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廣義的機會式通訊：無線行動網路中之競爭、合作與感知

子計畫三：感知無線行動網路之協力式擇路協定及服務品質控制

期中報告

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從媒介接取控制的觀點討論協力式通訊的效能

在無線網路通訊的範疇裡，由於通訊環境的不穩定，例如多重路徑衰弱通道（Multipath Fading Channel）的影響，各式各樣的分集技術（Diversity）因此而被提出以維持傳輸的品質。近幾年來，協力式通訊（Cooperative Communication）亦被提出來成為一種新的通訊模式，利用周遭的鄰近節點來提升自我的分集增益（Cooperative Diversity），進而改善點對點之間的通訊品質。於協力式通訊系統中，來源節點（Source Node）與目標節點(Destination Node)間的傳輸，將引進中繼節點(Relay Node)的協助，因而使目標節點得以取得多份相同的封包。進一步地，目標節點將這些相同的封包重新整合與解碼，有機會地降低接收端的位元錯誤率，以達到通訊可信度上的提升。

從實體層（Physical Layer）的角度上來評論，協力式通訊於接收可靠度的表現，似乎扮演著重要的角色。然而，在實作複雜度的限制下，半工傳輸（Half-Duplex）是現今大部分通訊系統的假設，因而，協力式通訊的模式往往便需要兩個階段才能完成，導致在傳輸時間上延伸變得是無可避免的。因此，若改由整體網路的吞吐量（Network Throughput）觀點來思考，協力式通訊不見得會帶來所期待的效能。在本報告中，我們將以 IEEE 802.11 媒介接取控制技術為基礎，佐以模擬驗證，利用二維的馬可夫鏈（Two Dimensional Markov Chain）的數學分析來探討協力式通訊於網路吞吐量的表現。在媒介接取控制的考量下，適當地找尋協力式通訊的使用時機。接著，將整合傳統點對點通訊系統及協力式通訊技術，進一步地思考這樣混合式通訊的必要性與存在性。

Performance Analysis of Cooperative Communications from MAC Layer Perspectives

Abstract

In recent years, cooperative communication has been proposed as a new communication paradigm that incorporates a relay node to assist the direct point-to-point transmission. By exploiting the cooperative diversity, different types of techniques have been proposed to improve the transmission reliability from the physical layer perspective, e.g. the cooperative automatic repeat request.

However, owing to the longer transmission time resulting from the cooperative schemes, there is no guarantee to enhance the network throughput in view of the medium access control (MAC) performance. In this paper, the system throughput of the cooperative communication is evaluated by exploiting the proposed analytical model based on the IEEE 802.11 MAC protocol. Both the relay-based and the original direct communications are considered in the analytical studies. Simulations are conducted to further validate the effectiveness of the proposed model. In terms of the network throughput, whether to adopt the cooperative schemes depends on the tradeoff between the cooperative transmission delay and the channel condition of the direct communication.

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Performance Analysis of Cooperative Communications from MAC Layer Perspectives

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Abstract—**In recent years, cooperative communication has been proposed as a new communication paradigm that incorporates a relay node to assist the direct point-to-point transmission. By exploiting the cooperative diversity, different types of techniques have been proposed to improve the transmission reliability from the physical layer perspective, e.g. the cooperative automatic repeat request. However, owing to the longer transmission time resulting from the cooperative schemes, there is no guarantee to enhance the network throughput in view of the medium access control (MAC) performance. In this paper, the system throughput of the cooperative communication is evaluated by exploiting the proposed analytical model based on the IEEE 802.11 MAC protocol. Both the relay-based and the original direct communications are considered in the analytical studies. Simulations are conducted to further validate the effectiveness of the proposed model. In terms of the network throughput, whether to adopt the cooperative schemes depends on the tradeoff between the cooperative transmission delay and the channel condition of the direct communication.**

Keywords: Cooperative communication, performance analysis, IEEE 802.11 protocol, medium access control.

I. INTRODUCTION

Due to the unreliable environments for wireless transmission, different types of diversity schemes have been developed to maintain the quality of communication. In recent years, techniques for cooperative communications are proposed to effectively enhance the diversity gain. Data communication between the source node (SN) and the destination node (DN) is captured by the surrounding relay node (RN), which duplicates the packets and consequently delivers to the same DN. In order to increase the communication reliability, the duplicated packets are received and combined at the DN by exploiting different algorithms, e.g. the amplify-and-forward (AF) and the decode-and-forward (DF) schemes. In the AF protocol, the RN simply amplifies and forwards the signals that are acquired from the SN; while the RN decodes the received signals and forwards them to the DN in the DF algorithm.

