Cooperative Communications in Multi-Hop Networking: a Case Study Based on the IEEE 802.11 Protocol

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Technical Report UTD/EE/03/2007
April 2007

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***Abstract*— This paper combines multi-hop networking with single-hop cooperative communications. The solution is built upon the standard IEEE 802.11 protocol operating in the ad hoc mode.**

A simulation based comparison is carried out in order to evaluate the performance gains and benefit of cooperative communications applied to multi-hop networking.

Preliminary results indicate that network performance in terms of both throughput and end-to-end delay improves. Additionally, cooperative communications increases robustness against uncertainties in the wireless channel.

I. INTRODUCTION

The broadcast nature of the wireless medium can be used to improve the system throughput by having a node, other than the source and the destination, actively help deliver the data frame correctly. This is referred to as cooperative communications.

One example is multi-hop networking, whereby data frames reach the final destination via multiple transmissions over a pre-determined sequence of wireless links [1], [2]. The essence of the idea is that a sequence of shorter transmissions improves the delivery success rate of a single transmission.

Another example is single-hop networking, whereby the data packet is transmitted directly to the destination, and other node(s), the *relay* node(s), overhear the transmission and may help improve the delivery success rate of the data frame [3], [4], [5], [6]. The essence of the idea is that, the destination benefits from data frames arriving via two (or more) statistically independent paths, i.e., spatial diversity. The advantages of cooperative communications include the ability to increase the radio channel capacity [3], [7], [8] and reduce the latency of automatic retransmission request protocols [9], [10], [11]. While the advantages of each of the two approaches above are well documented in a number of studies [1], [2], [3], [4], [5], [6], the effect of combining them remains to be studied in depth.

This paper presents a (simulation based) preliminary study aimed at assessing what performance gains and benefits (if any) should be expected when combing multi-hop networking and relay-based communications in the same radio network.

The study is carried out using IEEE 802.11 [12] as the MAC protocol. The IEEE 802.11 protocol operates in ad hoc mode in order to enable multi-hop networking. The standard protocol is slightly modified to provide relay based cooperative communications over each radio link [6] in the multi-hop route. For a simplified implementation of the radio transceiver and drivers [5], [13], [14], the transmitted power level is assumed to be fixed and constant for all radio nodes. Various distances for the next hop transmission are considered in conjunction with the use of one specific relay node for each hop transmission. For the performance assessment of the proposed solution, both end-to-end delay and saturation throughput of a *single* session are estimated and compared against the performance of a multi-hop networking solution without the use of cooperative communications.

Based on this preliminary study, both the saturation throughput and the end-to-end delay improve when cooperative communications is used. An additional advantage of cooperative communications when used in multi-hop networking is the increased robustness against possible uncertainties, e.g., uncertainties on the node position, wireless link quality, etc.

II. SYSTEM DESCRIPTION

The IEEE 802.11 protocol can operate in infrastructure or ad hoc mode. When operating in ad hoc mode, it is possible to transmit data over a multi-hop route. While the specifics of the routing protocol are not part of the standard, the standard provides support for multi-hop at the link layer, i.e., without using the network layer protocols.

Fig. 1 shows a typical ad hoc network and a multi-hop route from a source node S to a destination node D via intermediate nodes A, B, C and D. As seen in the figure, there are other nodes which do not participate in routing packets from S to D, but, due to the broadcast nature of the wireless medium and the broadcast nature of the IEEE 802.11 protocol, they overhear transmissions. This is normally seen as a negative effect in wireless communications. However, cooperative protocols [3], [4], [6] take advantage of it in order to improve the network performance.

This research is supported in part by NSF grants No. ECS-0225528 and CNS-0435429

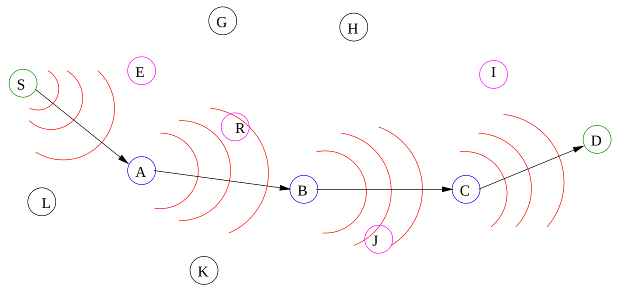

Fig. 1. Multi-hop ad hoc network.

The next section quickly reviews one wireless cooperative protocol, i.e., UTD MAC [6], and details how such protocol is applied to multi-hop networking.

A. *Multi-hop Networking with Cooperative Protocols*

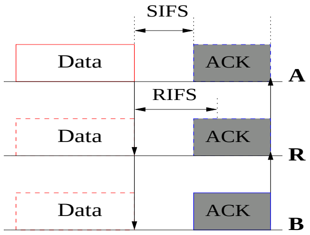

Fig. 2. Case 1: successful delivery of data and acknowledgment frames.

