Throughput and Energy Efficiency Comparison of One-hop, Two-hop, Virtual Relay and Cooperative Retransmission Schemes

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***Abstract*—Two main types of approaches exist for implementing cooperative communications at the MAC layer: virtual-hop relay and cooperative retransmission. While the virtual-hop relay schemes employ relay nodes to forward packets when higher end-to-end throughput can be achieved compared with the direct transmission, the cooperative retransmission schemes use relays to retransmit data only after the direct transmission fails. However, the performance of the these different approaches has not been compared in the literature, especially when energy efficiency is considered. In order to find out the best transmission scheme, this paper evaluates and compares the performance of the one-hop direct transmission, two-hop transmission, efficient multi-rate relaying, cooperative MAC and automatic cooperative retransmission schemes, in terms of throughput, packet delivery rate and energy efficiency in distributed wireless networks.**

I. INTRODUCTION

Diversity has been extensively studied to mitigate fading effects resulted from multi-path propagations in various transmission environments of wireless networks. Especially, spatial diversity in the context of multiple-input-multiple-output systems has attracted much attention in the past few years [1]. However, it may not be feasible to install multiple antennas on a wireless device due to size, cost or hardware limitations, and most current WLAN terminals in the market do not support multiple antennas yet. In such a context, cooperative communications have been proposed to achieve spatial diversity in a distributed way.

Cooperation communications have great potential for wireless ad hoc networking applications due to its terminal to terminal transmission mode. Since the wireless transmission intended for a particular destination station can be overheard by other neighboring stations, cooperative diversity can be achieved by requiring neighboring stations to forward their overheard information to the final destination. Many publications have come up with various approaches for implementing cooperative communications, and significant gains have been demonstrated in terms of capacity, throughput, network coverage and energy efficiency [2] [3].

There are two main types of approaches in the literature for implementing cooperative communications at the MAC layer: virtual-hop relay and cooperative retransmission. In the virtual-hop relay solution, for instance [4] $\sim$ [7], high data rate stations assist low data rate stations in their transmissions by forwarding their traffic. A helper node is selected beforehand to work as a virtual-hop node between the source and the destination. Each station selects either direct transmission or source-relay-destination transmission in order to minimize the total transmission time and hence the throughput bottleneck caused by low data rate stations is mitigated.

On the other hand, [8] $\sim$ [9] have proposed cooperative retransmission schemes, which apply distributed automatic repeat request to achieve cooperative diversity in wireless networks. In these schemes, first the source node sends its data packet to its destination directly following the original protocol. The relay node will be selected to forward the packet to the destination only when the direct transmission fails.

This paper aims to compare the performance of the above mentioned two types of cooperative MAC schemes that appeared in the literature. Efficient Multi-rate Relaying (EMR) MAC [4] and Cooperative MAC (CoopMAC) [7] are taken as examples of the virtual-hop schemes and Automatic Cooperative Retransmission (ACR) MAC [10] as an example of the cooperative retransmission schemes respectively. In addition, adaptive Modulation and Coding Scheme (MCS) is introduced to every scheme to exploit the channel capacity more efficiently. The performance of the different schemes is evaluated in a simplified three-node model with Rayleigh fading channels and compared with each other in terms of throughput, packet delivery rate and energy efficiency.

The rest of the paper is organized as follows. The system model and assumptions are introduced in Sec. II. Different transmission schemes are described in Sec. III. A multi-fold performance analysis is given in Sec. IV, and the simulation evaluations are presented in Sec. V. Finally a conclusion is drawn in Sec. VI.

II. SYSTEM MODEL AND ASSUMPTIONS

We consider a simple network for performance evaluation of the different schemes, as shown in Fig. 1. The model consists of a source station, S, a destination station, D, and a helper (or relay) node, R.

Each packet transmission starts from S, with the intended destination as D. With one-hop transmission, the data packet is transmitted to D directly. With two-hop transmission, R works as an intermediate hop between S and D. In the virtual-hop schemes, R is employed as an intermediate relay node only when the source-relay-destination link provides better performance. In cooperative retransmission schemes, R will forward the packet from S to D when the direct transmission fails.

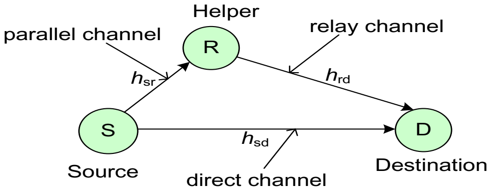

Fig. 1. A Three-node Network with Cooperative Communications.

A. Channel Assumption

For convenience, we name the channels between S and D, between S and R, and between R and D as *direct channel*, *parallel channel* and *relay channel* respectively. The channel fading on the these channels is assumed to be independent of each other. We further assume constant channel fading during the whole packet transmission period, with h_0, h_1 and h_2 representing the fading factor of the *direct*, *parallel* and *relay* channels, respectively.

