

A Route Establishment Scheme for Multi-route Coding in Multihop Cellular Networks

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Abstract—Since the network topology in multihop cellular networks is flexible, multiple routes from a user station to a base station can be established. To reduce packet reception errors of wireless links, a multi-route coding scheme was proposed. An important issue of the multi-route coding is to develop an efficient route establishment scheme. In this paper, we propose a route establishment scheme for multi-route coding in multihop cellular networks. Our proposed scheme consists of a route selection method based on the bit error rate of each wireless link and a hybrid-type multiple-tree routing protocol. We evaluate the performance of our proposed scheme by a computer simulation and show the resulting improvement in the packet error.

Index Terms—multihop cellular network, multi-route coding, routing protocol, routing metric

I. INTRODUCTION

A much higher data transmission rate and much larger capacity are required for future generation cellular systems. However, it would be impracticable to construct a large number of wired base stations due to high costs. One way to satisfy these requirements is to reduce the cell size, e.g., micro or pico cells. A functional solution is cellular networks using wireless multihop transmission, which have attracted considerable attention of many researchers [1]–[4].

There are three types of wireless stations in multihop cellular networks. A base station is located at the center of the cell, which is connected by a wired core network. Relay stations are not connected to the core network and have a simple structure, resulting in relatively low costs. Each relay station is equipped with an access point operation, which can be associated with a user station.

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A packet generated by the user station is transmitted to the base station via relay stations. The user station can move, but the base station and the relay stations are usually located by an operator. Multihop cellular networks therefore have a hierarchical structure with two different characteristics: a stable backbone network among the base station and the relay stations, and a dynamic access link between the relay stations and the user stations.

Since the network topology is flexible, multiple routes can be established from the user station to the base station [5]–[7]. Furthermore, the user station can be connected not only to the base station, which remains in its cell, but also to base stations in other cells via relay stations. Multiple routes are used for various purposes such as maintaining alternative routes, load balancing, and decreasing the effect of frequent topological changes. In multihop cellular networks, cumulative packet reception errors in wireless links due to packet relay degrade the system performance. Multi-route coding was proposed to reduce packet reception errors in wireless links [8]. In this system, the user station encodes a packet, divides it into subpackets, and sends them separately to the base station via several routes. The base station receives the subpackets, combines them into the packet, and then decodes the packet. This can reduce cumulative errors in wireless links for a coding and diversity gain.

An important issue of multi-route coding is to develop an efficient route establishment scheme, and the requirements for this are the following: (1) poor wireless links must not be selected so as to prevent degradation of the decoder performance, (2) as many routes as possible must be found for greater diversity, (3) disjointed routes must be selected to maximize the diversity effect, and (4) the number of control packets must be kept low to reduce the control overhead. Although several multipath routing protocols have been proposed in the field of mobile ad hoc networks (MANETs) [5]–[7], these are rarely specified for multi-route coding and cannot satisfy requirements (1)

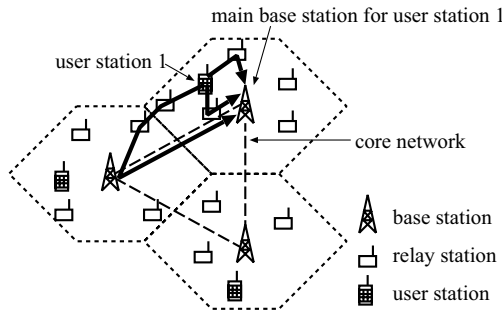


Figure 1. Multihop cellular networks.

and (2). Similar to multihop cellular networks, wireless mesh networks [9] have a hierarchical structure. Several routing protocols for wireless mesh networks have been also proposed, but almost none of them can establish multiple routes and satisfy requirements (2) and (3).

In this paper, we propose a route establishment scheme for multi-route coding in multihop cellular networks. For requirement (1), a route selection scheme is introduced, which considers the quality of the wireless links. Multihop cellular networks have a hierarchical structure, therefore, a hybrid routing protocol is employed. A route among the base stations and the relay stations is established proactively, and the route from the user station to the base station is established reactively. In the proactive phase, multiple trees whose roots are the identical base station are introduced to satisfy requirement (2). In the reactive phase, only disjoint routes are selected by the base station to meet requirement (3). Note that various schemes to reduce control overheads such as route cash have been proposed for MANETs. Since these schemes can be applied also to multihop cellular networks, this paper does not discuss requirement (4).