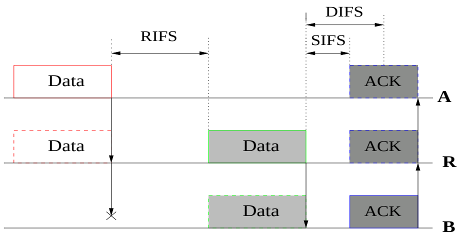

Fig. 3. Case 2: cooperation by R in retransmitting the data frame.

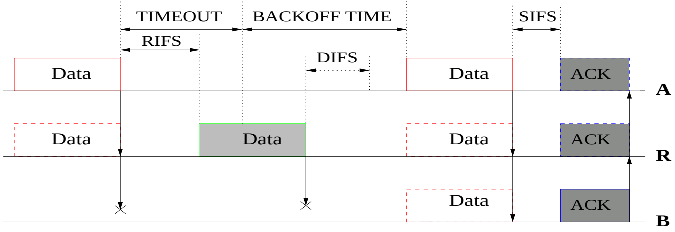

Fig. 4. Case 3: both A and R are unsuccessful.

The work in [6] defined the protocols and the timers for a simple three node network, i.e., a single hop configuration, as follows. Assume that A is sending a data frame to B and R has agreed to cooperate[1]. The cooperative MAC protocol is based on the distributed coordination function (DCF) defined for the ad hoc mode of the IEEE 802.11 standard. When transmitting a data frame, A makes a direct attempt to reach B. While transmission takes place, R receives and stores a copy of the data frame temporarily. Four cases are possible[2]. The time diagrams of the transmitted frames are shown in Figs. 2-5, respectively.

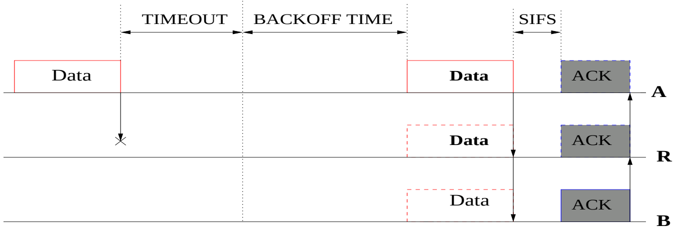

Fig. 5. Case 4: both B and R do not receive the data frame.

1) Fig. 2: the frame transmitted by A is successfully received at B. B responds with a positive acknowledgment (ACK).
2) Fig. 3: the frame transmitted by A is successfully received at R, but not at B. B does not acknowledge the received data frame. Not receiving the ACK from B, R assumes that A has attempted to reach B and has failed, therefore R proceeds with the transmission of the data frame copy. R transmitted frame is successfully received at B. B responds to A with an ACK.
3) Fig. 4: Same as case 2, but B does not receive the frame transmitted by R.
4) Fig. 5: the frame transmitted by A is neither received successfully at R nor at B.

For the cooperation protocol to work as described, time intervals between transmission attempts must be chosen carefully. Specifically, for the transmission of a data frame, A must sense the channel idle and wait for a time interval defined distributed inter-frame space (DIFS)[3]. For ACK transmission, B does not need to wait. ACK is then received at A and R no later than a time interval defined short inter-frame space (SIFS). SIFS takes into account various latency factors, e.g., MAC software, transceiver hardware, and radio signal propagation. Both DIFS and SIFS are defined in IEEE 802.11. For transmission of the data frame copy, R must wait a time interval denoted as relay inter-frame space (RIFS). RIFS was specifically introduced in [6] as a component of the cooperative protocol and is not defined in IEEE 802.11. RIFS must be chosen to both allow the detection at R of the ACK transmitted by B (RIFS $>$ SIFS), and prevent frame transmission of other nodes while the cooperation is taking place (RIFS $<$ DIFS). A possible value for RIFS is the point (coordination function) inter-frame space (PIFS). PIFS is defined in IEEE 802.11 to allow the point coordination function to have collision-free access to the channel for coordinating data frame transmissions in the infrastructure mode. Choosing RIFS=PIFS is a possible

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[1] The protocol required to reach a consensus among the three nodes willing to cooperate is beyond the scope of this paper. Routing protocols available in the literature can be extended and adapted to perform relay selection [15].

[2] In the four cases it is assumed that the acknowledgment is always received correctly by A and R. The extension to account for acknowledgment loss is omitted for simplicity.

[3] Exception to this rule is when multiple frames containing the fragments of the same packet are sequentially transmitted by the same sender.

option when operating the cooperative protocol in the ad hoc mode, as the point coordination function is not present. The backoff procedure at A is the same as in IEEE 802.11. When the predetermined maximum number of transmission attempts is reached, the data frame is discarded.

The cooperative protocol UTD MAC in [6] is extended to multi-hop networks in the following straightforward way. For each hop in the multi-hop route, one relay is chosen to cooperate and help the transmission of data from from one end point of the link to the other. For example, in Fig. 1, the hop from S to A can use E as relay, the hop from A to B can use R as relay, and so on.

III. RESULTS

This section discusses some of the assumptions used to obtain simulation results for the comparison between the IEEE 802.11 protocol and UTD MAC. Then, obtained results for throughput and end-to-end delay analysis are presented and discussed.