B. Power Consumption

The power consumption in different modes is described as follows. A transmitting node consumes P_T power units during transmission, but only $P_T(1-\alpha)$ is actually generated for Radio-Frequency (RF) transmission power, where $(1-\alpha)$ accounts for the efficiency of the RF power amplifier [11]. Any receiving node consumes P_R to receive the data. The power consumed in the idle state is neglected. The values of the parameters α, P_T and P_R are specified by the manufacturer and are assumed to be the same for all nodes in the network.

C. Received Signal Model

In this network, the signal received at D from S on the *direct* channel, at R from S on the *parallel* channel and at D from R on the *relay* channel are denoted as $y_i, i = 0, 1, 2$ respectively, and expressed in the following [12]:

$$y_i = \sqrt{P_T(1-\alpha)d_i^{-\gamma}}h_i x_i + n_i, i = 0, 1, 2 \qquad (1)$$

where $d_i, i = 0, 1, 2$ is the distance between S and D, between S and R, and between R and D, respectively; x_i is the transmitted signal on the above three channels respectively; $n_i, i = 0, 1, 2$ is the introduced Additive White Gaussian Noise (AWGN) noise signal correspondingly; and γ is the path loss exponent.

The Signal-to-Noise Ratio (SNR) of the received signals is calculated as follows, where N_0 is the spectral power density of the Gaussian white noise at the receiver and W is bandwidth in hertz available for transmission.

$$SNR_i = \frac{P_T(1-\alpha)\left|h_i\right|^2}{d_i^{\gamma} N_0 W}. \qquad (2)$$

D. MCS Selection

In our model, the transmission rate of the data packet is determined by the selected MCS scheme at the MAC layer according to the corresponding instantaneous channel condition. For instance, the channel condition between the transmitter and the receiver can be represented by the SNR value of the received signal at the receiver. By checking a threshold value, which is pre-determined to guarantee a certain bit error rate for each MCS scheme or to maximize the system throughput, an appropriate data rate is selected [13].

According to the instantaneous channel conditions of the *direct*, *parallel* and *relay* channels, which are represented by the measured SNR ratio from Eq. (2), the data rates R_{sd}, R_{sr}, R_{rd} are determined respectively for each channel. The required channel conditions are assumed to be obtained beforehand and the overhead is not considered in this study.

III. MAC Scheme Description

In this section, the direct transmission, two-hop transmission, virtual-hop relay and cooperative retransmission schemes are described in details.

A. One-Hop Direct Transmission

The direct data transmission follows the IEEE 802.11 Distributed Coordination Function (DCF) protocol [14]. The retry limit is set to be 1 in our analysis, i.e., the source will not retransmit the data packet if the direct transmission fails.

The message procedure is shown in Fig. 2. The source node listens to the channel for DCF InterFrame Space (DIFS) before it sends its data packet. A random backoff scheme is executed thereafter to avoid collision. If the destination node receives the data packet successfully, it returns an acknowledgment (ACK) frame after a Short InterFrame Space (SIFS) interval. The DATA and ACK packets are transmitted on the *direct* channel at the date rate R_{sd}. Note that ACK frame is transmitted at the same rate as the DATA packet.

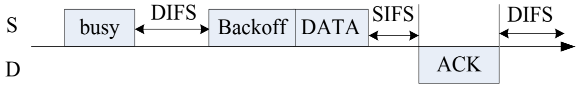

Fig. 2. Direct Transmission Scheme. The DATA and ACK Packets Are Transmitted at R_{sd}.

B. Traditional Two-Hop Transmission

In the two-hop transmission, R is an intermediate node between S and D. The data packet is first transmitted from S to R, then from R to D. Both S and R need to contend for channel access to transmit packets following the DCF protocol, as shown in Fig. 2. The DATA and ACK packets in each hop are transmitted at the date rate, R_{sr} and R_{rd}, respectively.

C. Virtual-hop Relay

With the virtual-hop relay schemes, different protocols have different criteria to decide whether the source-relay-destination link provides better performance than the direct channel. For example, in the CoopMAC protocol [7], R is adopted to forward its data packet when:

$$\frac{1}{R_{sr}} + \frac{1}{R_{rd}} < \frac{1}{R_{sd}}. \tag{3}$$

In another example, EMR MAC, the relay link is selected when it can provide higher effective throughput. The effective throughput is obtained based on the assumption that no data corruption occurs neither in the source-relay-destination link nor in the source-destination link [4].

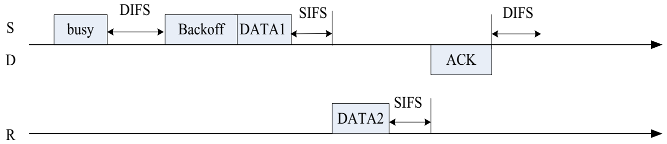

Fig. 3. Virtual-hop Relay Scheme. DATA1 at R_{sr}; DATA2 at R_{rd}; and ACK at R_{sd}.

