A Relaying Algorithm for Multihop TDMA TDD Networks using Diversity

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***Abstract* – Peer-to-peer multihop relaying in TDMA networks can provide significant gains in network throughput, particularly when relaying is combined with relaying diversity schemes such as multihop selection combining or multihop maximal ratio combining. This paper presents a novel diversity-aware routing algorithm adapted from the Bellman-Ford algorithm which results in significant throughput gains and reduction in outage without requiring additional time resources. Performance is evaluated in a WLAN environment. One feature of this algorithm is that routing can be done effectively regardless of shadowing or channel variations provided channel measurement is supported.**

I. INTRODUCTION

With the popularity of wireless networks and increasing demand for high data-rate services, Wireless Local Area Network (WLAN) technologies such as 802.11a and HiperLAN/2 are expected to be deployed extensively in the foreseeable future. However, the limited communication range of these technologies makes it difficult to offer high data-rate services for users at the periphery of service areas and in environments with harsh channel conditions. Through novel concepts such as multihop relaying and associated diversity techniques, it is possible to increase the performance of wireless TDMA networks such as WLANs.

This paper focuses on relaying in TDMA systems such as HiperLAN/2 due to its centrally controlled network architecture and extendibility of the MAC protocol for relaying [1]. Previous studies [2] found 2-hop relaying showed limited throughput gains except when shadow fading was present and multiroute diversity [4] was used, a technique where multiple nodes simultaneously transmit using the same frequency to a receiver. In this paper, we define simpler yet effective diversity techniques, such as multihop selection combining and multihop maximal ratio combining, and introduce routing algorithms that factor diversity in route selection to provide substantial throughput gains in the downlink and reduce outage.

II. SYSTEM MODEL

Modulation efficiency, frame segmentation, and relaying hop error rates, are key factors in selecting routes that maximize throughput in systems using a TDMA MAC. A disadvantage of using relaying in TDMA systems is the use of time slots or symbols to relay data; we term this effect frame segmentation. However, it is possible to increase throughput by relaying if the route provides lower error rates and increased modulation efficiency.

A. *Adaptive Modulation and Modulation Efficiency*

Networks using adaptive modulation can increase or decrease modulation efficiency by selecting an appropriate modulation and coding level (mode) denoted by m. Adaptive modulation and coding allow a link to be adapted such that the throughput is maximized for channel conditions. We define link throughput, T_l, seen between nodes r_i and r_{i+1} as

$$T_l = F \cdot S_l \cdot D_{i,i+1}(m_{i,i+1}) \cdot \left(1 - P_e(SNR_{i,i+1}, m_{i,i+1})\right). \qquad (1)$$

Selecting a particular mode for the link, $m_{i,i+1}$, selects a particular modulation efficiency, $D(m_{i,i+1})$, in information bits/OFDM sym. F is the number of MAC frames per second and S_l is the number of symbols allocated per frame for the link. The packet error rate of the link, $P_e(SNR, m)$, is a function of $m_{i,i+1}$ and link signal to noise ratio, $SNR_{i,i+1}$. Using expression (1), adaptive modulation can be expressed as

$$m_{i,i+1}^{(\max)} = \arg \max_{m \in M} \left(D_{i,i+1}(m_{i,i+1}) \cdot \left(1 - P_e(SNR_{i,i+1}, m_{i,i+1})\right)\right). \qquad (2)$$

Here $m_{i,i+1}^{(\max)}$ is the mode from the set of all modes, M, which maximizes the throughput for the link between nodes r_i and r_{i+1}. Relaying networks can benefit from adaptive modulation by selecting the modulation efficiency for any link (hop) to maximize the connection (source to destination) throughput.

B. *Relaying and Frame Segmentation*

Depending on the volume of traffic, the central controller or access point (AP) schedules the number of time slots per frame for all connections. A connection's resources are further segmented for relaying, where each segment corresponds to a hop in the route. All connections and segments are orthogonal in the time domain and no additional resources are consumed for relaying.