A. Simulation Setup

In order to eliminate the possible effect of distributed routing protocols on the network performance, the route selection procedure is kept very simple. Additionally, routes are static, i.e., routes are selected before starting the simulation and are never changed. Selection is performed using a shortest path algorithm over a graph $G(V, E)$, where V is the set of nodes, E is the set of available links. A link between two nodes is available if the two nodes are within transmission range. The same, multi-hop route selection is applied to both the IEEE 802.11 and UTD MAC. Results are presented for a wide range of the value of the transmission range, i.e., one hop distance (OHD). Once the sequence of links to be used in the multi-hop route is selected, a relay must be chosen for each link when using UTD MAC. The choice is based on an exhaustive search among all possible relays. The chosen relay is the one that maximizes the single hop throughput based on the analytical model presented in [16]. Once the multi-hop route and relays are chosen, the data rates for the various node pairs have to be selected. For every link in the route that includes a transmitter A, receiver B, and relay R, a search of all possible rate combinations A-R and R-B rates is done. Four rates are considered, i.e., 1 Mbps, 2 Mbps, 5.5 Mbps, and 11 Mbps. The rate combination that yields the maximum link throughput is chosen. For the plain IEEE 802.11, for each link, the search is conducted over the four possible rates. The rate that yields the maximum link throughput is chosen. The channel model is described in detail in [16]. The channel is assumed to have a flat Rayleigh fading that remains constant for the duration of a data frame. The parameters used for simulation are tabulated in Table I. The sensing threshold is set to -107 dBm. Whenever a node senses a power level that is higher than -107 dBm, it will sense the channel as busy. The interference threshold is set at -137 dBm. Any interference can be seen by a node only if the power level is greater than -137 dBm. Spatial reuse is possible because of the finite sensitivity range value[4].

TABLE I

PARAMETERS USED IN SIMULATION

Path Loss Exponent β = 4	Fading is Flat Rayleigh
Average Transmitter Power = 100 mW	PHY Header = 192 bits
SIFS = 10 μs	RIFS = 30 μs
DIFS = 50 μs	Slot Time = 20 μs
Vulnerable Period = 20 μs	Max Retrans. Attempts = 6
Frame Size = 1023 bytes	CWmin = 31 slots
CWmax = 255 slots	MAC Header = 34 bytes
MAC ACK = 14 bytes	Sensitivity = -107 dBm

B. Saturation Throughput Analysis

The saturation throughput analysis is performed first for a three node scenario, i.e., nodes S, R and D. The relay R is at the center of the line joining S-D. The S-D distance is varied along the x-axis in Fig. 6. The throughput-distance product for the IEEE 802.11 and the UTD MAC protocols are shown in the y-axis in Fig. 6.

Throughput is defined as the number of MAC payload bits that are successfully delivered and acknowledged by the destination D per unit of time. We find that IEEE 802.11 performs at its best at a distance of 40 m and UTD MAC at a distance of 60 m.

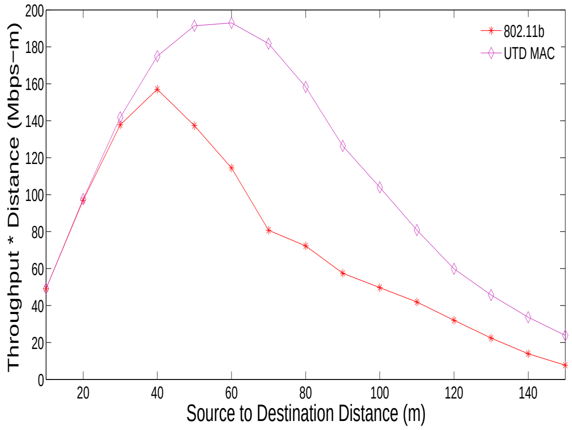

Fig. 6. Throughput-distance product vs. S-D distance , R is at center for UTD MAC.

The next set of results is obtained considering a linear topology as shown in Fig. 7. All the nodes are positioned along a line with source S and destination D at the extremes. The S-D distance is 420 m. Intermediate nodes are equally spaced[5] and the inter-node distance is 10 m. When using UTD MAC, a relay is identified and selected for each hop.

Fig. 8 shows the throughput for IEEE 802.11 and UTD MAC protocol for OHD varying from 30 m to 150 m. IEEE 802.11 has its peak throughput at the OHD of 40 m and UTD MAC at 60 m. Additionally, UTD MAC achieves a higher throughput than IEEE 802.11. Notice that when, UTD MAC

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[4] -107 dBm sensing range with a transmitted power of 100 mW correspond to about 150 m in a nonfading channel where the path loss exponent β is 4.

[5] Notice that not necessarily every node participates in the multi-hop or cooperative communications. Only those selected to be in the shortest path algorithm or to be relays, play an active role in the simulation.

Fig. 7. Linear Topology showing the one hop and internode distances

has OHD at 60 m, the relay is placed in the middle of each hop. Contrary to intuition, UTD MAC with OHD = 60 m significantly outperforms IEEE 802.11 with OHD = 30 m.

