Adaptive Cooperative Multi-Hop Transmission in Ad Hoc Networks

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***Abstract*— Cooperative communication techniques have been proposed in order to improve the quality of the received signals at the receivers by using the diversity added by duplication of signals sent by relay terminals situating between each transmission pair. This paper proposes an adaptive cooperation technique for frame transmissions in Ad Hoc networks that is compatible to both of the basic access mode and the optional access mode of IEEE 802.11 Medium Access Control (MAC) protocol. The transmission mode for each data frame is adaptively switched between a cooperative mode and a non-cooperative mode based on the absence of acknowledge (ACK) frame. Simulations show that transmission performance is improved by decreasing the number of re-transmissions due to frame errors; thus, chances of multi-hop mode transitions that are costly in time and bandwidth are alleviated. The analysis of the proposition performance indicates the interest of the adaptation paradigm. It puts forward that, in addition to the channel quality parameter, the channel availability parameter must be concerned in the adaptation process.**

Keywords-adaptive cooperation; cooperative transmissions; IEEE 802.11

I. INTRODUCTION

In wireless communications, fading causes errors on data transmissions. Based on IEEE 802.11 MAC standard, re-transmission processes are required when error data frames are detected. Obviously, re-transmissions increase delay and decrease the packet delivery ratio (PDR) of the networks. More precisely, in multi-hop networks, if the re-transmission counter (Re-Tx) reaches the threshold, a route recovery process is activated. For example, considering Ad Hoc On-Demand Distance Vector (AODV) routing protocol [1], the route recovery process is done by an AODV source-initiated route re-discovery method. The source terminal (S) broadcasts a route request (RREQ) packet to re-find a route to the destination terminal (D). The RREQ packet will be re-broadcasted through the network. Therefore, the network is flooded and is led to network congestion problems.

In addition, if the route re-discovery process occurs when the direct path (S-to-D) is dropped, instead of receiving the RREQ packet from S, D receives the RREQ packet from an intermediate terminal (I) locating between S and D terminals. Thus, the transmission mode is switched from direct transmission mode to multi-hop transmission mode as shown in Fig.1. Rather than directly transmits a data frame from S to D in one time slot, the multi-hop transmission requires two time slots to send this data frame from S to I and from I to D, respectively. Therefore, similar to re-transmissions, multi-hop transmissions also increase the delay and decrease the PDR of the networks.

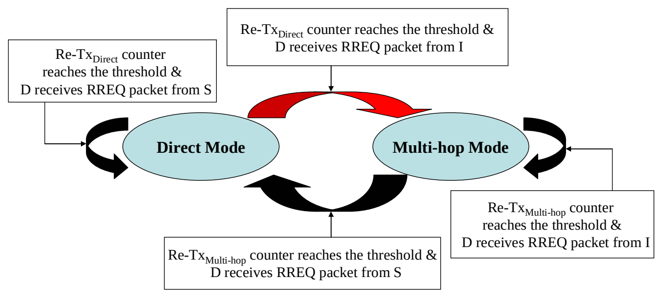

Figure 1. Transmission mode transitions.

Since multi-hop mode transitions happen when the Re-Tx counter of the direct mode transmission (Rx-Tx$_{Direct}$) reaches the threshold, transmission performance of the direct mode must be improved in order to reduce the number of re-transmissions. Multiple-input Multiple-output (MIMO) is an example of transmission techniques that have been proposed to improve transmission performance in wireless communications. MIMO provide advantages of spatial diversity by uncorrelated signal components generated from antenna array at a source terminal and/or a destination terminal. However, each antenna in the antenna array must be separated at least $\lambda/2$ in order to provide independent signals. λ is the wave length of the system signal and it can be calculated as follows;

$$\lambda = \frac{c}{f_c} \tag{1}$$

Where c is a speed of light (3×10^8 m/s) and f_c is a carrier frequency. Thus, for commonly used 2.4GHz frequency band, the space between antennas at 6.125 cm is required. These requirements make MIMO technique to be impractical to employ in networks with small wireless terminals such as sensor networks. In addition, MIMO requires multiple antennas, which are costly. For these kinds of contexts, cooperative communications provide an interesting

