}$$

3. *The proposed system which uses multi-route diversity by selecting the link per hop basis:*

$$\begin{aligned} P_{out\_total} &= 1 - \Pr(\text{a packet not dropped on the } 1\textit{st hop}) \cdot \Pr(\text{a packet not dropped on the } 2\textit{nd hop}) \\ &= 1 - (1 - P_{out,a} \cdot P_{out,c})\{(1 - P_{out,b})\Pr(\textit{link } a \text{ selected}) + (1 - P_{out,d})\Pr(\textit{link } c \text{ selected})\} \\ &= 1 - (1 - P^2{}_{out})(1 - P_{out}) \end{aligned}$$

B. General *m-path n-hop* network

The result of the simple two-path two-hop system can be extended to the general *m-path n-hop* system that is illustrated in Figure 2 (b). For this system, each node has *m* multiple paths to the next hop destination and the distance from the source node to the destination is *n* hops. The outage power probability could be derived as following.

1. *The system without multi-route diversity (conventional routing protocol):*

$$\begin{aligned} P_{out\_total} &= 1 - \prod_{i=1}^{n} \Pr(\text{a packet not dropped on link } i) \\ &= 1 - \prod_{i=1}^{n} (1 - P_{out,i}) \\ &= 1 - (1 - P_{out})^{n} \end{aligned}$$

2. *The system with multi-route diversity sending through all available paths:*

$$\begin{aligned} P_{out\_total} &= \prod_{j=1}^{m} \Pr(\text{a packet dropped on the route } j) \\ &= \prod_{j=1}^{m} \left\{ 1 - \prod_{i=1}^{n} (1 - (P_{out,i})_{route\ j}) \right\} \\ &= \left\{ 1 - (1 - P_{out})^{n} \right\}^{m} \end{aligned}$$

3. *The proposed system which uses multi-route diversity by selecting the link per hop basis:*

$$\begin{aligned} P_{out\_total} &= 1 - \prod_{i=1}^{n-1} \Pr(\text{a packet not dropped on the } i^{th} \text{ hop}) \cdot \Pr(\text{a packet not dropped on the } n^{th} \text{ hop}) \\ &= 1 - \prod_{i=1}^{n-1} \left(1 - \prod_{j=1}^{m} \left(P_{out,j} \right)_{i} \right) \cdot \left(\sum_{k=1}^{m^{n}} \left(1 - \left(P_{out,k} \right)_{n} \right) \Pr(link\ k \text{ selected at the last hop}) \right) \\ &= 1 - \left(1 - P^{m}{}_{out} \right)^{n-1} \cdot \left(1 - P_{out} \right) \end{aligned}$$

where, $P_{out,i}$ denotes outage probability of i^{th} link of a node, $(P_{out,i})_j$ denotes the outage power probability of i^{th} link at j^{th} hop and $(P_{out,i})_{route\ j}$. denotes the outage power probability of the i^{th} link of the j^{th} route.

4. Simulation results

The simulation is performed for the proposed system and compared with the conventional system that does not use the multi-route diversity and that uses multi-route diversity by sending the same data to all the routes available. The two-ray propagation model [9] is used for the path loss calculation and the outage power threshold is fixed to –94.47dB for AT&T WaveLAN 802.11b wireless LAN card [7]. The total outage power probability of the system is measured at the average power level from –90dB to –65dB, at the receiver. Figure 3 shows the result of the simulation for (a) *two-path two-hop* network and (b) *three-path two-hop* network. The simulation result shows that multi-route diversity with two-path increases the performance significantly compared to the system that does not use the multi-route diversity, without increasing the network bandwidth consumption.