This paper is organized as follows. Multihop cellular networks are explained in Section II, and multi-route coding is briefly described in Section III. A route establishment scheme is proposed in Section IV, and its performance is evaluated in Section V. Finally, conclusions are provided in Section VI.

II. MULTIHOP CELLULAR NETWORKS

Multihop cellular networks are modeled, as shown in Fig. 1. They consist of user stations, relay stations, and base stations. The user stations are mobile, but the relay stations and the base stations are fixed. The base stations are located at the center of their cell similar to current cellular systems, and are connected by a core network.

This paper considers up-link transmissions from a user station to a base station. One or more routes are established from the user station to the main base station. Furthermore, the user station can transmit a packet not only to the base station in its fixed cell, but also to the other base stations via relay stations. The base station in its fixed cell, which is called the main base station, gathers subpackets received by the other base stations via

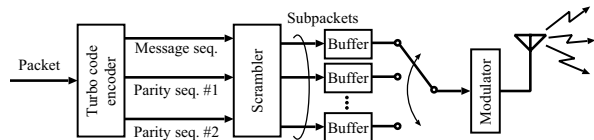


Figure 2. Transmitter structure of user station.

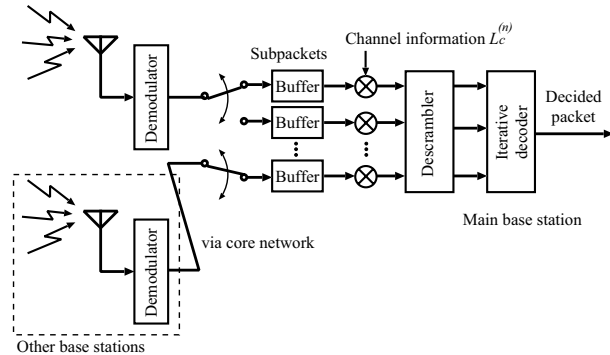


Figure 3. Receiver structure of base station.

the core network. Note that the user stations do not relay any packets generated by the other user stations.

III. MULTI-ROUTE CODING

Multi-route coding in wireless multi-hop networks is explained in this section. Although some multi-route coding methods have been proposed, this section briefly describes the method using a turbo code [8].

The transmitter structure of the user station is shown in Fig. 2. A packet is encoded by the turbo encoder, and a message sequence and two parity sequences are generated. Note that the message sequence is more important than the parity sequences for correctly recovering the transmitted data sequence [10]. The message sequence is scrambled uniformly in subpackets to enhance the diversity effect, and is divided into subpackets for multiple routes. The number of subpackets is equal to the number of multiple routes. These subpackets are stored in buffers. Each stored subpacket is modulated and transmitted along its own route. This procedure is repeated until all the subpackets have been transmitted to the next station.

The relay station employs regenerative relay. The received signal is demodulated to a hard-valued binary sequence, remodulated, and transmitted to the next station. Note that error correction and error detection are not performed at the relay station because each relay station receives only one of the subpackets, which is only a part of the encoded packet.

Figure 3 shows the receiver structure of the base station. The received subpacket is demodulated and stored in a buffer. The main base station gathers the subpackets received by the other base stations, and also stores them in the buffers. Each subpacket is multiplied by a weight, which is calculated according to the quality of all the wireless links on its route. It is then descrambled and decoded by an iterative decoder.

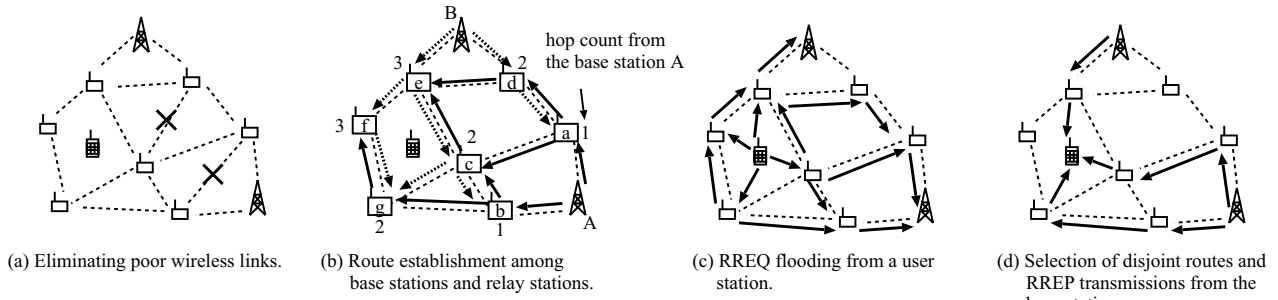


Figure 4. Procedure of the proposed route establishment scheme.