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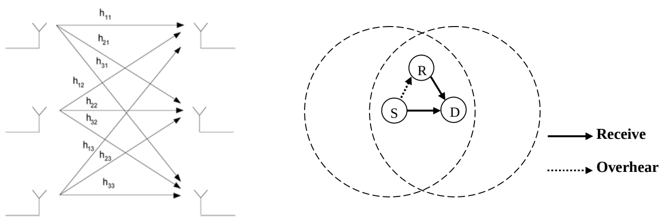
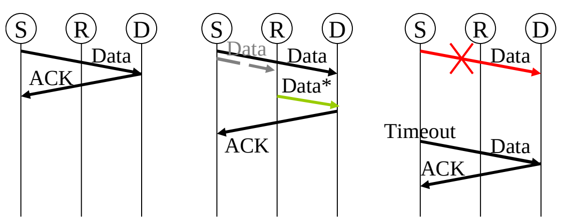
alternative that can gain benefits of spatial diversity while a single antenna is required on each terminal. Illustrations of MIMO and cooperative transmissions are respectively shown in Fig. 2a and Fig. 2b.



(a) (b)

Figure 2. Illustrations of (a) MIMO and (b) Cooperative transmissions.

Cooperative transmissions have been introduced by [2] to [4]. The concept of cooperative transmissions is to exploit the broadcast nature of the wireless medium and to transform single-antenna neighbour nodes, to work as virtual antenna arrays. As shown in Fig. 3, cooperative transmissions (Fig. 3b) utilize more medium than non-cooperative transmissions (Fig. 3a) when the channel quality of the direct path (S-to-D) is good. However, if the channel quality of the direct path is dropped, non-cooperative transmissions with re-transmission processes (Fig. 3c) consumes more medium than cooperative transmissions. Therefore, cooperative transmissions are interesting and should be used when the channel quality of the direct path is dropped. Rather than remain the transmission mode in cooperative mode (named fixed cooperative transmission), cooperative transmissions should be able to switch their transmission modes between cooperative mode and non-cooperative one. These cooperative transmissions are called adaptive cooperative transmissions.



(a) (b) (c)

Figure 3. Message flows of (a) Non-cooperative transmissions (b) Cooperative transmissions and (c) Non-cooperative transmissions with re-transmission processes.

In adaptive cooperative transmissions, generally inspired from the IEEE 802.11 MAC standard [5], the activation and deactivation of these cooperative transmission modes require extra control frames, which are modified from Request-To-Send (RTS) or Clear-To-Send (CTS) frames [6] and [7] and/or are created in new frame formats [8] and [9]. These adaptive cooperative transmissions cannot be implemented in IEEE 802.11 networks with basic access mode and also have interoperability problems with legacy systems.

For example, the message flow of an adaptive cooperative transmission protocol called CoopMAC [6] is shown in Fig. 4. CoopMAC uses CoopRTS frames (modified from RTS frames), HTS frames (Helper ready To Send, modified from CTS frame), and CTR frames to activate and deactivate cooperative transmission modes among terminals. Therefore, CoopMAC can be implemented only in the optional access mode of IEEE 802.11 networks.

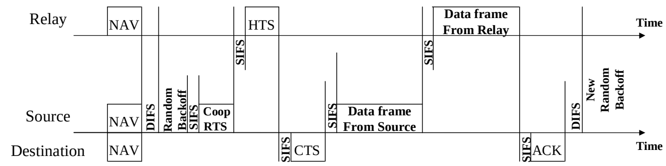


Figure 4. Message flows in CoopMAC protocol [6].

To overcome these problems, we propose a simple but effective transmission method called Adaptive Cooperation Multi-Hop Transmission (ACMHT). In order to have our proposition compatibly work with terminals without cooperative functionality in legacy systems, only some process modifications are required and affect only the nodes with cooperative functionality. In addition, our method does not use or modify RTS or CTS frames; therefore, it can work compatibly with both of the basic and the optional access methods of the IEEE 802.11 MAC protocol. Transmission mode of ACMHT can be switched between cooperative and non-cooperative mode based on the absence of ACK frames.

Our proposition intends to increase the link quality by a cooperative mechanism, and also to prevent unnecessary routing processes such as route maintenance and re-route discovery. In addition, the proposed method alleviates probability of multi-hop mode transitions in order to reduce costs of multi-hop mode transmissions. To evaluate the interest of our proposition, the transmission performance in term of PDR is considered.

The rest of the paper is organized as follows. In Section II, details of the proposition are presented. Section III is devoted to the system model while Section IV concerns with simulation results and analysis. Finally, the conclusion is drawn in Section V.