For both CoopMAC and EMR MAC, if the relay node satisfies the requirement of cooperation, the data packet is first sent to R at R_{sr}, and then forwarded by R to the destination D at R_{rd} after SIFS, as shown in Fig. 3. Different from other cooperative schemes, an ACK packet is returned back to S *directly* at R_{sd} if D decodes the packet correctly. Otherwise, if the relay link is not better than the direct link, the data transmission will be executed according to the original DCF protocol in Fig. 2.

D. Cooperative Retransmission

As the first step of cooperative retransmission, node S sends out its data packet to D at R_{sr} according to the original DCF in 802.11. If the direct transmission succeeds, the message sequence will proceed exactly the same as the original scheme. Otherwise, if R has decoded its received data packet correctly, R will automatically forward the packet to D at R_{rd} after ACK timeout, without waiting for DIFS. If the cooperative transmission through R succeeds, an ACK will be sent to R at R_{rd} and then relayed to S by R at R_{sr} in a two-hop manner, in order to guarantee a reliable transmission. If even the cooperative retransmission fails, S has to wait for a longer ACK timeout, which is twice of the sum of SIFS and ACK transmission time, to initiate the next transmission. The message sequences when the cooperative retransmission is executed successfully are illustrated in Fig. 4.

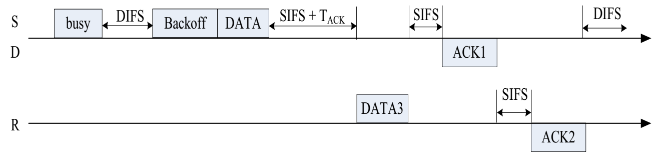

Fig. 4. Cooperative Retransmission Scheme. DATA at R_{sd}; DATA3 at R_{rd}; ACK1 at R_{rd}; and ACK2 at R_{sr}.

IV. PERFORMANCE ANALYSIS

Packet Delivery Rate (PDR) at the MAC layer, normalized system saturation throughput, and energy consumption of the different schemes described in Sec. III are analyzed in this section.

A. One-Hop Direct Transmission Scheme

The PDR of the one-hop transmission scheme is the packet successful rate on the direct link.

$$PDR^a = 1 - p_{sd}, \tag{4}$$

where p_{sd} is the packet error rate on the *direct* channel, which is determined by the selected rate R_{sd}, the given packet length and the instantaneous channel condition.

The throughput performance can be obtained by calculating the average number of successfully transmitted payload information bits within average unit time consumed during the transmission:

$$\eta^a = \frac{PDR^a L}{\bar{\delta} + L/R_{sd} + L_{ACK}/R_{sd} + SIFS + DIFS}, \tag{5}$$

where L and L_{ACK} are the length of the DATA and ACK packets in bits respectively; and $\bar{\delta}$ is the average backoff time before each data transmission, which is half of the size of the minimal contention window multiplied by the duration of a slot time.

As mentioned in Sec. II, the energy consumed at an idle node is neglected. Therefore, the *total* energy consumed in the network for transmitting and receiving data packets is calculated as follows.

$$E^a = (P_T + P_R)(L/R_{sd} + (1 - p_{sd})L_{ACK}/R_{sd}). \tag{6}$$

B. Traditional Two-Hop Transmission Scheme

In the two-hop transmission, the data packet is received correctly at the destination node only if both the first hop transmission on the *parallel* channel and the second hop transmission on the *relay* channel are successful. Therefore, the PDR performance of the traditional two-hop transmission can be calculated as:

$$PDR^b = (1 - p_{sr})(1 - p_{rd}), \tag{7}$$

where p_{sr} and p_{rd} are the packet error rate on the *parallel* and *relay* channels respectively and can be determined accordingly by R_{sr} and R_{rd} in given channel conditions.

The throughput can be obtained in a similar way as in the direct transmission scheme:

$$\eta^b = \frac{PDR^b L}{D^b}, \tag{8}$$

where D^b is the time used for the two-hop transmission of the data packet and expressed as follows.

$$\begin{gathered} D^b = \bar{\delta} + L/R_{sr} + L_{ACK}/R_{sr} + SIFS + DIFS + \\ (1 - p_{sr})(\bar{\delta} + SIFS + DIFS + L/R_{rd} + L_{ACK}/R_{rd}). \end{gathered} \tag{9}$$

The *total* energy consumed during the data transmission in the network is calculated as follows.

$$\begin{gathered} E^b = (P_T + P_R)(L/R_{sr} + (1 - p_{sr})L_{ACK}/R_{sr}) + \\ (P_T + P_R)(1 - p_{sr})(L/R_{rd} + (1 - p_{rd})L_{ACK}/R_{rd}), \end{gathered} \tag{10}$$

where the two terms in the right side correspond to the first hop transmission and the second hop transmission respectively. The second hop transmission happens only when R decodes the data packet from S correctly.

C. Virtual-hop Relay Schemes

The performance analysis for both CoopMAC and EMR can be expressed in the same way. The only difference lies in their cooperation decision-making schemes. CoopMAC uses Eq. (3) to decide whether the relay node is adopted in data transmission while EMR chooses the path with higher effective throughput.