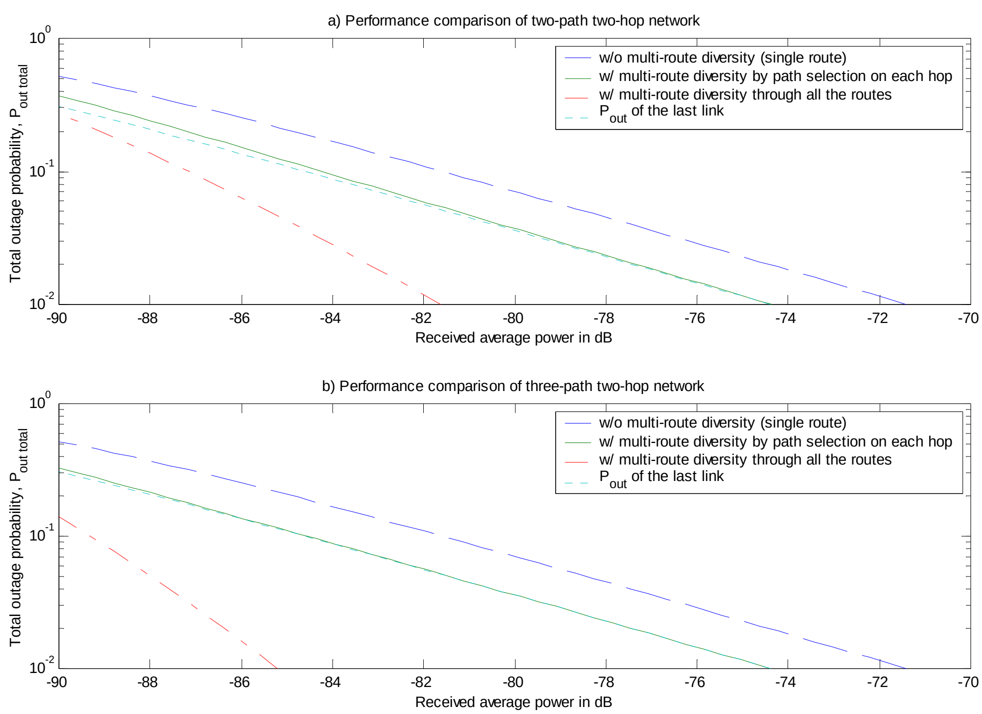

Figure 3. Performance of the proposed system for (a) *two-path two-hop* system and for (b) *three-path two-hop* system.

For the two-path two-hop network, the proposed system utilizes two-path multi-route diversity and the performance gain is approximately 3dB at P_{out_total} = 0.01. If the network is extended to the three-path two-hop network, the proposed system can utilize three-path multi-route diversity. The performance comparison is given in the Figure 3 (b). Since the performance of the proposed system is limited by the outage power probability of the last link of the route, the increase of the number of paths to the next-hop nodes results in little performance increase. The graphs (a) and (b) in Figure 3 shows that as we increase the number of the path to the next-hop from two to three, there is only small performance increase for the proposed system. As the number of paths to the next-hop increases, the performance of the proposed system converges to the last link outage power probability, which is the lower bound of the proposed system performance. Although the conventional system that uses the multi-route diversity by sending the same data through all the routes performs better than the proposed system, the network bandwidth consumption increases proportionally to the increase of the number of multi-route to the destination. Since the bandwidth (resource) of the network is limited in general, the system that sends the same data through all possible multiple routes cannot be used for the purpose of the network performance increase.

The simulation result in Figure 4 shows the relation between the system performance and the number hops from the source node to the destination. For the *two-path three-hop* system, the performance gain is approximately 5dB at the total outage power probability of 0.01. As the network expands to *four-hop* network, the performance gain increases to 6dB and for *ten-hop* network, the performance gain is approximately 10dB at P_{out_total} = 0.01. Clearly, as the number of hops increases, the performance gain also increases significantly. In graph (c) of the Figure 4, when the number of hops to the destination becomes 10, at P_{out_total} = 0.01, the performance of the proposed system gets closer to the performance of the system that uses the multi-route diversity by sending the same data through all the multiple routes. Since the proposed system sends only one data packet to the destination, it doesn't increase the network bandwidth consumption.

Figure 5 shows the performance of the proposed system as the number of hops to the destination increases. For this simulation, the system used only *two-path* multi-route diversity scheme, which means it selects the path that has the best channel condition between two paths to the next-hop. Figure 5 shows that the required average power for the proposed system is approximately flat as the number of hops increases, while the other two conventional systems needs power increase to obtain the same total outage power probability. This is because the proposed system selects the path to the next-hop that has best channel condition at each hop basis. Clearly, as the size of the network becomes larger, the proposed system outperforms other systems that use conventional multi-route diversity.