This result is consistent with the three node study described above. It can also be observed that the UTD MAC is more robust in terms of throughput when OHD is in and around the optimal value of 60 m. The initial throughput increase can be attributed to the fact that that the number of hops decreases as OHD increases. However, when OHD increases further, frame errors increase causing a fall in throughput. There is a trade-off in minimizing the number of hops by increasing the value of OHD.

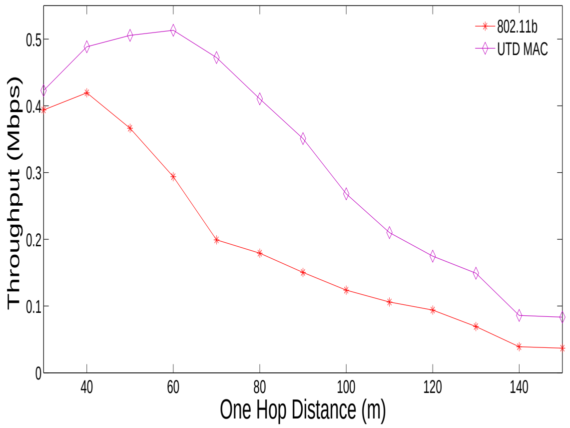

Fig. 8. Throughput vs. OHD, S-D distance is 420 m, inter-node distance is 10 m.

The robustness of UTD MAC to the choice of OHD is studied by considering inaccurate node location knowledge. A regular grid topology of 30 × 30 nodes is considered. Inter-node distance along the x and y axes is 10 m. In this simulation, the route selection is performed in the same way as the previous experiment. However, after route selection all nodes are moved from their position[6]. The random movement of nodes from their positions is characterized by a two dimensional Gaussian random variable with zero correlation, i.e., movement along the two directions is independent of each other. The value of throughput reported for each standard deviation is the averaged value across various simulation runs. Reported values of throughput have a confidence interval of 10% or better over a confidence level of 95%.

Values for OHD of 40 m, 50 m and 60 m are considered for analysis. The source node is the one at $(0, 0)$ and the destination is at $(290, 90)$. Fig. 9 shows that UTD MAC is less affected by inaccurate topology information than IEEE 802.11. Alternatively, UTD MAC can perform well even with less frequent routing table updates that can, for example, be triggered frequently because of mobility. Additional simulation runs for different choices of S and D led to similar results.

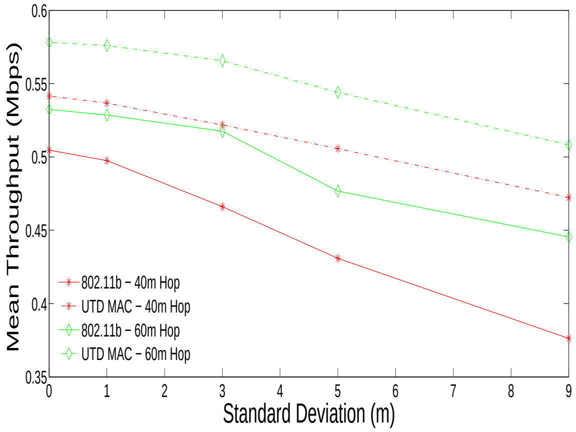

Fig. 9. Throughput vs. standard deviation, 30 × 10 Grid Topology, S at $(0, 0)$ and D at $(290, 90)$.

C. Delay Analysis

With real time applications such as voice, the network should operate at non-saturated conditions to control delay. In such applications, end-to-end delay is the main factor that determines the performance of the system. For voice application a typical constraint is that latency should be less than 150 ms. Reported results are based on two popular codecs used in VoIP applications, i.e., the G.711 codec which generates a voice payload of 80 bytes and the G.729 codec which generates a voice payload of 20 bytes [17]. The two codecs generate a data rate of 64 kbps and 8 kbps respectively.

End-to-end delay is measured as the time elapsed between the creation of the packet at the application, i.e., when the application passes the voice packet to either the IEEE 802.11 or UTD MAC, and the time the packet is successfully received by the destination application layer. Fig. 10 shows the average end-to-end delay (AD) across various one hop distances for IEEE 802.11 and UTD MAC for the G.729 codec. Since the voice packets are of size 20 bytes and are being generated at 8 kbps, it takes 20 ms for a packet to be generated and enter the MAC queue. In order for packets to satisfy the 150 ms latency requirement, the end-to-end delay should be less than 130 ms. Fig. 10 shows that UTD MAC is able to deliver packets within the requirement and that its delay is lower than IEEE 802.11. The property of robustness, holds true for the UTD MAC when considering delay too. Differently from the results in section III-B the optimum value of OHD for UTD MAC is 70 m. This can be explained with the following: the G.729 codec generates data frames (payload plus headers) of total length 60 bytes, while results presented in section III-B are obtained using a data frame length of 1023 bytes. With the same bit error probability, G.729 data frames have a smaller frame error rate the data frames containing 1023 bytes.

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[6] Nodes S and D do not move.