II. Adaptive Cooperative Multi-Hop Transmission

Our proposition is designed for a WiFi network using an IEEE 802.11 MAC protocol. For interoperability purposes, rather than specifying a new protocol, we decided to derive benefit from the handshaking access mechanisms to activate or deactivate the cooperative mode. Mechanisms of ACMHT when it works with the basic access method (also called two-way handshaking; Data/ACK) are shown in Fig. 5a and Fig. 5b and with the optional access method (also called four-way handshaking; RTS/CTS/Data/ACK) are shown in Fig. 5c and Fig. 5d. S, R, and D stand for Source, Relay, and Destination respectively. R is assumed to be chosen and is located in the transmission ranges of S and D. Fig. 5a and Fig. 5c represent ACMHT message flows when it works in a non-cooperative transmission mode and when it works in a cooperative transmission mode are shown in Fig. 5b and Fig. 5d.

The proposition is adaptive because its transmission mode is able to switch between a direct mode and a cooperative multi-hop mode. The appearance of an ACK

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frame informs R that the direct transmission is successful; thus, cooperative multi-hop mode is automatically turned off. The network transmission mode rests at the direct transmission mode. R remains quiet and S continues to transmit its next data frame in the direct path.

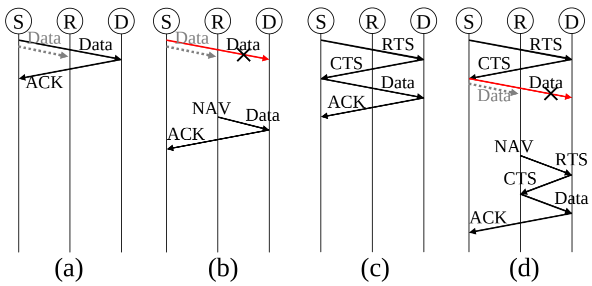

Figure 5. Message flows of our proposition (ACMHT).

On the contrary, in Fig. 5b and 4d, when D fails to decode a data frame and the network allocation vector (NAV) of R reaches to zero, the cooperative multi-hop mode transmission of the ACMHT is automatically turned on. The transmission mode of the network is temporally switched from direct mode to cooperative multi-hop mode as shown in Fig. 6. Without any changes in the header, R helps S to forward the data to D, and then the transmission mode of the network is automatically switched back to the direct mode. If D successfully decodes the data sent from R, it replies an ACK back to S. The Re-Tx counter at S is reset, and then S sends its next data frame. When the Re-Tx counter is reset, chances of multi-hop mode transition are alleviated.

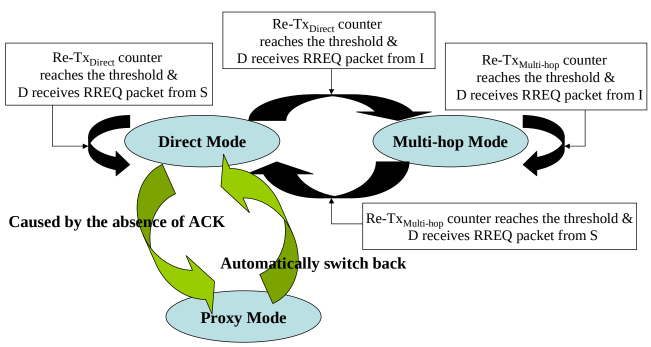

Figure 6. Transmission mode transition of ACMHT.

A MAC layer table is specified at terminal R in order to allow R to be able to filter and relay data frames sent from S to D correctly. MAC addresses of the transmission pair (S and D) are indicated in the table. These addresses are acquired by upper layer protocols such as Hello or routing protocols in the network layer. For data relaying, MAC layer relaying is chosen instead of network layer forwarding. R acts as a dynamical bridge since forwarded data frames do not need to be sent up to the network layer; thus, queuing delays and processing delays are alleviated. R directly forward exactly the same data frame (received from S) to D through its MAC layer. In addition, after forwarding the data, R does not need to wait ACK frames from D.

If adaptive cooperative transmission done by R is also fail or the ACK frame sent from D is lost, S waits until its retransmission timer reaches to zero, then the data is retransmitted. To prevent collision between re-transmissions done by S and cooperative multi-hip transmissions done by R, S must extend its timeout at least two times of the value indicated in IEEE 802.11 MAC standard.