The relay stations employ regenerative relay. This means that soft decision values of the subpacket received at the relay station are lost and cannot be transmitted beyond the relay station. On the other hand, hard decision values of the subpacket are remodulated and transmitted to the base station, i.e., the base station can use the hard decision values that contain hard valued reliability information of every wireless link on the route. We can regard whole wireless links on each route as a virtual binary symmetric channel (BSC), and multiple routes are considered as multiple virtual BSCs [8]. Each virtual BSC is characterized by the properties of all the wireless links on its route, which corresponds to the bit error rate (BER) of the virtual BSC. Channel information $L_c^{(n)}$ of the n th route, which is a log likelihood ratio of the BER, is used as the weight of the receiver.

IV. PROPOSED SCHEME

The route selection method and the routing protocol must satisfy the requirements for multi-route coding, which are described in this section. Figure 4 shows the procedure of our proposed scheme.

A. Route Selection Method

In this subsection, a route selection method that can satisfy requirement (1) is discussed.

As described in Section III, each route is regarded as a virtual BSC, and its quality is characterized by BER of whole wireless links on the route. If this BER is large, channel information $L_c^{(n)}$, by which the received subpacket is multiplied, becomes small. Therefore, the received subpacket contributes to the diversity gain only if the BER of its transmitted virtual BSC is small. If we select some virtual BSCs whose BERs are below a pre-defined threshold, this will effectively enhance the diversity and coding effect of multi-route coding.

Let $M^{(n)}$ be the number of hops on the n th route. Ignoring cases in which errors on the same bit of a subpacket do not occur more than two times, the BER

TABLE I.
SIMULATION PARAMETERS FOR COMPARING OF THE ROUTE SELECTION METHODS.

Number of available routes L	10
Number of hops $M^{(n)}$	3
Distance between stations	100–150 m
Path loss exponent	3.5 (received SNR = 20 dB at distance 100 m)
Standard deviation of lognormal shadowing	7.0 dB
Fading	Flat Rayleigh
Modulation scheme	BPSK
Packet length	1,000 bits
Turbo code	Rate 1/3, (37,21) RSC number of iterations = 5

of the n th virtual BSC, $p^{(n)}$ can be derived as

$$\begin{aligned}
 p^{(n)} &\approx 1 - \prod_{m=1}^{M^{(n)}} (1 - p^{(n,m)}) \\
 &\approx \sum_{m=1}^{M^{(n)}} p^{(n,m)}, \quad (1)
 \end{aligned}$$

where $p^{(n,m)}$ is the BER of the m th wireless link on the n th route. From this equation, the BER of the virtual BSC is approximated to the sum of whole BERs of wireless links on its route. Since the value of BER changes with the order of a figure, the maximum BER among the BERs of all the wireless links on the route is the dominant factor of the BER of the virtual BSC. Therefore, the selection of virtual BSCs whose BERs are below the threshold corresponds to the selection of wireless links whose BERs are below the threshold.

Let us compare the performance of these two route selection methods. One method is to select routes such that the BER of each virtual BSC is below the threshold. The other method is to select routes such that the BERs of all the wireless links on each route are below the threshold. Given L route candidates, some routes are selected from them by both methods. Table I shows simulation parameters. Each wireless link is affected by path loss, lognormal shadowing, and Rayleigh fading. It is assumed that the BERs of virtual BSCs or wireless links can be estimated free from error. Because of the rapid

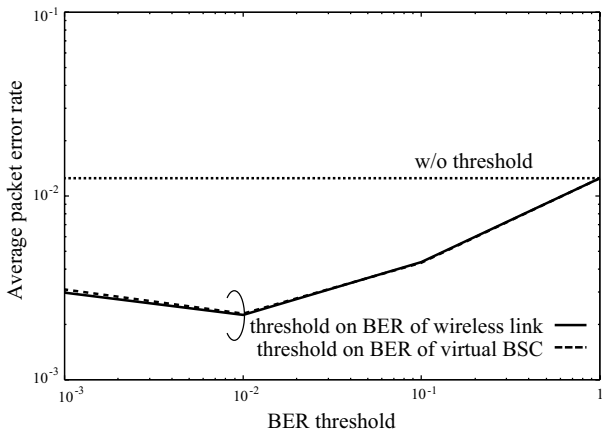


Figure 5. Comparison of average packet error rates between the route selection methods.

fluctuation of Rayleigh fading, its effect is not considered in the estimated BER; however, the packet error rate performance is evaluated in consideration of Rayleigh fading in the simulation.