When the source-relay-destination link is chosen for data transmission, the PDR performance of the virtual-hop relay schemes, PDR_c, is the same as PDR_b in the two-hop transmission scheme. This is because the data packet is received correctly at the destination node only if both the transmissions on the *parallel* channel and on the *relay* channel are successful. Otherwise, PDR_c is the same as PDR_a in the direct transmission scheme.

$$PDR^c = \begin{cases} PDR^b & \text{if relay} \\ PDR^a & \text{otherwise.} \end{cases} \tag{11}$$

The throughput can be expressed correspondingly in two cases:

$$\eta^c = \begin{cases} PDR^b L/D^{CT} & \text{if relay} \\ T^a & \text{otherwise,} \end{cases} \tag{12}$$

where D^{CT} is the time used for the transmission of the data packet through the source-relay-destination link in the virtual-hop relay scheme.

$$\begin{aligned} D^{CT} = \bar{\delta} + L/R_{sr} + L/R_{rd} + L_{ACK}/R_{sd} \\ +2SIFS + DIFS. \end{aligned} \tag{13}$$

The total energy consumed during the data transmission in the virtual-hop relay scheme is therefore expressed as follows.

$$E^c = \begin{cases} E^{CT} & \text{if relay} \\ E^a & \text{otherwise,} \end{cases} \tag{14}$$

where E^{CT} is the energy consumption when the relay node is adopted to forward data and expressed in the following.

$$\begin{aligned} E^{CT} = (P_T + P_R)L/R_{sr} + (P_T + P_R)(1 - p_{sr}) \\ L/R_{rd} + (P_T + P_R)(1 - p_{sr})(1 - p^b_{rd})L_{ACK}/R_{sd}, \end{aligned} \tag{15}$$

where the first two terms in the right side correspond to the DATA1 and DATA2 transmissions in Fig. 3, respectively, and the last term accounts for the ACK transmission when D decodes the data packet successfully.

D. Cooperative Retransmission Scheme

In the cooperative transmission scheme in Fig. 4, D receives the signal from S in the direct transmission phase with the date rate R_{sd} and the packet error rate p_{sd}. Meanwhile, the packet error rate on the *parallel* channel p^c_{sr} is determined by R_{sd} and the instantaneous *parallel* channel condition. The packet error rate p_{rd} on the *relay* channel in the cooperative retransmission phase can be obtained by R_{rd} in a similar way.

Based on the above information, the PDR of the cooperative retransmission scheme is the sum of the successful probability of the direct transmission and the successful probability of the cooperative retransmission, as expressed in the following.

$$PDR^d = (1 - p_{sd}) + p_{sd}(1 - p^c_{sr})(1 - p_{rd}). \tag{16}$$

The throughput is derived based on the above information:

$$\eta^d = \frac{PDR^d L}{D^d}, \tag{17}$$

where D^d is the average time used for the whole transmission procedure in the cooperative retransmission scheme and is shown in the following.

$$\begin{aligned} D^d = \bar{\delta} + L/R_{sd} + L_{ACK}/R_{sd} + SIFS + DIFS + \\ (L/R_{rd} + L_{ACK}/R_{rd} + L_{ACK}/R_{sr} + 2SIFS) \\ p_{sd}(1 - p^c_{sr}). \end{aligned} \tag{18}$$

The total energy assumed during the cooperative data transmission is calculated as:

$$\begin{aligned} E^d = (P_T + 2P_R)L/R_{sd} + (1 - p_{sd})L_{ACK}/R_{sd} + \\ (P_T + P_R)p_{sd}(1 - p^c_{sr})L/R_{rd} + (P_T + P_R)p_{sd} \\ (1 - p^c_{sr})(1 - p_{rd})(L_{ACK}/R_{rd} + L_{ACK}/R_{sr}), \end{aligned} \tag{19}$$

where the first term in the right hand side corresponds to the direct DATA packet transmission; the second term corresponds to the ACK transmission when the direct transmission succeeds; the third term accounts for the cooperative DATA3 packet retransmission in Fig. 4, which happens when R decodes the data packet from S correctly; and the last term accounts for the ACK transmission when D decodes the data packet successfully after the cooperative retransmission.

V. PERFORMANCE EVALUATION

The performance of the different schemes is evaluated and compared with each other through simulations in this section. The source node and the destination node are placed 50 m apart from each other (i.e., (-25 m, 0) and (25 m, 0) for the source and destination nodes respectively). Three topologies are investigated for performance comparison, as shown in Fig. 5: 1) R is in the middle of S and D, (0, 5 m); 2) R is close to S, (-20 m, 5 m); 3) R is close to D, (20 m, 5 m). All the channels between each transmission pair are subject to independent Rayleigh fading.

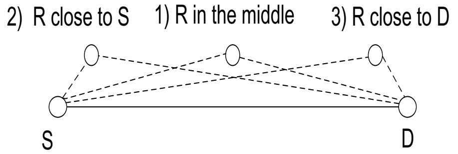

Fig. 5. Relay Topologies for Performance Comparison.