TABLE II
COMPARISON OF IEEE 802.11 AND UTD MAC FOR VOICE APPLICATIONS

	OHD (m)	G.729		G.711	
		802.11	UTD MAC	802.11	UTD MAC
AD (ms)	30	34.7	32.7	1228.5	204.4
	40	26.1	22.4	122.2	61.8
	50	21.4	17.3	101.2	40.4
	60	19.2	13.3	796.9	28.2
	70	17.6	11.7	365.3	25.3
DR (%)	30	99.966	99.968	97.9824	99.956
	40	99.992	99.996	99.6137	100
	50	99.983	99.992	99.721	100
	60	99.992	99.991	99.578	99.984
	70	99.964	100	99.344	100
TR (Mbps)		SD	$SR-RD$	SD	$SR-RD$
	30	11	11 - 11	11	11 - 11
	40	5.5	11 - 11	11	11 - 11
	50	5.5	11 - 11	5.5	11 - 11
	60	2	5.5 - 11	2	11 - 11
	70	2	5.5 - 11	2	5.5 - 11

Similar studies were carried out on other topologies leading to similar results. Table II lists the end-to-end delay (AD), delivery ratio (DR), and transmission rates (TR) used by IEEE 802.11 and UTD MAC for a few values of OHD. UTD MAC has better packet delivery ratios (DR) as well. This is another requirements of voice applications [17].

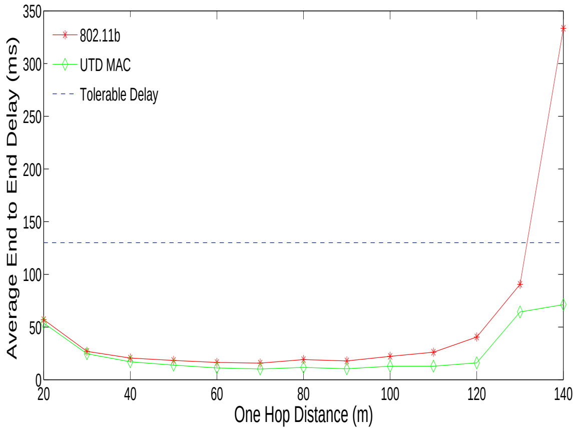

Fig. 10. Average end-to-end delay vs. OHD, G.729 codec, S-D distance is 420 m, inter-node distance 10m.

Fig. 11 shows results obtained repeating the previous experiment using the G.711 codec. Voice packets are 80 bytes long and are being generated at 64 kbps. It takes then 10 ms for a packet to be created. In order for the voice data to reach the destination within 150 ms, the end-to-end delay should be less than 140 ms. For most one hop distances, IEEE 802.11 is not able to deliver packets within the required latency, while UTD MAC is able to do it for values of OHD up to 90 m. Hence, UTD MAC provides a better support for real time data applications by exploiting cooperative communications.

IV. EXTENDED RESULTS

Figs. 12 and 13 show the Throughput across various OHD when the inter-node distance is 15 m and 20 m respectively. This network is sparse as compared to Fig. 8. The increase in throughput gained by UTD MAC over IEEE 802.11 is observed to stay even in such sparse networks.

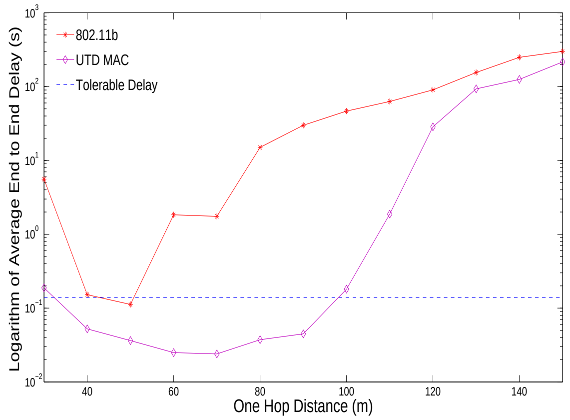

Fig. 11. Average end-to-end delay vs. OHD, G.711 codec, S-D distance is 420 m, inter-node distance 10 m.

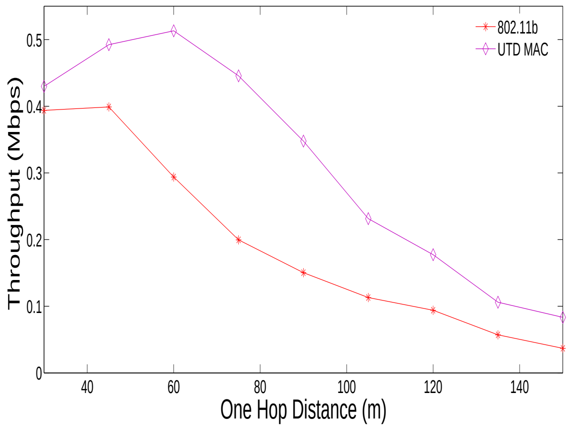

Fig. 12. Throughput Vs OneHopDistance , S-D distance is 420 m, InterNode distance is 15 m

The linear topology experiment was also conducted on one other network in which the end-to-end distance is 300 m. The throughput analysis was carried out for inter-node distances of 10 m, 15 m and 20 m. Fig. 14 shows the plot of Throughput Vs OHD for a linear topology of length 300 m. The Throughput provided by UTD MAC is much higher and robust as compared to the IEEE 802.11 protocol. It may be noted that the UTD MAC is really robust in OHD of 50 m and 60 m with subtle throughput improvement at 60 m. Again, the results here corroborate the study carried out for the 420 m linear topology described previously.