The packet error rate after iterative decoding of multi-route coding is shown in Fig. 5. From this figure, the packet error rate can be improved by selecting routes according to the BER threshold. When the threshold is high, bad routes degrade the packet error rate. On the other hand, the diversity effect is degraded when the threshold is low; therefore, there is an optimum value for the threshold. The difference between two methods is not shown in Fig. 5. Therefore, we can use the selection method in which the BERs of all the wireless links on every route are below the threshold. This method is very useful because routing protocols based on hop count criteria can be used after the wireless links whose BERs are below the threshold are eliminated by link filtering [11]. Many conventional routing protocols use hop count as a criterion to select a route.

B. Concept of the Routing Protocol

In order to meet requirements (2) and (3), our proposed routing protocol has the following properties. Note that we mention only the basic concept of the routing protocol in this paper because we are focusing on the improvement of the multi-route coding performance by customizing the routing protocol.

Hybrid Type

Since multihop cellular networks have a hierarchical structure, a hybrid routing protocol is employed. A route among the base stations and the relay stations is established proactively, and the route from the user station to the base station is established reactively.

In multihop cellular networks, base stations and relay stations are located by the operator and do not move. In the proactive phase, the refresh period of route establishment can be extended. A user station is mobile and sometimes powers up or down, so a route from

the user station to the base station is established when a communication request is received. This allows the control overhead to be reduced, which contributes to the solution of requirement (4).

Proactive Phase: Multi-Tree Structure

In multihop cellular networks, almost all packets generated by a user station are forwarded to a base station. Therefore, it is effective to construct tree-topology routes whose root is the base station, similar to the hybrid wireless mesh protocol (HWMP) of IEEE 802.11s.

In the proactive phase, every base station advertises a route reference (RREF) message, to which a sequence number is assigned. When each relay station receives the RREF, it checks the sequence number of the RREF message. If it has not received the RREF message before, it re-broadcasts the RREF message. By propagating the RREF message, the tree route whose root is the base station is established.

We also propose to establish multiple trees whose root is a base station for the solution of requirement (2). Multiple trees are established by keeping information of RREF messages as candidates of routes if each relay station receives the RREF message whose sequence number and hop count from the base station are the same as those of the RREF received previously. This process is depicted in Fig. 4(b), where the number of hops from base station A is also shown. Relay station c receives two RREF messages of base station A from both relay stations a and b. Since the numbers of hops of these messages are identical, relay station c keeps information of both RREF messages as candidates for routes. Note that relay station c re-broadcasts the RREF message only once and does not duplicate the RREF message.

Reactive Phase: Disjoint Route Selection

In the reactive phase, multiple routes from a user station to a base station are established. In order to satisfy requirement (3), only the disjoint routes are selected in this phase.

When a communication request is initiated at the user station, a route request (RREQ) message is broadcast. All relay stations receiving the RREQ message forward it to the base station by referring to the multiple trees established in the proactive phase (Fig. 4(c)). The RREQ message includes not only information about forwarded relay stations, but also the total BER of whole wireless links, which can be calculated by adding the BER of each wireless link (see (1)).

When the base station receives several RREQ messages, it selects at most N_{max} disjoint routes from them. Some route selection criteria are discussed in [12]. In this paper, the minimum BER of virtual BSCs are used as a route selection criterion. This procedure is as follows:

- 1) The route with the minimum BER is selected among all route candidates.
- 2) The route with the smallest BER is selected among the route candidates, which are disjoint with the already selected routes.

- 3) If there are some route candidates that are disjoint with the already selected routes, and the number of selected routes is below N_{\max} , go to step 2).

The base station sends route reply (RREP) messages to the user station via the selected routes. Finally, multiple disjoint routes can be established (Fig. 4(d)).