Let us consider the generic relaying scenario with n hops shown in Fig. 1, where the *0* 'th node in the route, r_0, represents the source, node r_n represents the destination, and nodes r_1 through r_{n-1} represent relaying nodes according to the order of the route. The following constraint states that the amount of data entering any given relaying node, r_i, must equal the amount of data exiting the node,

$$s_{i-1,i} \cdot D_{i-1,i} = s_{i,i+1} \cdot D_{i,i+1} \qquad i \in \{1, \ldots, n-1\}. \qquad (3)$$

Here $s_{i,j}$ represents the number of symbols allocated for the hop between nodes r_i and r_j, and $D_{i,j}$ represents the information bits per symbol of the hop between nodes r_i and r_j. Note that expression (3) applies to the generic case where adaptive modulation is used in the system and the hop data rates $D_{i,j}$ vary per hop in the route.

Furthermore, if a total of S symbols per frame have been allocated for a connection from source to destination,

$$S = \sum_{i=1}^{n} s_{i-1,i} \qquad i \in \{1,\ldots,n-1\}, \tag{4}$$

then solving for equations (3) and (4) yields,

$$s_{i-1,i} = \frac{S}{\sum_{j=1}^{n} \frac{D_{i-1,i}}{D_{j-1,j}}}, \qquad i \in \{1,\ldots,n-1\}. \tag{5}$$

Expression (5) implies that for the i'th hop between nodes r_{i-1} and r_i, with link modulation efficiency $D_{i-1,i}$, $s_{i-1,i}$ symbols should be allocated per frame. When $n = 1$, $s_{0,1} = S$ indicating the complete frame or time resource can be used to transmit data. When relaying, $n > 1$, expression (5) evaluates to $s_{i-1,i} < S$ indicating frame segmentation. Time slots are used to relay data and we have fewer slots for original data transmission.

C. Packet Error Rate for Relaying

When using a multihop connection the reduction in packet error rate (PER) may offset loss of resources due to frame segmentation. Multihop diversity, illustrated in Fig. 2, may have greater effect on reducing PER. As illustrated, nodes involved in the route receive signals from all previous nodes. Taking advantage of data redundancy in relaying, multihop diversity does not require additional radio resources such as transmit power and time slots.

The packet error rate models discussed here assume relaying nodes employ digital forwarding and that incorrectly detected signals are not relayed to subsequent nodes in the route; eliminating detection error propagation [4]. Relaying does not use ARQ at the hop level. However, ARQ may be applied to the end-to-end connection. Under these assumptions, simple packet error rate models are created for multihop, multihop selection combining diversity, and multihop maximal ratio combining diversity forms of relaying.

(C.1) Multihop (MH)

Generalizing the multihop scenario illustrated in Fig. 1, the packet error rate seen at the i'th node in a route, r_i, can be expressed as,

$$PER_i = PER_{i-1} + (1 - PER_{i-1})P_{i-1,i} \qquad i \in \{1,\ldots,n\}. \tag{6}$$

The PER at the source node, r_0, is $PER_0=0$ and the PER for the link between any nodes r_i and r_j is denoted by $P_{i,j}$. It should be noted that $P_{i,j} = P_e(SNR_{i,j}, m_{i,j})$. The PER for the destination node can be calculated by evaluating for $i = n$.

(C.2) Multihop Selection Combining Diversity (MHSC)

Using multihop selection combining diversity, nodes receive signals from all previous nodes in the route and attempt to decode the multiple signals individually until the packet is decoded correctly. Using our "best-effort" relaying approach, the i'th node in a route, r_i, will receive a maximum of i independent signals from the previous i nodes.

The packet error rate can be expressed as

$$PER_i = \prod_{j=0}^{i-1} \left(PER_j + (1 - PER_j)P_{j,i} \right), \qquad i \in \{1,\ldots,n\}. \tag{7}$$

(C.3) Multihop Maximal Ratio Combining Diversity (MHMRC)

Multihop maximal ratio combining diversity combines signals received on previous hops with similar mode to reduce PER. Fig. 3 illustrates receiver operation for an example scenario. In the first stage of the receiver, signals transmitted on previous hops using similar modes are MRC combined reducing the PER of the resultant signal. In a secondary stage the receiver decodes the signals from the MRC combiners separately. In essence, the second stage performs selection combining of MRC combined signals. If hops do not use the same mode, MHMRC diversity performs as MHSC diversity.