The simulation parameters are listed in Table. I. The adopted MCS schemes and their corresponding threshold values of the received signal strength are shown in Table. II. The threshold values are determined in order to achieve the highest throughput in given channel conditions. The path loss exponent

γ is set to be 4.0 for indoor environments. The efficiency of RF power amplifier α is set to be 0.5. The power consumption for transmitting is set to be 1400 mW with 700 mW for RF transmission, and the power consumption for receiving is 900 mW [15].

TABLE I
SIMULATION PARAMETERS.

Payload length	500 bytes or 50 bytes
MPDU header	24 bytes
PHY header	20 μs
Basic datarate	6 Mbps
RTS	20 bytes
CTS	14 bytes
CFR	14 bytes
DIFS	34 μs
SIFS	16 μs
Slottime	9 μs

TABLE II
MODULATION AND CODING SCHEME SET.

MCS Scheme	Data Rate	Threshold (500 B)	Threshold (50 B)
BPSK 1/2	6 Mbps	<3.2 dB	<2.2 dB
QPSK 3/4	18 Mbps	3.2 dB ∼ 4.8 dB	2.2 dB ∼ 3.8 dB
16QAM 1/2	24 Mbps	4.8 dB ∼ 6.8 dB	3.8 dB ∼ 5.8 dB
16QAM 3/4	36 Mbps	6.8 dB ∼ 10.2 dB	5.8 dB ∼ 9.2 dB
64QAM 3/4	54 Mbps	>10.2 dB	>9.2 dB

Moreover, E_t/N_0 is used to describe the channel conditions in our simulation environments, where E_t is the transmitted energy per bit at the transmitter and N_0 is the spectral power density of the Gaussian white noise at the receiver. The reason is that the transmitting power is fixed for all nodes in our simulations. The strength of the received signal from a transmitting node that is closer to the destination is higher than from one far away from the receiver, resulting in different received SNRs from different transmitters at the receiver. Therefore, E_t/N_0 is a more sensible metric than E_b/N_0 to illustrate the performance of different schemes. That also explains why the range of the x-axis in the figures of this section seems to be unexpectedly high.

In the following subsections, simulations are made first with packet size of 500 bytes to investigate the protocol performance with different relay topologies, and then packet size of 50 bytes is adopted in the third subsection to investigate the protocol performance with small packets.

A. Topology 1: Relay in the Middle

The throughput performance of different schemes with the relay in the middle between S and D is shown in Fig. 6. It is obvious that both the cooperative retransmission (ACR) and virtual-hop relay (EMR and CoopMAC) schemes have better performance than the direct one-hop transmission when the channel condition is poor and cooperation is necessary (125 dB ∼ 155 dB in the E_t/N_0 field). In this figure, the throughput curves of EMR and CoopMAC collide with each other exactly, which indicates that the virtual-hop relay schemes are not sensitive to their cooperation requirements. ACR has inferior performance than the virtual-hop relay schemes because of its lower efficiency of utilizing channel capacity. We can also observe that two-hop transmission outperforms the direct transmission when E_t/N_0 is between 125 dB and 144 dB. It proves that with higher data rates adopted separately on the *parallel* channel and *relay* channels, higher throughput can be achieved in the two-hop transmission scheme.

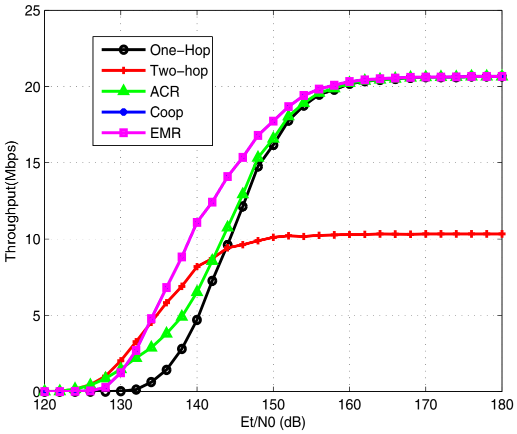

Fig. 6. Throughput Performance with Relay in the Middle.

Fig. 7 depicts the PDR performance of the different schemes. We can observe from the figure that the packet delivery rate is improved by all the cooperative schemes compared with direct transmission. That is because that the relay node in the middle of source and destination provides more reliable link for data transmission. In this figure, EMR and CoopMAC show identical PDR performance, which is lower than the ACR and two-hop schemes. The reason is both EMR and CoopMAC are designed aiming at higher throughput instead of higher transmission reliability. The source-relay-destination link is chosen only when it can provide higher throughput, which results in that the relay node is not used as frequently as in the other schemes. Therefore, less packet delivery rate is provided in these two schemes.