Research work have been conducted to explore the cooperative communications from various aspects. The analysis of the cooperative diversity has been investigated in [1–3]; while [4–6] propose the capacity computation for cooperative communications. The work presented in [7–10] deliver the cooperative schemes from the physical (PHY) layer perspectives. Numerical analysis is also conducted to evaluate the protocol performance based on the frame error rate (FER). Moreover, cooperative automatic repeat request (ARQ) techniques [11–13] take advantage of the cooperative diversity to achieve efficient transmission. In these schemes, the DN requests retransmissions with cooperative algorithms after the failure of the initial direct transmission between the SN and the DN. On the other hand, the approaches proposed in [14–16] employ the cooperation concept to the MAC protocol design. The performance of the cooperative algorithm proposed in [14] is further validated in [17].

It is noticeable to observe that most of recent research [1–10] focus on the cooperative communications from the viewpoint of PHY layer design and information theory. Although the FER can be ameliorated by means of the cooperative diversity, there is no assurance to result in enhanced network throughput due to the tradeoff between the FER and the longer packet transmission time. In general, the cooperative schemes will lead to elongated packet transmission time no matter the AF or the DF based protocols are applied. Two phases are required for the relay-based communication in order to complete a data transmission, i.e. data packets are delivered from the SN to both the DN and the RN with additional duplicated packets transmitted from the RN to the DN.

In order to evaluate the cooperative communications in terms of the network throughput, a suitable analytical model from the MAC perspectives should be exploited. The IEEE 802.11 [18] has been considered a well-adopted standard for the wireless LANs. In the IEEE 802.11 MAC protocol, the distributed coordination function (DCF) is utilized as the basic mechanism for channel access. The DCF ensures that each node can acquire a fair opportunity to access the wireless medium according to the carrier sensing multiple access with collision avoidance (CSMA/CA) scheme. A random backoff process is executed in each node for the purpose of decreasing the probability of data collision. Moreover, the request-to-send (RTS)/ clear-to-send (CTS) exchange before the data transmission is employed in order to resolve the potential hidden terminal problem. A large amount of existing research [19–22] contribute to establish the analytical models for the IEEE 802.11 MAC protocol. The saturation throughput of the IEEE 802.11 DCF is obtained via a two-dimensional Markov chain model as proposed in [19]. The work presented in [20–22] further adopted the channel error conditions into the design of the analytical models.

In this paper, the backoff model of the IEEE 802.11 MAC extended from [19; 20] is adopted to analyze the saturation throughput of the cooperative technology. Based on the required two-phase process of the cooperative communication, a cooperative handshake process is integrated with a Markov chain model to obtain the network throughput. Both the cooperative and the direct communications are considered in the design of the proposed analytical model. Simulations are also exploited

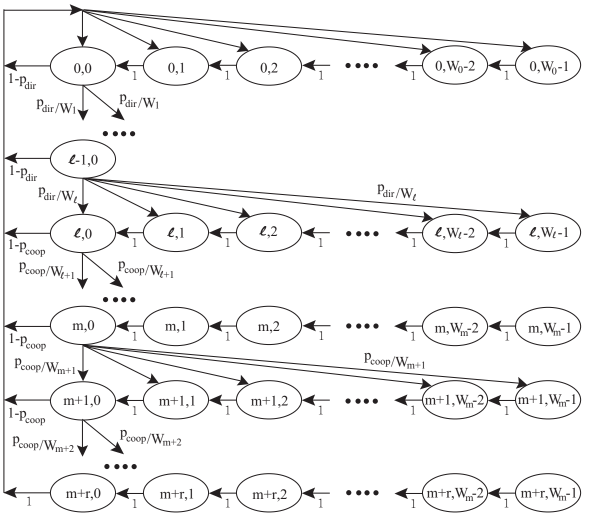

Fig. 1. Markov chain model for the backoff mechanism with the combined cooperative/direct strategy.

for validating the effectiveness of the proposed model. It is observed from the analytical results that the performance of the cooperative communication is affected by various factors, especially the FER and the packet transmission delay. Cooperative schemes in general result in decreased FER; while the rerouting delay incurred by the cooperative process can considerably degrades the network throughput. Whether to adopt the cooperative algorithms for packet transmission is suggested to consider the tradeoff between the FER and the transmission delay for the enhancement of network throughput.