For connections with nodes using MRC diversity, the packet error rate seen at any node, r_i, is expressed as

$$PER_i = \prod_{m \in M} PER_i^{(m)}(N_m), \qquad i \in \{1,\ldots,n\}, \tag{8}$$

Where, $N_m = \{ j \mid m_{j-1,j} = m, j = \{1 \ldots i-1\} \}$,

$$PER_i^{(m)}(N_m) = \begin{cases} 1, & |N_m| = 0 \\ PER_j + (1 - PER_j)P_{j,i}, & |N_m| = 1 \\ E(P_e^{(m)}), & |N_m| > 1 \end{cases}$$

$$E(P_e^{(m)}) = \sum_{N \in 2^{N_m}} \left[\left(\prod_{j \in N_m - N} PER_j \right) \left(\prod_{j \in N} (1 - PER_j) \right) P_e\left(\sum_{j \in N} SNR_{j,i}^{(m)}, m \right) \right]$$

Here M specifies the set of possible modes, m specifies the mode of the signals we are attempting to combine, N_m is the set of nodes transmitting with mode m, $E(P_e^{(m)})$ is the mean packet error rate of the signal received at node r_i from the previous nodes transmitting with mode m, and $SNR_{j,i}^{(m)}$ represents the SNR of the signal of mode m received at node r_i from node r_j. Nodes only relay packets received correctly, therefore, the probability a relaying node relays a signal is weighted in the mean packet error rate expression. Here 2^{N_m}, the power set of N_m, contains all combinations of node transmission for nodes using mode m.

III. RELAYING NODE SELECTION ALGORITHM

A. Routing Metric

The throughput expression may be used to form a routing metric. For an n-hop connection throughput is defined as,

$$T_n = F \cdot s_{i-1,i} \cdot D_{i-1,i} \cdot (1 - PER_n) \qquad i \in \{1,\ldots,n\}. \tag{9}$$

Using the results from (5), throughput expression (9) yields a routing metric for a n-hop connection, C_n, to the destination node r_n,

$$C_n = \frac{(1 - PER_n)}{\sum_{i=1}^{n} \frac{1}{D_{i-1,i}}}, \qquad i \in \{1, \ldots, n\}. \tag{10}$$

To facilitate expression of routing, the metric is rewritten as

$$C(R_d, M_d) = \frac{(1 - PER_n)}{\sum_{i=0}^{n-1} \frac{1}{D_i}}. \tag{11}$$

For n-hop connections, $R_d = (r_0, r_1, \ldots, r_n)$ and $M_d = (m_0, m_1, \ldots, m_{n-1})$. R_d is a n-hop route used to relay data to node d and is an ordered set consisting of $n+1$ relaying nodes where r_i denotes the i'th relaying node in the route. The final node in the ordered set is the destination, node d, $r_n = d$. r_0 denotes the source; this will always be the central controller in the downlink scenario. M_d is an ordered set of modes used on hops, where m_i denotes the mode of the i'th hop between nodes r_i and r_{i+1}. An n-hop connection contains n modes. D_i is simply the modulation efficiency in bits/sym of the i'th hop between nodes r_i and r_{i+1} using mode m_i for that hop. PER_n is the packet error rate seen at the destination node, r_n. The PER_n expression may be evaluated using equations (6), (7), or (8) depending if the diversity used at nodes is MH (no diversity), MHSC, or MHMRC respectively.

However, an effective method to estimate link packet error rates, $P_e(SNR, m)$, is required to calculate routing metrics. Global channel-state (link SNR) updates between nodes are required to estimate PER. Using updates also allow performance gain regardless of varying radio-link quality.