For simplicity, similar to [6] [7] [10] and [11], in our proposition, the received signals at the destination terminal transmitted by S and R are not combined. If signal combinations in signal-level are needed, signal combiners such as maximum ratio combiners require fading amplitudes and phase compensations of the source and the relay terminals at both of transmitter and receiver sides [12]. These requirements cause system complexities. Moreover, additional hardware such as a signal combiner at the receiver side is required and it gains cost to the system.

III. SYSTEM MODEL

The performance evaluation of the proposed method is done by simulations and compared with a non-cooperative transmission. NS 2.30 simulator is used [13]. Effects of channel quality and channel availability to ACMHT performance are studied. Three scenarios of 5-terminal networks (see Fig. 7) and a scenario of a 9-terminal network (see Fig. 8) are simulated. In Fig. 7a, a scenario in which only the relay terminal (R) is interfered by an A-B transmission pair is presented. Assume that the channel between A and B is perfect. Scenarios that all terminals (S, R, and D) are interfered and only R is not interfered are illustrated in Fig. 7b and Fig. 7c respectively. Note that terminals locating in the interference area cannot correctly decode received signals but they are interfered.

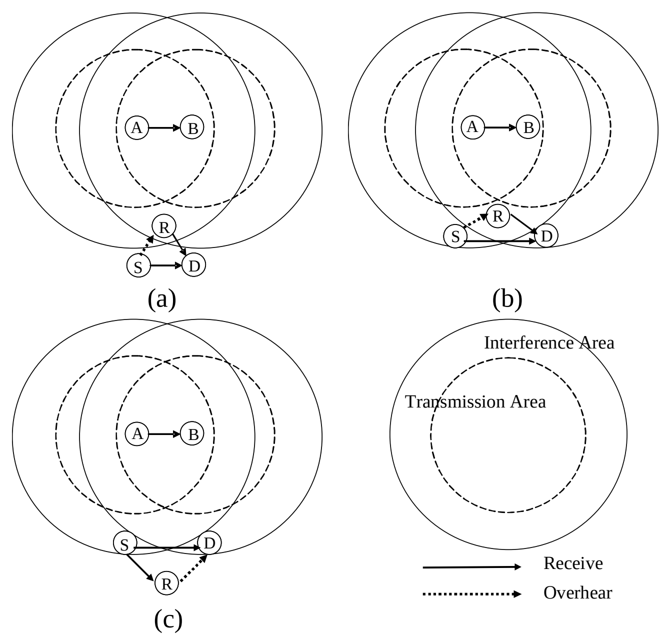

Figure 7. Three scenarios of 5-terminal networks

In Fig. 8, every case presented in Fig. 7 is included. There are three transmission pairs; i.e. S1 to D1, S2 to D2, and S3 to D3 with one relay terminal (i.e., R1, R2, and R3) for each transmission pair.

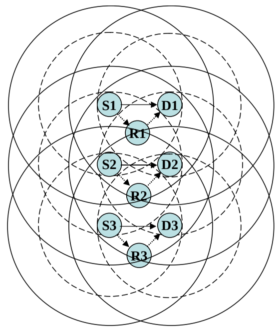

Figure 8. A scenario of a 9-terminal network.

To study the effects of channel quality to the ACMHT transmission performance in term of PDR, channel quality in term of error probabilities in the direct path (Si to Di) and the multi-hop paths (Si to Ri and Ri to Di) are varied. The frame error probabilities of the direct path (P1) are set at 0.1 and 0.2 per frame, while those of the multi-hop paths (P2) varied from 0.025 to 0.4 per frame. For physical channels, the two ray ground propagation model is used while IEEE 802.11 [5], and AODV [1] are used as the MAC, and the routing protocols. The User Datagram Protocol (UDP) agents are created to send Constant Bit Rate (CBR) traffic with data rate 448kbps and packet size equals to 210 bytes. The simulation time is 300 seconds.

IV. Simulation Results and Analysis

In the first scenario of the 5-terminal networks, where only the terminal R is interfered by the A-B transmission pair, there is no transmission state transition in both of non-cooperative and ACMHT transmissions; thus, the percentages of data frames sent in multi-hop mode equal to zero as shown in Fig. 9. The x-axis represents values of P1 over P2 (P1/P2). The frame error probability of the direct path (P1) is set at 0.1 and 0.2 per frame and the frame error probability of each proxy path (P2) is varied from 0.03 to 0.4 per frame.