The rest of this paper is organized as follows. The modeling of the backoff operations with combined cooperative/direct strategy is presented in Section II. Section III describes the analysis for the saturation throughput based on the proposed model. Numerical evaluation is performed in Section IV; while Section V draws the conclusions.

II. MARKOVIAN MODEL WITH COMBINED COOPERATIVE/DIRECT STRATEGY

In order to evaluate the performance by adopting the cooperative strategy, the conventional model for the backoff mechanism is adjusted to incorporate both the direct and cooperative schemes. The modified Markov chain model of the backoff mechanism is shown in Fig. 1. The backoff operation $(s(t), b(t))$ consists of two stochastic processes, where $s(t) \in [0, m+r]$ indicates the backoff stage with the maximum stage $m+r$, and $b(t)$ denotes the backoff timer whose value at the ith stage can be represented as

$$W_i = \begin{cases} 2^i \cdot W & 0 \le i \le m \\ 2^m \cdot W & m \le i \le m+r \end{cases} \tag{1}$$

where W denotes the minimum contention window. A new parameter ℓ (for $0 \le \ell \le m+r$) is introduced as illustrated in Fig. 1, which is utilized to model the strategy for implementing both the cooperative and the non-cooperative techniques. In other words, the cooperative scheme will be activated after the conventional direct communication from the SN to the DN has failed for ℓ times. It is noted that the cooperative scheme corresponds to either the DF or the AF based algorithm, in which the DN combines the signals from both the SN and the RN.

Moreover, the parameters p_{dir} and p_{coop} are introduced as the probabilities for receiving inaccurate packet at the DN via the direct and the cooperative communication respectively. It is noted that the unsuccessful reception of data packets at the DN is considered to result from either the packet collision or the channel noises. Therefore, the transition probabilities, which are defined as $P_t(i_1, k_1 \mid i_0, k_0) \triangleq P_t(s(t+1) = i_1, b(t+1) = k_1 \mid s(t) = i_0, b(t) = k_0)$, can be obtained as

$$\begin{cases} P_t(i,k \mid i,k{+}1) = 1 & k \in [0, W_i{-}2], i \in [0, m{+}r] \\ P_t(i,k \mid i{-}1,0) = \frac{p_{dir}}{W_i} & k \in [0, W_i{-}1], i \in [1, \ell] \\ P_t(i,k \mid i{-}1,0) = \frac{p_{coop}}{W_i} & k \in [0, W_i{-}1], i \in [\ell{+}1, m{+}r] \\ P_t(0,k \mid i,0) = \frac{1-p_{dir}}{W_0} & k \in [0, W_0{-}1], i \in [0, \ell{-}1] \\ P_t(0,k \mid i,0) = \frac{1-p_{coop}}{W_0} & k \in [0, W_0{-}1], i \in [\ell, m{+}r{-}1] \\ P_t(0,k \mid m{+}r,0) = \frac{1}{W_0} & k \in [0, W_0{-}1] \end{cases} \tag{2}$$

Let $\pi_{i,k} \triangleq \lim_{t\to\infty} P_t(s(t) = i, b(t) = k)$ be defined as the stationary distribution with $i \in [0, m+r]$ and $k \in [0, W_i - 1]$, the state probabilities can be correlated to $\pi_{0,0}$ as follows:

$$\begin{cases} \pi_{i,k} = \frac{W_i - k}{W_i} \cdot \pi_{i,0} & k \in [0, W_i - 1], i \in [0, m+r] \\ \pi_{i,0} = p_{dir}^{i} \cdot \pi_{0,0} & i \in [0, \ell] \\ \pi_{i,0} = p_{dir}^{\ell} \cdot p_{coop}^{i-\ell} \cdot \pi_{0,0} & i \in [\ell+1, m+r] \end{cases} \tag{3}$$

Consequently, the state probability $\pi_{0,0}$ can be obtained based on $\sum_{i=0}^{m+r} \sum_{k=0}^{W_i-1} \pi_{i,k} = 1$. According to the values of ℓ, two cases are considered for the determination of $\pi_{0,0}$. As $\ell \le m$,

$$\pi_{0,0} = \left[\sum_{i=0}^{\ell} p_{dir}^{i} w_i + \sum_{i=\ell+1}^{m} p_{dir}^{\ell} p_{coop}^{i-\ell} w_i + \sum_{i=m+1}^{m+r} p_{dir}^{\ell} p_{coop}^{i-\ell} w_m \right]^{-1} \tag{4}$$

where $w_i = (W_i + 1)/2$. On the other hand, as $\ell > m$,

$$\pi_{0,0} = \left[\sum_{i=0}^{m} p_{dir}^{i} w_i + \sum_{i=m+1}^{\ell} p_{dir}^{i} w_m + \sum_{i=\ell+1}^{m+r} p_{dir}^{\ell} p_{coop}^{i-\ell} w_m \right]^{-1} \tag{5}$$

The characteristics of the proposed Markov chain model with combined strategy can be illustrated via (2)-(5) after p_{dir} and p_{coop} can be obtained. The determination of these two probabilities is explained as follows.