Figs. 15 and 16 shows the plot of Throughput Vs OHD for internode distances 15 m and 20 m. Here again, UTD MAC is robust and better in terms of throughput than the counterpart IEEE 802.11 protocol.

Fig. 17 shows a grid network of nodes arranged in a regular manner. In our study, 30 × 30 nodes are placed in a regular grid structure. The figure shows the path chosen for

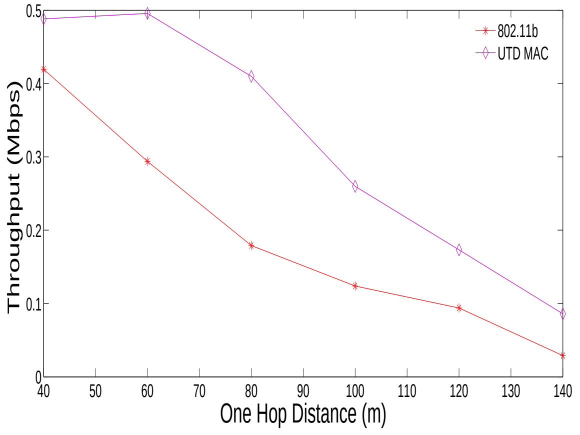

Fig. 13. Throughput Vs OneHopDistance , S-D distance is 420m, InterNode distance is 20 m

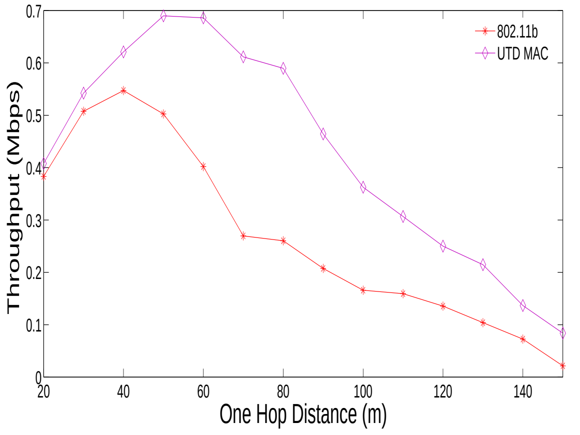

Fig. 14. Throughput Vs OneHopDistance , S-D distance is 300 m, InterNode distance is 10 m

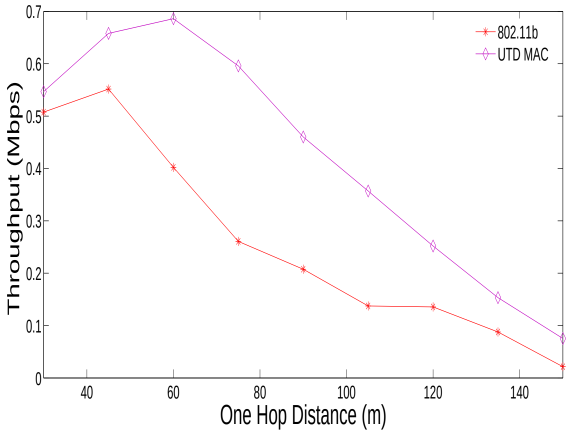

Fig. 15. Throughput Vs OneHopDistance , S-D distance is 300 m, InterNode distance is 15 m

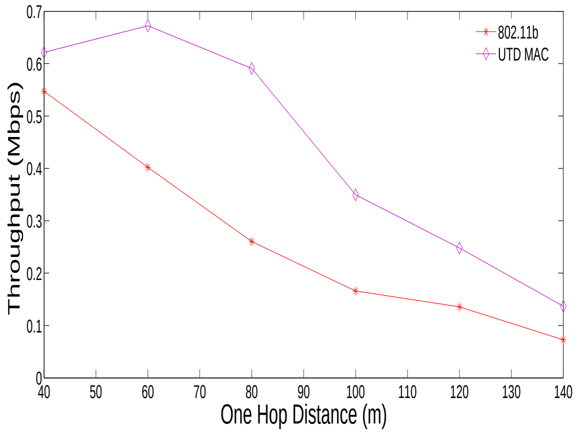

Fig. 16. Throughput Vs OneHopDistance , S-D distance is 300 m, InterNode distance is 20 m

destinations at $(290, 90)$ and $(290, 190)$ for OHD of 40 m and 60 m. The throughput analysis for the destination at $(290, 90)$ has been presented in the results section.