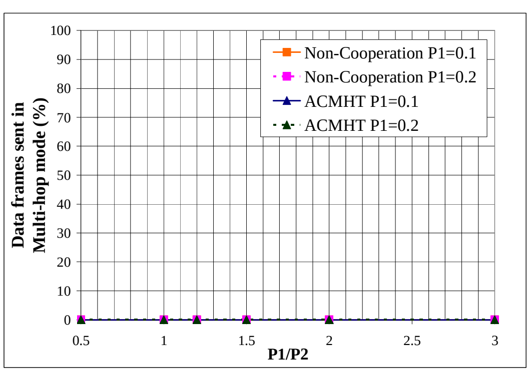

Figure 9. The percentage of data frames sent in multi-hop mode in scenario 1 of the 5-terminal networks.

PDRs of the systems with non-cooperative and ACMHT transmission in different link quality configurations are shown in Fig. 10. The PDRs of ACMHT are less than those of the non-cooperative transmission because of the effect of the extended timeout in ACMHT. If the quality of the multi-hop paths is not good and R cannot relay data to D efficiently, S in ACMHT has to re-transmit the data with the extended timeout, which causes longer delay comparing to the re-transmission processes in non-cooperative transmissions. Therefore, in non-cooperative transmissions, if there is no transmission state transition from direct mode to multi-hop mode, ACMHT is not interesting. The PDRs of the non-cooperative transmission are nearly constant because all data are sent in the direct mode; thus, the performance of the system is only function of the link quality of the direct path. The increasing of P2 does not affect the performance.

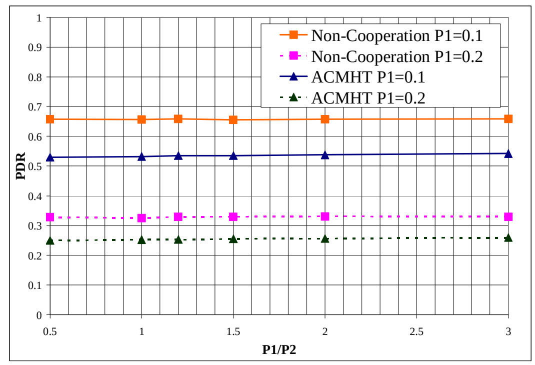

Figure 10. PDR of non-cooperative and ACMHT transmissions in scenario 1 of the 5-terminal networks.

In the second scenario of the 5-terminal networks, where all terminals are interfered by the A-B transmission pair, transmission state transitions occur in both of non-cooperative and ACMHT transmissions (see Fig. 11). However, the percentage of data frames in ACMHT that are sent in multi-hop mode is very less compared with the non-cooperative transmission. The result confirms that ACMHT can alleviate multi-hop transmission mode transitions.

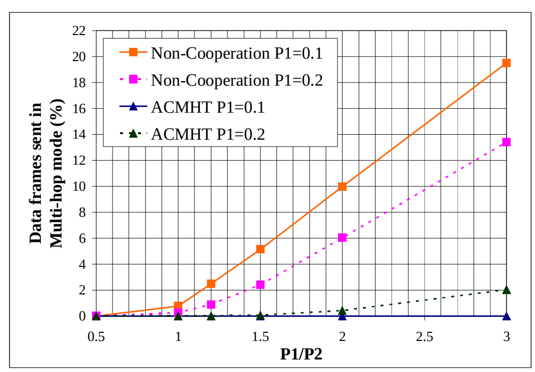

Figure 11. The percentage of data frames sent in multi-hop mode in scenario 2 of the 5-terminal networks.

In Fig. 12, ACMHT generally has higher PDRs than those of the non-cooperative transmission. Thus, we can conclude that ACMHT is interesting when every terminal has same condition of channel availability and there are chances of transmission mode transition in non-cooperative transmission to transit from direct mode to multi-hop mode.

On the left-hand side of Fig. 12 when P1= 0.2, the PDR of ACMHT is lower than that of non-cooperative transmission because channel qualities of the multi-hop paths are very poor. This problem leads to two major drawbacks. First, when R missed-hears ACK packets, it competes with S to transmit data; thus, the collisions are occurred. Second, R is not able to help S on data relaying because it is unable to decode the data frame sent from S; therefore, D has to wait for the re-transmission done by S after the extended timeout, which is twice longer than the non-cooperative technique.