B. Routing Algorithm

Using the metric in (11), routing can maximize throughput for a multihop connection. Here we define an algorithm, adapted from the Bellman-Ford algorithm, capable of finding routes with throughput greater than or equal to singlehop and optimal 2-hop routes. The algorithm is described as,

$k = 0$
$N_c^{(0)} = N$
$\forall i$, $R_i^{(0)} = (cc, \quad i)$, $M_i^{(0)} = (m_{cc,i}^{(\max)})$
while $|N_c^{(k)}| > 0$
  $N_c^{(k+1)} = \{\}$
  $\forall i$, $R_i^{(k+1)} = R_i^{(k)}$, $M_i^{(k+1)} = M_i^{(k)}$
  for all $s \in N_c^{(k)}$
    for all $d \in N - R_s^{(k)}$
      if $C(R_s^{(k)} \cup \{d\}, M_s^{(k)} \cup \{m_{s,d}^{(\max)}\}) > C(R_d^{(k+1)}, M_d^{(k+1)})$
        $R_d^{(k+1)} = R_s^{(k)} \cup \{d\}$
        $M_d^{(k+1)} = M_s^{(k)} \cup \{m_{s,d}^{(\max)}\}$
        $N_c^{(k+1)} = N_c^{(k+1)} \cup \{d\}$
      end if
    end for
  end for
  $k = k + 1$
end while

Where,
N = set of all nodes, not including the central controller (AP),
cc = element symbol denoting the central controller node,
i, s, d = element symbol denoting a mobile node,
$N_c^{(k)}$ = set of nodes which have a route change at iteration k,
$R_i^{(k)}$ = ordered set of relay nodes to node i at iteration k,
$M_i^{(k)}$ = ordered set of modes used on hops in relay route to node i at iteration k,
$m_{i,j}^{(\max)}$ = mode of hop between nodes i and j, selected by adaptive modulation (2),
$C(R, M)$ = routing metric to the destination node in the ordered set R using the ordered set M of modes used on hops.

We define $Z = X \cup Y = (x_0, x_1, \ldots, x_{n-1}, y_0, y_1, \ldots, y_{m-1})$ where X and Y are ordered sets containing n and m elements respectively, and the ordered set Z contains $n+m$ elements.

The algorithm can be viewed as a trellis containing the routes to nodes in the network, where the path through the trellis to a given node denotes the route in the network generating the maximum metric (throughput) for the particular node. Initially nodes begin with single-hop routes from the AP to the node, $R_i^{(0)} = (cc, \ i)$, $\forall i$. The hop modes are selected according to expression (2), $M_i^{(0)} = (m_{cc,i}^{(\max)})$, $\forall i$. For every iteration, k, we examine all routes, $R_s^{(k)}$, from the set of candidate relaying nodes, $s \in N_c^{(k)}$, to all other candidate destination nodes, $d \in N - R_s^{(k)}$. Initially the candidate relaying node set $N_c^{(k)}$ contains all mobile nodes, $N_c^{(k)} = N$. Candidate destination nodes are limited to those nodes not already in the relaying nodes route, $R_s^{(k)}$. A potential route to node d is created by appending node d to the route of the candidate relaying node, written as $R_s^{(k)} \cup \{d\}$. Similarly a potential hop mode set is formed from the candidate relaying nodes set of hop modes, written as $M_s^{(k)} \cup \{m_{s,d}^{(\max)}\}$. Potential route/mode sets generating a larger metric than the destinations route/mode set, $R_d^{(k+1)}$ and $M_d^{(k+1)}$, will replace the set for node d on the next iteration. The node will be added to the candidate relaying node set for the next iteration, $N_c^{(k+1)}$. At the beginning of an iteration, $N_c^{(k)}$ is set to $N_c^{(k+1)}$, and $N_c^{(k+1)}$ is cleared to the null set. The next iteration routes/modes are set to the current routes/modes for all nodes, $R_i^{(k+1)} = R_i^{(k)}$ and $M_i^{(k+1)} = M_i^{(k)}$. The next iteration routes/modes are built from the routes/modes from the previous iteration which generated maximum metrics, $R_{i \in N_c^{(k)}}$ and $M_{i \in N_c^{(k)}}$. Since $N_c^{(k)}$ contains only the nodes which had a route change from the previous iteration, we cull previously examined routes and reduce processing complexity. The algorithm will stop searching when $N_c^{(k)}$ is the null set. This indicates potential routes in the next iteration will not provide a greater metric than routes in the current iteration. Routes and hop modes used in the current iteration provide maximum throughput for relaying.