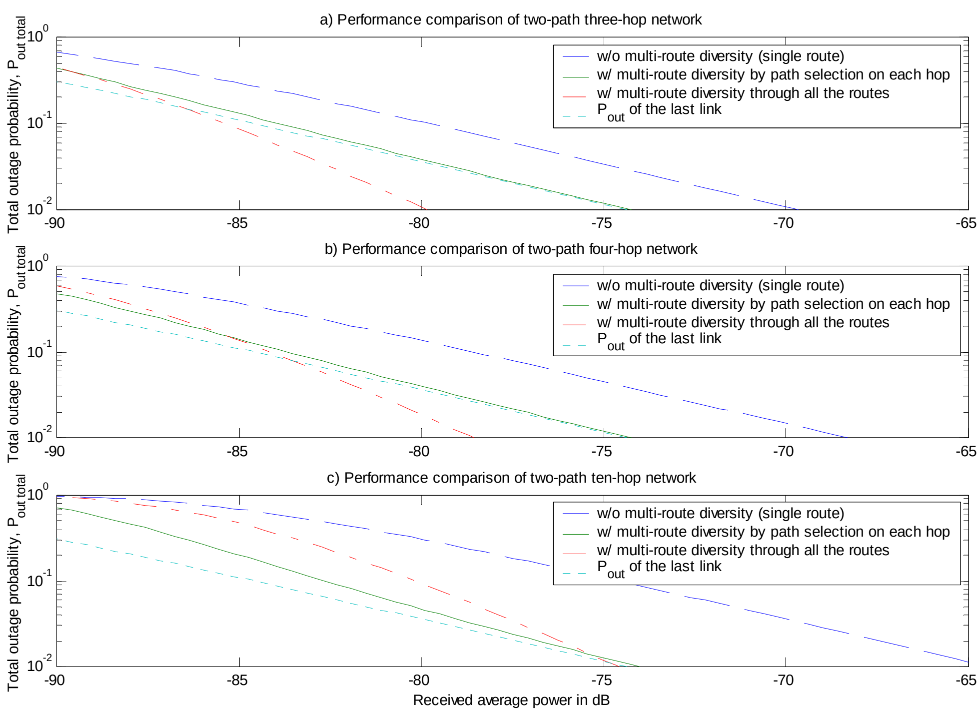

Figure 4. Performance of the proposed system for *two-path* multi-route diversity for a) *three-hop* network, b) *four-hop* network and c) *ten-hop* network.

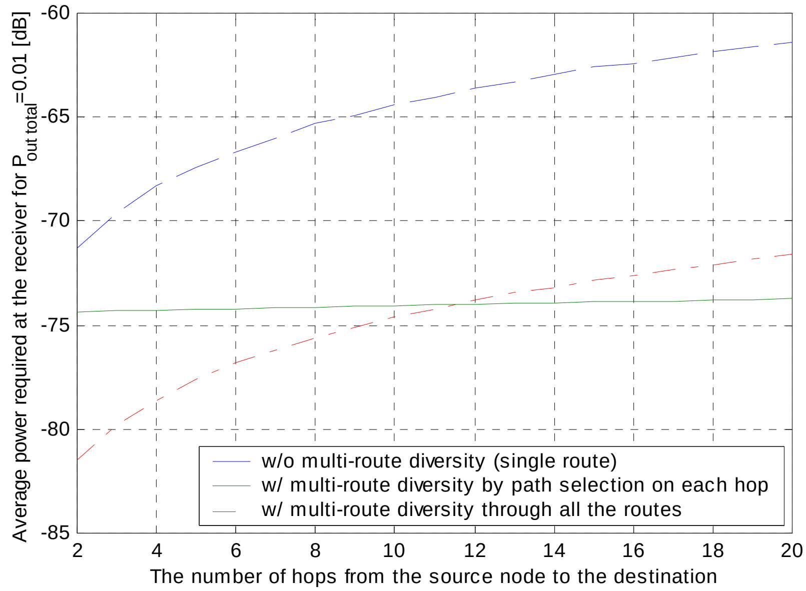

Figure 5. Performance of the proposed system as the number of hops to the destination increases

Notice that if the number of hops to the destination is greater than 12, at $P_{out\_total} = 0.01$, the proposed system performs better than the system that uses multi-route diversity by sending the same data through all the routes. This shows that the performance of the proposed system doesn't depend on the size of the network. In other words, the proposed system scales.

5. Conclusions

In this paper, we proposed the MAC layer protocol and Ad hoc network routing protocol to utilize the wireless channel information of the physical layer for the multi-route diversity, and analyzed the performance of the proposed system using the outage power probability of each link. The performance analysis and simulation results of the proposed system show that

A. The proposed system, which uses mulit-route diversity scheme by selecting the link to the next-hop that has the best channel condition, outperforms the system that transmits data through only a single route without using multi-route diversity. Moreover, the performance gain increases significantly as the number of hops from the source node to the destination increases.

B. The performance of the proposed system is even better than the system that uses the multi-route diversity by sending the same data on all the multiple routes to the destination, when the number of hops from the source node to the destination node is large enough.

C. The performance of the proposed system is stable as the network size grows, that is, as the number of hops from the source to the destination increases, the average received power at each node that is required to obtain the same total outage power probability is approximately the same.

These results show that the utilization of the wireless channel information at the network layer routing protocol enhances the performance of the wireless network significantly.

6. References

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