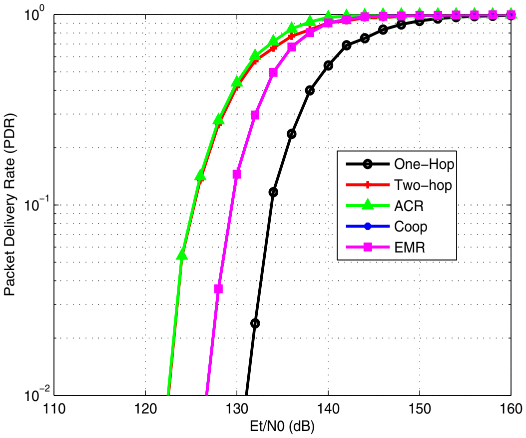

Fig. 7. Packet Delivery Rate with Relay in the Middle.

Furthermore, the energy consumption feature of the different schemes is shown in Fig. 8. There are a couple of interesting observations in this figure. Firstly, ACR consumes most energy among all the schemes when E_t/N_0 is between 120 dB and 155 dB. This is because that the relay node in ACR needs to capture and decode the data packet from the source node every time, no matter if the retransmission is necessary or not. The peak value appears when E_t/N_0 is 130 dB, when cooperative retransmission is most likely executed and thus most transmitting power is consumed. When the channel condition gets better, the energy consumption declines since fewer cooperative retransmissions are needed. In addition, ACR consumes more energy than the two-hop transmission scheme since it takes longer time for the relay node to receive the data packet from S. The reason is that the relay node in ACR captures the packet from the direct link at rate R_{sd} which is generally lower than the rate on the *parallel* channel R_{sr} adopted in the two-hop transmission schemes.

Secondly, the energy consumption curves of the two-hop and direct transmission schemes intersect with each other twice in Fig. 8. More energy is consumed in two-hop transmission, when E_t/N_0 is lower than 132 dB. It is because that when the channel condition is poor, only very low data rate can be supported. Hence, the time used for data transmission cannot be saved in the two-hop transmission scheme but more energy is consumed at the intermediate node. Moreover, the intermediate node only transmits data to D when it has decoded the received packet from S successfully. That is why the peak value of two-hop transmission curve appears at 126 dB, when the second hop transmission from R to D most likely happens at a low data rate. With higher E_t/N_0, higher data rate is adopted in *parallel* and *relay* channels in two-hop transmission and thus less time is consumed. Consequently, the energy consumption begins to drop. When E_t/N_0 is between 132 dB and 150 dB, the *parallel* and *relay* channels can adopt more efficient MCS schemes for higher data rate. Thus, much less transmission time is used in the combined two-hop link than the direct link and correspondingly less energy is consumed. When the channel condition gets even better (E_t/N_0 is above 150 dB), the direct link itself is efficient enough with high data rate. Both curves become flat afterwards when the highest data rate in the MCS set of the system has been adopted on all the three channels. Besides, the difference between these two curves is the extra energy cost for transmitting and receiving data at the intermediate node in the two-hop transmission mode.

Furthermore, we could also observe that CoopMAC and EMR consume even less energy than the direct transmission when E_t/N_0 is between 120 dB and 158 dB. The reason is that more efficient MCS schemes are adopted on both the *parallel* and *relay* channels, which results in less transmission time in total and thus less energy consumption.

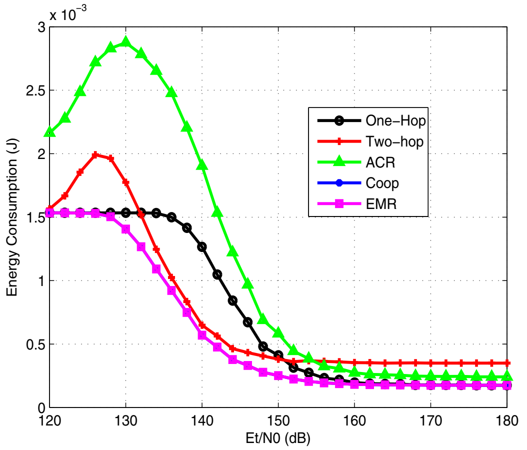

Fig. 8. Energy Consumption with Relay in the Middle.

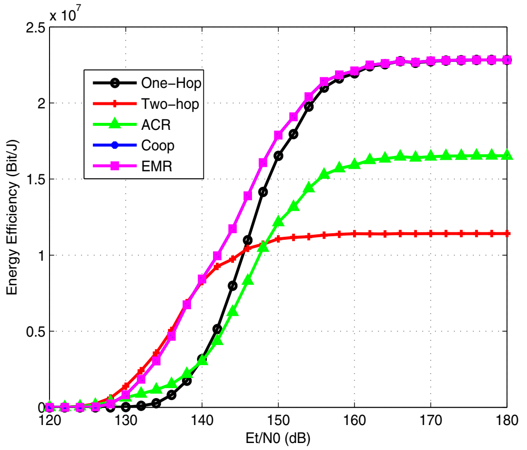

Fig. 9. Energy Efficiency with Relay in the Middle.