C. Overall Procedure

The overall procedure of our proposed route establishment scheme is as follows.

- 1) The BER of every wireless link is measured periodically. If the BER of a wireless link is below the threshold, it is not used, i.e., data or control messages are not transmitted via that wireless link (Fig. 4(a)).
- 2) Routes among the base and relay stations are established proactively. The base station broadcasts an RREF message. When the relay station receives the RREF message, it decides whether to re-broadcast the message. If the relay station has received the same RREF message, it discards the message, otherwise it re-broadcasts the message. Furthermore, the relay station keeps information about the RREF message as one of the route candidates, when it receives multiple RREF messages whose hop count is the same. This process is repeated until multiple-tree routes from the base station to the relay stations are established (Fig. 4(b)).
- 3) When the user station makes a transmission request, routes from the user station to the base stations are established reactively. First, the user station floods an RREQ message. The relay stations receiving this packet forward it to the base station by referring to the routes established in the proactive phase (Fig. 4(c)).
- 4) The base station selects at most N_{\max} disjoint routes from the route candidates in order of lowest BER of routes. Then, the base station returns the RREP messages to the user station via the selected routes (Fig. 4(d)).

V. NUMERICAL EXAMPLES

In this section, we evaluate the performance of the proposed route establishment scheme. Simulation parameters are shown in Table II. The simulation assumes that all control messages are successfully transmitted and that the BER of each wireless link can be estimated without any error.

For comparison, we also evaluate the performance of the following two schemes.

MDSR: After eliminating bad wireless links described in Section IV-A, multiple routes are established using a multipath dynamic source routing (MDSR) protocol [6]. MDSR is based on a dynamic source routing (DSR) protocol. A user station advertises an RREQ message. The base station selects at most N_{\max} disjoint routes according to the criterion of minimum hop from the

TABLE II.
SIMULATION PARAMETERS FOR NUMERICAL EXAMPLES.

Number of cells	7
Location of base stations	Center of each cell
Distance between base stations	1,000 m
Location of relay stations	Uniform distribution
Number of relay stations	292
Location of user stations	Uniform distribution
Path loss exponent	3.5 (received SNR = 20 dB at distance 100m)
Standard deviation of lognormal shadowing	7.0 dB
Fading	Flat Rayleigh
Modulation scheme	BPSK
Packet length	1,000 bits
Turbo code	Rate 1/3, (37,21) RSC number of iterations = 5

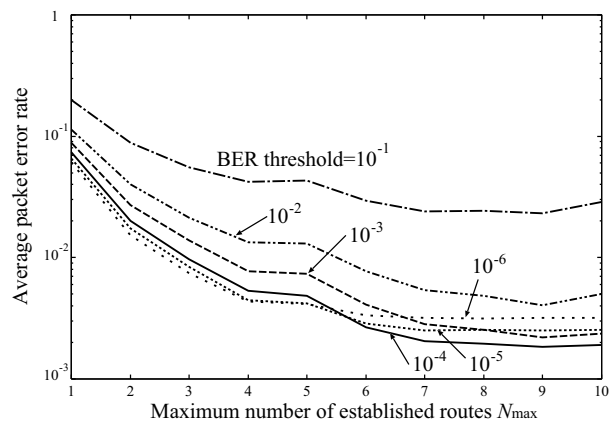


Figure 6. Average packet error rate performance as a parameter of the BER threshold.

routes on which the RREQ messages are transmitted. This scheme is different from our proposed scheme since a hybrid routing protocol is not used and the minimum hop count criterion is employed.

Single tree: In the proactive phase of our proposed hybrid routing protocol described in Section IV-B, a single tree is constructed rather than multiple trees.

Figure 6 shows the average packet error rate performance as a parameter of BER threshold of every wireless link. The horizontal axis is the maximum number of established routes, N_{\max} . As in Fig. 5, the optimal value of the threshold can be seen, which is 10^{-4} . As the maximum number of established routes, N_{\max} , is set to be larger, the average packet error rate with an optimal threshold becomes smaller for $N_{\max} \leq 7$ and hardly changes for $N_{\max} > 7$. Since it is better to decrease the maximum number of routes for reduction of control overhead, there is an optimum value of the maximum number of routes.