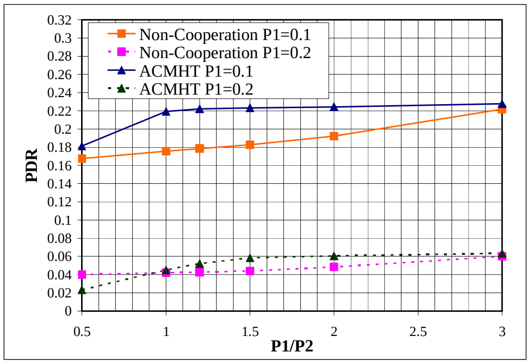

Figure 12. PDR of non-cooperative and ACMHT transmissions in scenario 2 of the 5-terminal networks.

In the third scenario of the 5-terminal networks, where only the terminal R is not interfered by the A-B transmission pair, transmission state transitions occur in non-cooperative transmission but not in ACMHT. The percentage of data frames in ACMHT that are sent in multi-hop mode equals to zero while non-cooperative transmission has high percentage of data frames sent in multi-hop mode, as shown in Fig. 13. Thus, probabilities of multi-hop transmission mode transitions are alleviated.

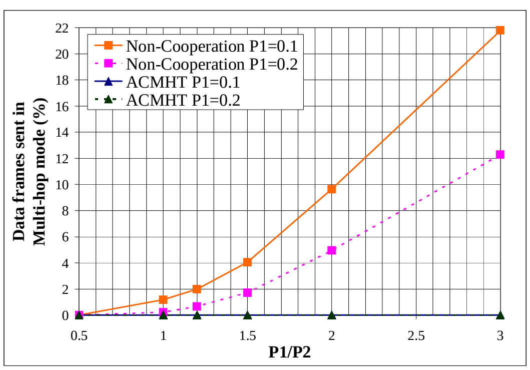

Figure 13. The percentage of data frames sent in multi-hop mode in scenario 3 of the 5-terminal networks.

Similar to the second case, ACMHT is interesting when there are chances of transmission state transition from direct mode to multi-hop mode. In addition, since R is not interfered by the A-B transmission pair, it can well perform on data relaying. Therefore, ACMHT is outperformed and has higher PDR compared to the non-cooperative transmission as shown in Fig. 14 when P1= 0.1. However, on the right-hand side of Fig. 14 when P1= 0.2 and multi-hop paths have very high channel qualities, ACMHT yields lower PDR than that of the non-cooperative transmission because the terminal D in ACMHT has to reply ACK frames through the direct path with P1= 0.2 while the non-cooperative transmission works in multi-hop mode and its ACK frames are sent through the multi-hop paths with P2 < 0.1.

In the third scenario of the 5-terminal networks, we can conclude that ACMHT is interesting when terminal R has good condition on channel availability and there are chances of transmission mode transition in non-cooperative transmission to transit from direct mode to multi-hop mode. However, if the channel qualities of the multi-hop paths are much higher than that of the direct path, ACMHT should switch its transmission mode from direct mode and cooperative multi-hop mode to multi-hop mode.

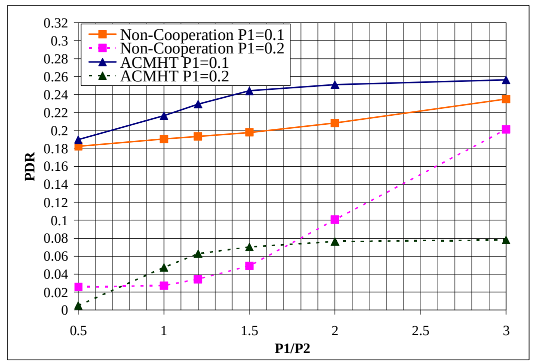

Figure 14. PDR of non-cooperative and ACMHT transmissions in scenario 3 of the 5-terminal networks.

In the 9-terminal network, the x-axis represents values of P1 over P2 (P1/P2). P1 is set at 0.1 and 0.2 per frame and P2 is varied from 0.025 to 0.4 per frame. Transmission state transitions occur in both of non-cooperative and ACMHT transmissions. However, the percentage of data frames in ACMHT that are sent in multi-hop mode is very less compared with non-cooperative transmission (see Fig. 15). Thus, the probabilities of multi-hop transmission mode transitions are also alleviated in the 9-terminal network.