Fig. 9 illustrates the energy efficiency for information delivery of the different schemes. The energy efficiency is defined as the successfully delivered information bits by each consumed joule of energy. It can be observed that EMR and CoopMAC have the highest energy efficiency. The ACR scheme is not as efficient as the virtual-hop schemes not only because the throughput performance is not as high but also more energy is consumed at the relay node. The two-hop scheme is best energy efficient when the channel condition is poor and gradually becomes the worst in good channel conditions. The reason is that when the channel condition is poor, the two-hop transmission can provide higher packet delivery ratio and hence higher throughput, at a cost of extra energy at the intermediate node. However, when the channel condition gets better, the intermediate relay node is made redundant in the data transmission, and the extra energy consumed decreases the energy efficiency of the scheme significantly.

B. *Topologies 2, 3: Relay Close to Source or Destination*

The throughput and reliability performance of the different schemes when the relay node is placed close to S or D is shown in Fig. 10 and Fig. 11, respectively. In those figures, we can see that the throughput and PDR curves from these two topologies collide with each other for each transmission scheme. The reason is that the wireless channels in these two cases are reciprocal. When R is close to S, the *parallel* channel provides a higher probability for a successful data transmission, but meanwhile the *relay* channel transmission

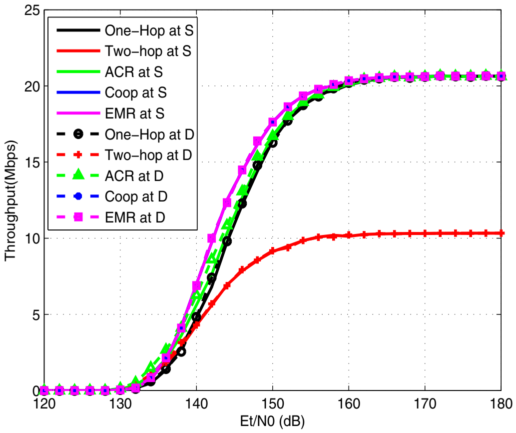

Fig. 10. Throughput Performance with Relay Close to Source or Destination.

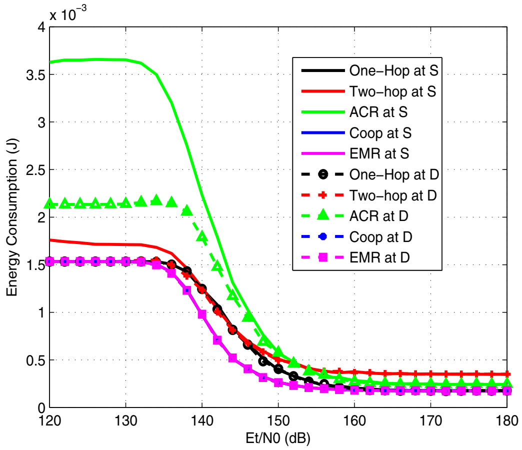

Fig. 12. Energy Consumption with Relay Close to Source or Destination.

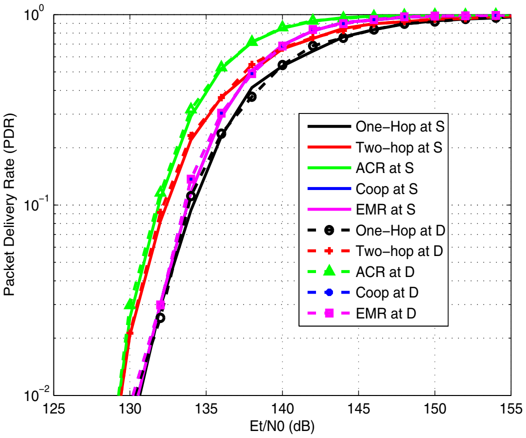

Fig. 11. Packet Delivery Rate with Relay Close to Source or Destination.

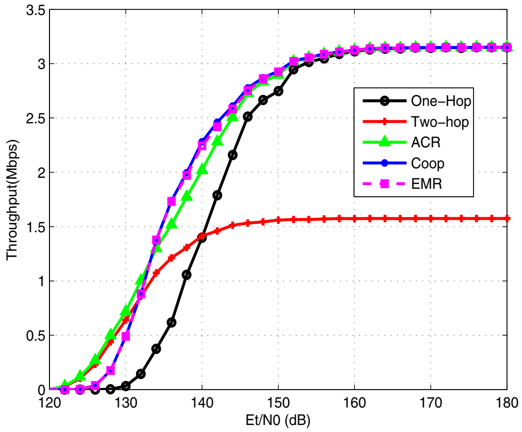

Fig. 13. Throughput Performance with 50-byte Packets.

has a higher probability to fail, and vice versa. Thus, the whole source-relay-destination link provides almost identical performance with these two symmetric topologies. Compared with Fig. 6 and Fig. 7, it is evident that the performance enhancement of the cooperative schemes is more evident when the relay node is placed in the middle between S and D. This is because that more reliable source-relay-destination link is provided when the relay node is placed in the middle.

Fig. 12 depicts the energy consumption feature of the different schemes with the relay node located close to S or D. It can be observed that the energy consumed by the ACR, CoopMAC and two-hop schemes is much less when the relay node is placed close to destination where E_t/N_0 is between 120 dB and 140 dB. The reason is explained as follows. The relay node only forwards data to destination when it receives the packet correctly from S. When R is situated close to D and far away from S, the probability that R receives the packet successfully from S is much lower than when it is placed close to S and far away from D. Therefore, fewer packets are forwarded through the relay node during the simulation of 1000 packet transmissions, resulting in less energy consumption.