IV. SIMULATION MODEL

The simulation model assumes a propagation environment consistent with the ETSI-A channel model for office non-line-of-sight environments; a slow-fading Rayleigh channel model with a 50 ns RMS delay spread. Packet error rate, $P_e(SNR, m)$, lookup tables for the ETSI-A channel are obtainable from previous studies [3], [5]. A shadow fading standard deviation of 5.1 dB is used and links are static for the duration of transmission. Received signals include white noise with a power of -90 dBm. The propagation exponent is set to 3.4.

Using a hexagonal cellular structure, we consider a simple case where constant interference originates from the center of the six nearest co-channel cells for the duration of transmission. We use a cluster size of 12, and a hexagonal cell radius of 128 m or 256 m. The AP, placed in the center of the cell, services 64 subscriber nodes that are randomly and uniformly located throughout the cell. All nodes transmit with a maximum power of 23 dBm using omni-directional antennas.

Nodes use adaptive modulation in the downlink. Table I defines mode settings and corresponding modulation efficiency, *D*, for various SNR ranges for the ETSI-A propagation environment [3].

TABLE I – Adaptive modulation settings

SNR [dB]	PHY-mode, $m^{(max)}$	D, [info. bits/ OFDM symbol]
< 8.09	QPSK ½	48
< 10.25	QPSK ¾	72
< 15.57	16-QAM 9/16	108
< 20.17	16-QAM ¾	144
> 20.17	64-QAM ¾	216

Factors such as mobility and overhead due to relaying are omitted from the simulations.

V. SIMULATION RESULTS

Fig. 4 and Fig. 5, depicting the CDF of network throughput for 128 m and 256 m cells respectively, indicate significant gains in throughput when using diversity and the algorithm presented in Sec. III. The probability of outage, the percentage of users who transmit with 0 Mbps, decreases from ~39% to ~0%, and from ~83% to ~0%, when using relaying in 128 m and 256 m cells respectively. Table II summarizes the results. Routing type indicates the diversity model used to evaluate PER in the routing algorithm. Here SH = single hop.

TABLE II – Simulation results

Routing Type	Avg. Throughput [Mbps]		Avg. Hops in Route	
	128 m Cell	256 m Cell	128 m Cell	256 m Cell
SH	7.75	2.07	1	1
MH	12.77	4.17	2.21	2.93
MHSC	13.17	4.70	2.64	4.17
MHMRC	13.19	4.70	2.62	4.14

Routing with diversity can improve data rates by almost 0.5 Mbps in the case of MHSC as compared to basic multihop relaying. This diversity gain is essentially "free" since extra time slots and transmit power is not required. However, using relaying requires a greater number of hops and increases load on nodes as shown in Fig. 6 and Fig. 7. MHMRC performance does not show much gain compared to MHSC since nodes only relay when packets are received correctly. MRC combining may show considerable gains if nodes relay incorrectly decoded packets. Research is in progress in this regard.

VI. DISCUSSIONS AND CONCLUSIONS

In this paper we investigated the effects of various multihop diversity relaying schemes and introduced a novel relaying algorithm able to find routes in a network factoring diversity advantages using multihop SC and multihop MRC combining. Our results show significant increase in network throughput and reduced outage probability without the need for extra time slots. Increased load on mobile nodes due to relaying may be mitigated by allowing relaying only when this yields gains in throughput greater than a certain threshold.

While there is promising reasons for using multihop relaying with diversity, there still remain open issues requiring further investigation. One particular extension is the use of analog relaying or digital relaying with error propagation to increase performance when using MRC combining with relaying. More powerful diversity schemes such as code combining [6] can also be used to increase relaying performance.