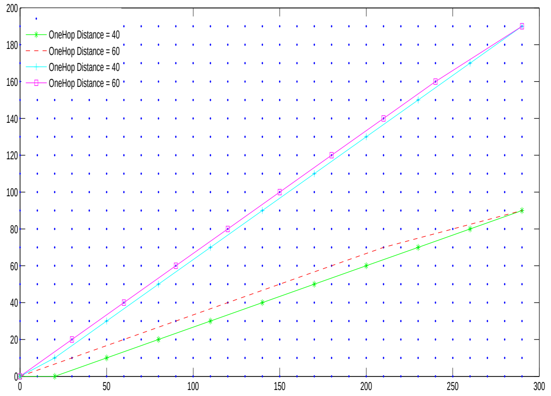

Fig. 17. Grid Topology showing the destinations at $(290, 90)$ and $(290, 190)$ and the paths chosen for the one hop distance of 40 m and 60 m

Two destinations $(290, 0)$ and $(290, 190)$ in the grid are considered for study. OHD used are 40 m and 60 m. Note that from three node scenario, 40 m is the optimum OHD for IEEE 802.11 and 60 m is the optimum for UTD MAC. For $(290, 0)$ alone, OHD of 50 m was also studied. The source node is at $(0, 0)$. All nodes except the source and destination are moved from their original positions. The movement is characterized by a two dimensional gaussian random varible with zero correlation. This is to mimic the actual movement of nodes after a route has been chosen. It is expected that the movement will cause a fall in throughput. Fig. 18 shows the Throughput vs. standard deviation for such a scenerio in which S-D distance is 290 m (S is at $(0, 0)$ and D is at $(290, 0)$) and other nodes along the line joining S and D separated by 10 m. Standard deviation of zero corresponds to no movement. It is seen that the Throughput decreases as mobility increases. It is also obeserved that UTD MAC is more robust to movement as the throughput of UTD MAC does not degrade much when compared to that of IEEE 802.11.

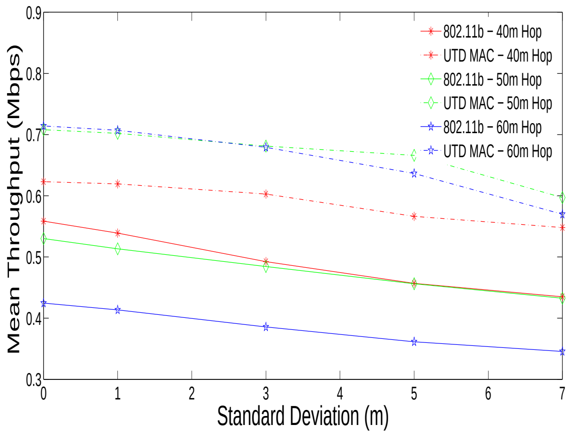

Fig. 18. Mean Throughput Vs Standard Deviation ,Linear Topology with S-D distance is 290 m

Fig. 19 shows the study carried out for S at $(0, 0)$ and D at $(290, 190)$. The robustness of UTD MAC in terms of throughput is reiterated in this plot as well. It should be noted that a OHD of 60 m does not necessarily imply that the distance between the nodes in the grid is 60 m. It just means that the maximum distance till which a node will have link to other node is 60 m.

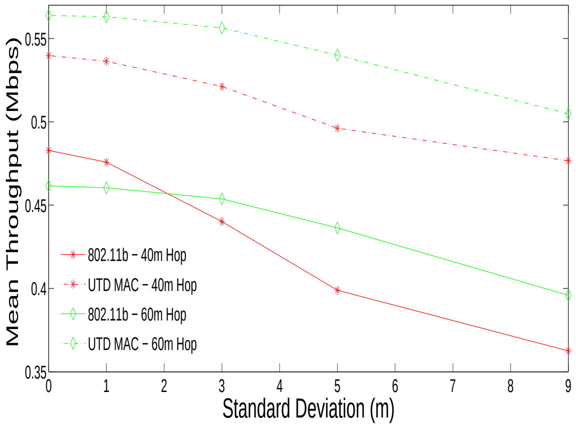

Fig. 19. Throughput vs. standard deviation, 30 × 10 Grid Topology, S at $(0, 0)$ and D at $(290, 190)$.

Fig. 20 shows the plot of Throughput Vs Standard Deviation for the mobility experiment conducted on a linear topology of length 420 m. The movement of nodes other than the source and destination is just along the horizontal axis. The movement is again gaussian. Here again, UTD MAC is robust when compared to IEEE 802.11 protocol.

Delay analysis for linear topology of length 420 m was carried out for inter-node distances of 15 m and 20 m. The vocoder used is G.729. The end-to-end delay requirements have been discussed in previous section. UTD MAC is better than IEEE 802.11 in terms of end-to-end delay. Even here UTD MAC is robust in terms of delay to changes in OHD. Figs. 21 and 22 shows the results obtained.