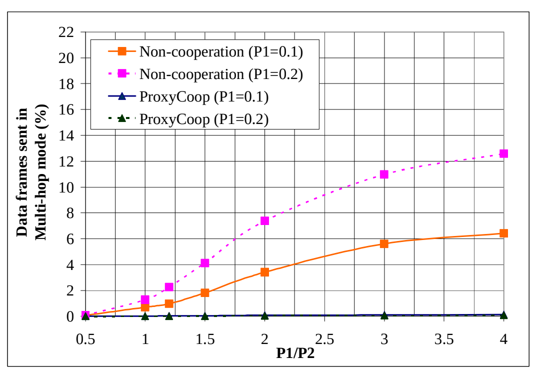

Figure 15. The percentage of data frames sent in multi-hop mode in the 9-terminal network.

In Fig. 16, on the left-hand side, when the link qualities of the proxy paths are worse than those of the direct paths, the PDR of ACMHT is lower than those of the non-cooperative transmissions because of two major reasons. First, because of the collisions generated by R when it missed-hears ACK packets. Ri competes with Si on data transmissions. Second, due to the extended re-transmission time introduced by the inefficient relay transmission; i.e., Ri should be activated to help Si, but it is also unable to decode the data frame; thus, Di has to wait for the re-transmission done by Si after the extended timeout, which is twice longer than that of the non-cooperative technique, reaches to zero. Nevertheless, when the link qualities of the proxy paths are increased, the PDRs of ACMHT are continually increased. In some ranges of P1/P2, the ACMHT provides higher PDRs than those of the non-cooperative transmissions.

In contrast, when the link qualities of the proxy paths are increased, the PDRs of for non-cooperative transmissions are decreased due to multi-hop transmission delays. However, when multi-hop paths have very high channel qualities compared to the direct path, transmissions through multi-hop paths are more interesting than re-transmissions through the direct paths with low channel qualities. Thus, on the right-hand side of Fig. 16, the PDRs of non-cooperative transmissions are increased when the number of multi-hop transmissions is increased.

Similar to the third scenario of the 5-terminal networks, the crossing point on the right-hand side of Fig. 16 when P1= 0.2 and multi-hop paths have very high channel qualities, ACMHT yields a little bit lower PDR than that of the non-cooperative transmission because the terminal Di in ACMHT has to reply ACK frames through the direct path with P1= 0.2 while the non-cooperative transmission works in multi-hop mode and its ACK frames are sent through the multi-hop paths with P2 < 0.053.

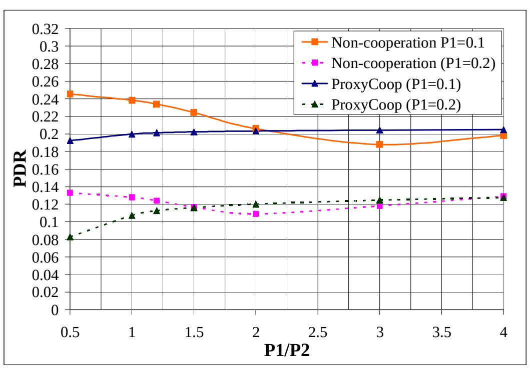

Figure 16. PDR of non-cooperative and ACMHT transmissions in the 9-terminal network.

Therefore, to improve the performance of ACMHT, rather than to switch the transmission mode of ACMHT based only on the absence of ACK frames, both of channel qualities and channel availabilities of the direct path and multi-hop paths must be considered.

V. Conclusion

In this paper, an adaptive cooperative multi-hop transmission that can work compatibly with the legacy systems and is compatible to both of the basic and the optional access methods of the IEEE 802.11 MAC protocol is proposed. Beyond the proposition, the interest of the presented work concerns the study of the proposition validity that leads to determine some adaptation rules.

From simulation results, it is shown that ACMHT transmission mode must be adaptable. The proposed method outperforms the non-cooperative transmissions in terms of transmission performance (evaluated by PDR), when channel distributions of the direct path (S-to-D) can cause multi-hop mode transitions in non-cooperative transmissions and a good relay is selected. A good relay means a relay terminal having high channel availability and high channel quality of its cooperative multi-hop paths (S-to-R and R-to-D)

Thus, the control protocol in charge of relay selection (AODV routing protocol for Ad Hoc networks or Hybrid Wireless Mesh Protocol (HWMP) for wireless mesh networks for examples) has to collect information on channel qualities by measuring the frame SNR, and we also conclude that it has to collect information of channel availabilities by measuring for example the number of frames overheard by each potential relay terminal.

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