Again, the energy consumption curves of CoopMAC and EMR with different topologies collide with each other in Fig. 12. This is because in CoopMAC and EMR, whether to adopt the relay node for cooperative transmissions depends on whether the whole source-relay-destination link provides higher throughput. Since the two locations of R are symmetric between S and D, the energy consumption in these two schemes is not influenced by these two different network topologies.

C. Performance Comparison with Small Packet Size

In this subsection, the packets for simulations are set to be 50 bytes in order to investigate the impact of packet size on protocol performance. Figs. 13-16 depict the throughput, PDR, energy consumption and energy efficiency features of different schemes respectively.

From those figures, we can conclude that the performance and energy consumption comparison results with 500-byte packet length hold true with small packets. Moreover,it can be observed that the throughput enhancement of the cooperative schemes becomes more evident when the packet size is small. ACR outperforms EMR and CoopMAC only when E_t/N_0 is between 120 dB and 134 dB due to its higher efficiency to exploit channel capacity with small packets in poor channel conditions and lower efficiency in good channel conditions. In Fig. 16, the two-hop transmission becomes the most energy efficient scheme in poor channel conditions. Moreover, the energy consumption of all these schemes is less efficient than the large packet case due to relatively larger protocol overhead.

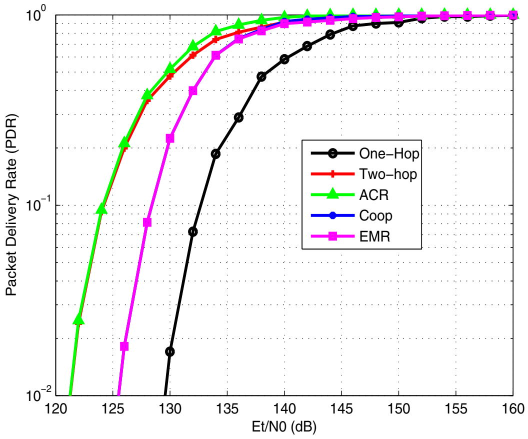

Fig. 14. Packet Delivery Rate with 50-byte Packets.

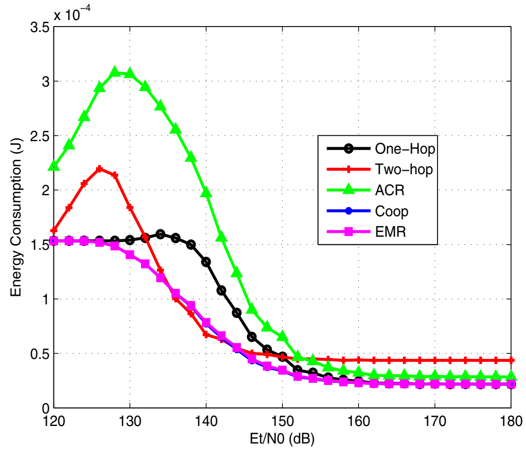

Fig. 15. Energy Consumption with 50-byte Packets.

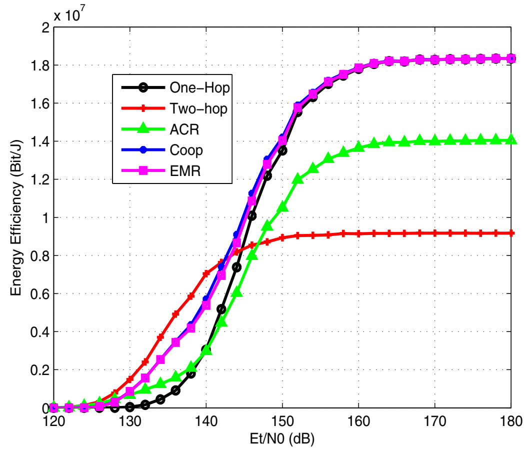

Fig. 16. Energy Efficiency with 50-byte Packets.

VI. CONCLUSIONS

In this paper, the performance of one-hop, two-hop, virtual-hop relay (EMR and CoopMAC) and cooperative retransmission (ACR) schemes has been evaluated and compared with each other in terms of throughput, packet delivery rate and energy consumption.

The obtained simulation results show that ACR outperforms the other schemes in PDR performance at a cost of higher energy consumption. CoopMAC and EMR are successful with throughput enhancement, and meanwhile they are the most energy efficient schemes. Furthermore, the performance curves of EMR and CoopMAC collide with each other, indicating that the virtual-hop relay schemes are not sensitive to their cooperation requirements.

Moreover, the impact of the relay node placement is also investigated. The relay node when placed in the middle of source and destination can provide higher throughput and PDR performance for all the cooperative schemes. The relay node that is placed close to source or destination provides almost the same throughput and PDR performance, but it is more energy efficient when the relay node is located close to destination.

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