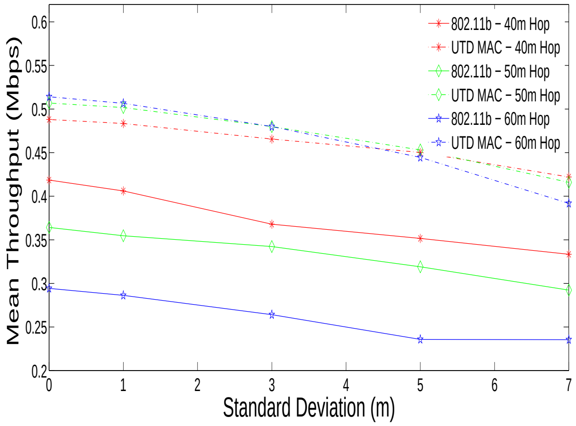

Fig. 20. Mean Throughput Vs Standard Deviation ,Linear Topology with S-D distance is 420 m.

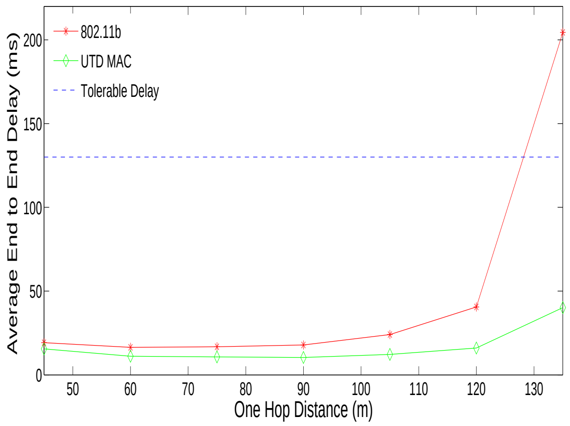

Fig. 21. Average End to End Delay Vs OneHop Distances , For Voice application at 8kbps S-D distance is 420m with InterNode Distance =15m

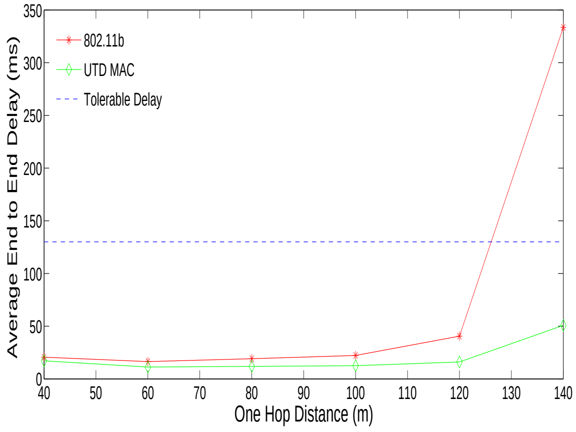

Fig. 22. Average End to End Delay Vs OneHop Distances , For Voice application at 8kbps S-D distance is 420m with InterNode Distance =20m

The delay analysis is also studied for a different vocoder G.711. The internode distances considered here are 15 m and 20 m. UTD MAC is consistently better in terms of end-to-end delay and is significantly better than IEEE 802.11. Figs. 23 and 24 shows the results obtained for G.711 vocoder. The plots are in log scale. UTD MAC is robust to changes in OHD in these plots.

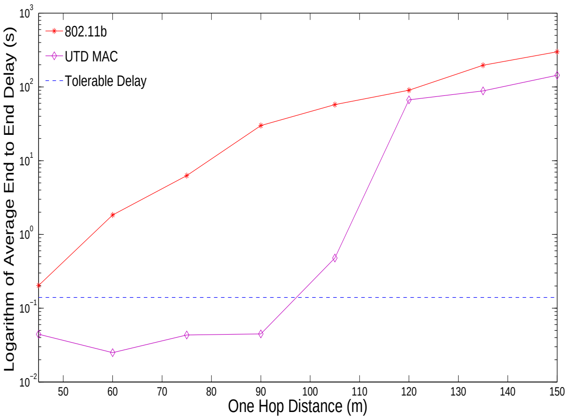

Fig. 23. Average End to End Delay Vs OneHop Distances , For Voice application at 64kbps S-D distance is 420m with InterNode Distance =15m

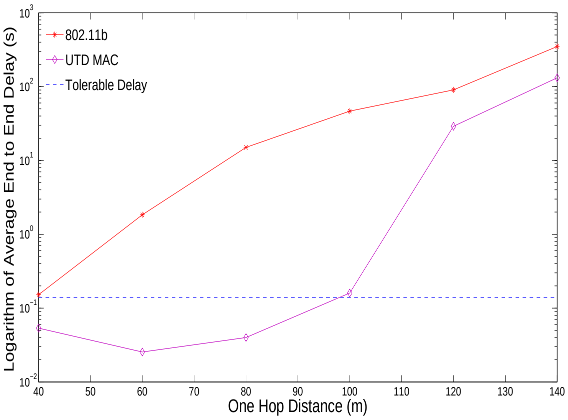

Fig. 24. Average End to End Delay Vs OneHop Distances , For Voice application at 64kbps S-D distance is 420m with InterNode Distance =20m

V. CONCLUSIONS

The paper presented preliminary results that assess the performance gain obtained by using cooperative communications with multi-hop when compared to multi-hop. The study is performed using one of the most widely used protocols for wireless communications, i.e., the IEEE 802.11. Obtained results show that cooperative communications adds robustness against uncertainties, e.g. node positions, as well.

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