ACKNOWLEDGEMENT

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REFERENCES

[1] N. Esseling et. al., "Supporting cost efficient public 5GHz-W-LAN roll out with a multi hop HiperLAN/2 concept," *VTC 2002 Spring*, pp. 1180-1184, 2002.

[2] W. Zirwas et. al., "Broadband multi hop networks with reduced protocol overhead," *European Wireless Conference*, 2002.

[3] J. Habetha, S. Mangold, and J. Weigert, "802.11a versus HiperLAN/2 – A comparison of decentralized and centralized MAC protocols for multihop Ad Hoc Radio Network," *Systemics Cybernetics and Informatics Conference*, 2001.

[4] J. Boyer, D. Falconer, and H. Yanikomeroglu, "A theoretical characterization of the multihop wireless communications channel with diversity," *IEEE Globecom*, 2001.

[5] J. Khun-Jush, P. Schramm, U. Wachsmann, and F. Wenger, "Structure and performance of the HiperLAN/2 physical layer," *VTC 1999 Fall*, pp. 2667-2671, 1999.

[6] D. Chase, "Code combining - A maximum-likelihood decoding approach for combining an arbitrary number of packets," *IEEE Trans. on Communications*, vol. 33, no. 5, pp. 385-393, 1985.

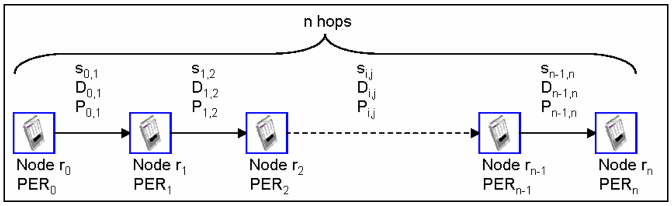

Fig. 1 – Multihop relaying

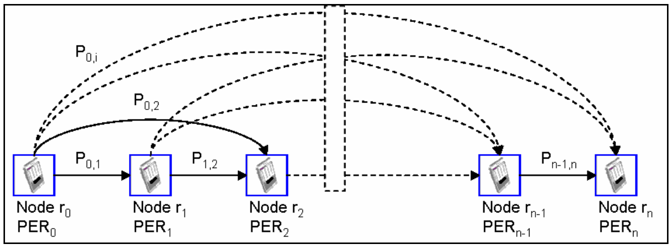

Fig. 2 – Multihop relaying diversity

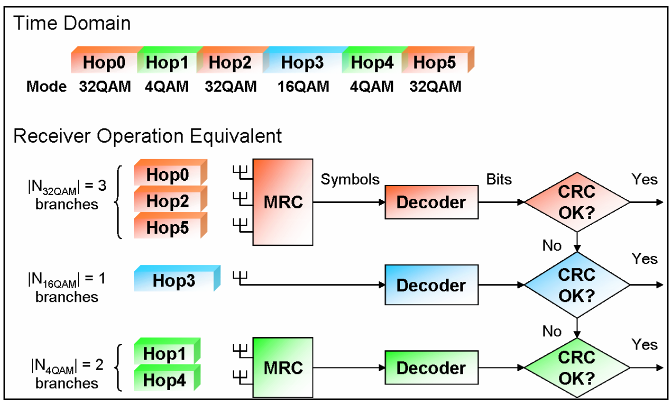

Fig. 3 – Example of a MHMRC diversity receiver for a 6 hop connection

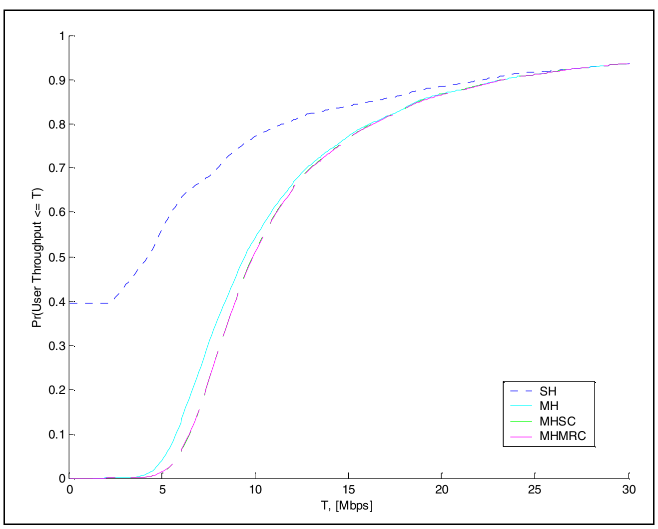

Fig. 4 – CDF of throughput, 128 m

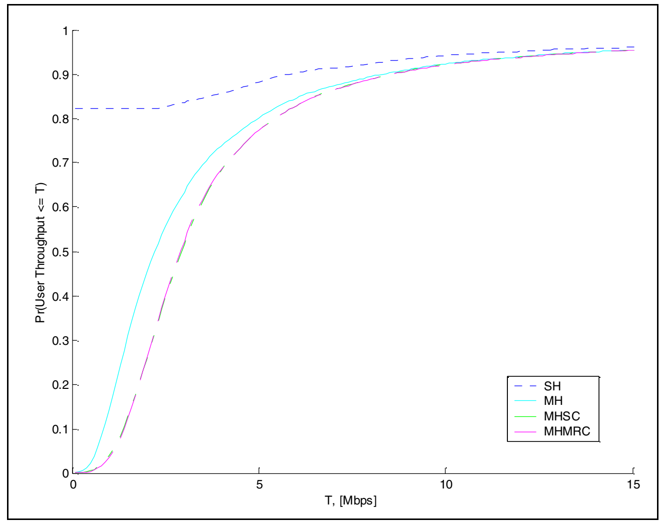

Fig. 5 – CDF of throughput 256 m

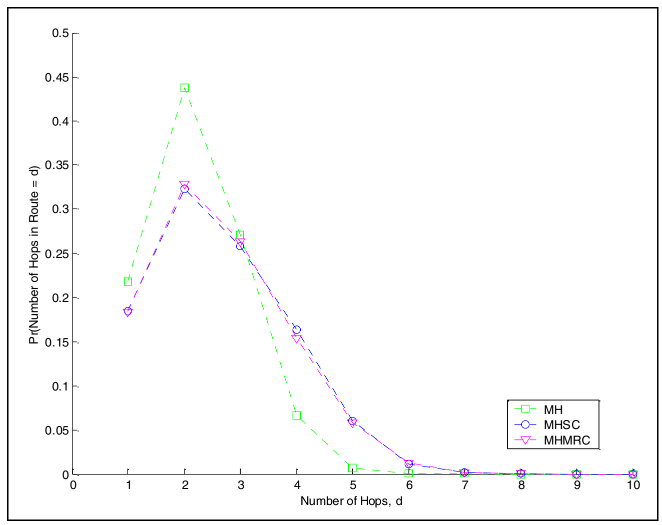

Fig. 6 – PDF of number of hops, 128 m

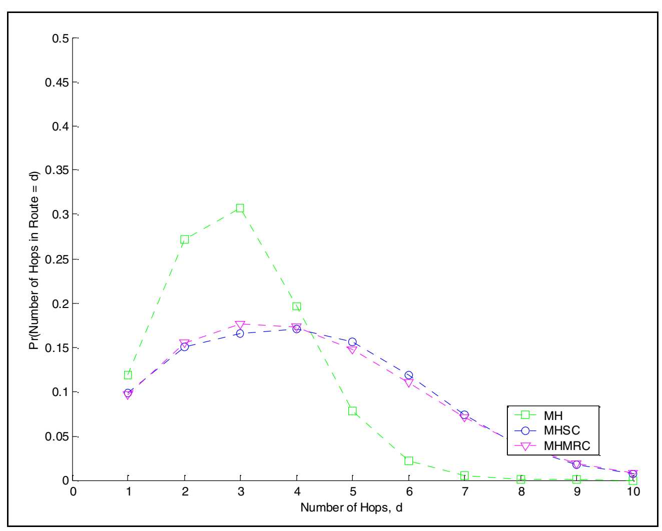

Fig. 7 – PDF of number of hops, 256 m