Figure 7 shows the average packet error rate performance of several route establishment schemes. From this figure, it is evident that the average packet error rate of our proposed scheme is the best among the error rates of all the other schemes. The average packet error rate

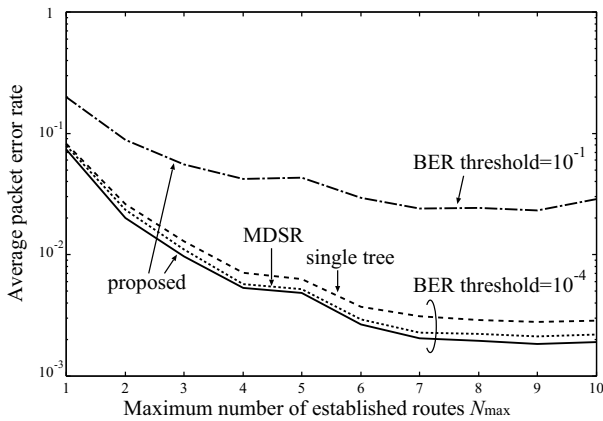


Figure 7. Comparison of several route establishment schemes in terms of average packet error rate performance.

of MDSR becomes worse since it uses the hop count criteria. Compared with the average packet error rate of a single tree, an effective solution for improving multi-route coding is to construct multiple trees.

Figure 8 shows the probability density function of the number of route candidates, which is the number of routes before the route selection of 4) of the route establishment procedure described in Section IV-C. It is expected that the number of route candidates will be reduced as the threshold becomes smaller. Compared with the single tree scheme, our proposed scheme can obtain a slightly larger number of route candidates and improves the average packet error rate, as shown in Fig. 7. The number of route candidates of MDSR is a slightly larger than that of our proposed scheme. This is because MDSR looks for route candidates by advertising an RREQ message, i.e., the scope of the search is larger than that of our proposed scheme.

The probability density function of the number of hops of each established route is shown in Fig. 9. The number of hops becomes larger as the threshold becomes lower. Usually, the wireless link with low BER functions over a short distance, which is why the number of hops becomes large. Since MDSR employs the minimum hop count criterion, the number of hops is much smaller than that in our proposed scheme. Because routes are selected in order of small BER of the virtual BSC in the reactive phase, the number of hops in our proposed scheme is slightly larger than it is in the single tree.

VI. CONCLUSIONS

In this paper, we have proposed a route establishment scheme for multi-route coding in multihop cellular networks. Our proposed scheme consists of a route selection method based on the BER of each wireless link and a hybrid multiple-tree routing protocol. We have also evaluated the packet error rate, and shown that it is improved by the proposed scheme.

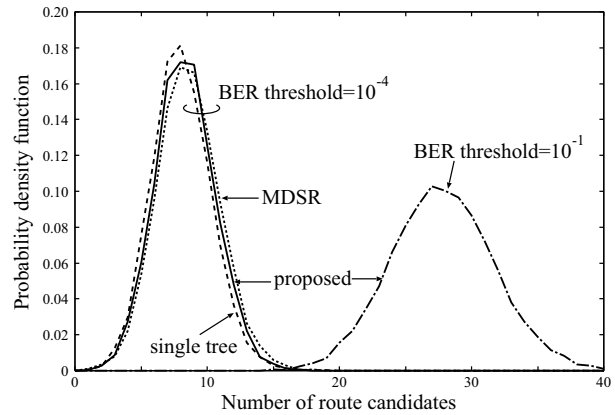


Figure 8. Probability density function of the number of route candidates.

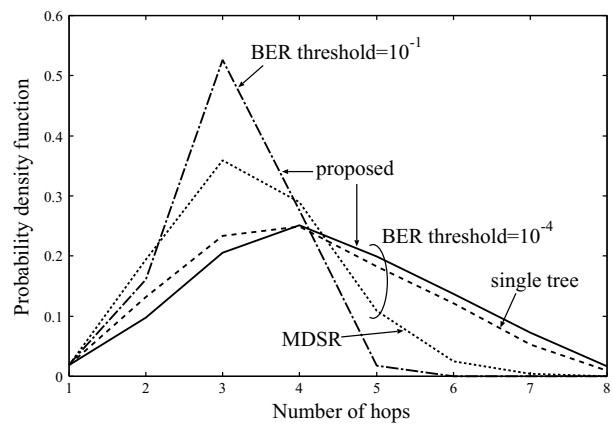


Figure 9. Probability density function of the number of hops of each established route.

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