The probability of any transmission within a randomly selected time slot, i.e. the conditional transmission probability τ, can be expressed as

$$\tau = \sum_{i=0}^{m+r} \pi_{i,0} = \pi_{0,0} \left(\frac{1 - p_{dir}^{\ell+1}}{1 - p_{dir}} + p_{dir}^{\ell} \frac{1 - p_{coop}^{m+r-\ell}}{1 - p_{coop}} p_{coop} \right) \tag{6}$$

It is assumed that $p_{fe(dir)}$ and $p_{fe(coop)}$ are denoted as the FER resulted from the channel noises for the direct and the cooperative communications respectively. The following relationships can be obtained:

$$p_{dir} = 1 - (1 - p_{fe(dir)})(1 - p_c) \tag{7}$$

$$p_{coop} = 1 - (1 - p_{fe(coop)})(1 - p_c) \tag{8}$$

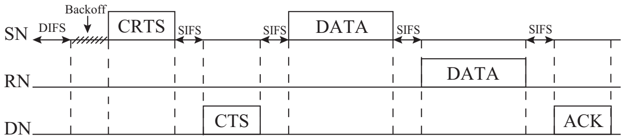

Fig. 2. The schematic diagram of the CRTS/CTS handshake operation for the cooperative communication.

where the probability of a packet collision $p_c = 1-(1-\tau)^{n-1}$ with n denoting the total number of interfering neighbors. Therefore, it can be observed that both p_{dir} and p_{coop} are functions of the conditional transmission probability τ. On the other hand, by substituting (4) and (5) into (6), the probability τ can be represented as a function of p_{dir} and p_{coop}. As a result, the values of p_{dir} and p_{coop} can be acquired through numerically solving the nonlinear equations (6) to (8).

Moreover, both $p_{fe(dir)}$ and $p_{fe(coop)}$ can be obtained from the signal-to-noise ratio (SNR) via their corresponding channel conditions, as was derived in [7; 23]. The FER $p_{fe(dir)}$ can be computed from the SNR value of the direct channel between the SN and the DN. On the other hand, the cooperative FER $p_{fe(coop)}$ is derived from the combined effect of the SNR values via the corresponding three channels, i.e. channels between (SN, RN), (RN, DN), and (SN, DN). The derivation between these two FERs and their corresponding SNR values is neglected. It is noticed that the objective of this paper is to observe the relationship between the FERs and the resulting network throughput. What type of cooperative scheme that results in its corresponding FER $p_{fe(coop)}$ is not the major concern in this paper. In the numerical evaluation section, it will be shown that certain type of cooperative algorithms which results in its corresponding FER value $p_{fe(coop)}$ is suggested to be adopted under a specific value of the FER $p_{fe(dir)}$.

III. SATURATION THROUGHPUT ANALYSIS

It is examined from [7; 15] that two phases are required to accomplish a data transmission for both the AF and the DF based schemes. In the first phase, the SN transmits the data packets to both the RN and the DN within its transmission range. The RN will continue to forward the received packets to the DN, which completes the second phase of the cooperative scheme. A exemplified contention-based MAC protocol with cooperative communication is illustrated in Fig. 2. It is designed based on the IEEE 802.11 CSMA/CA scheme associated with the adoption of the RTS/CTS exchanges. It is assumed that the RN has been pre-selected and identified by the SN before the cooperative communication. For the purpose of informing the RN regarding the activation of the cooperative link, the conventional RTS packet is extended to become the cooperative RTS (CRTS), which includes additional bytes for recording the address of the RN. Similarly, the channel will be secured to be collision-free after the exchange of the CRTS and CTS packets. The SN starts to initiate the delivery of data packets to both the RN and the DN. Subsequently, the RN will forward the received data packet to the DN as shown in Fig. 2. It is noted that the duration between these two data transmissions is also designed to be a short inter-frame space (SIFS). Due to the much smaller size compared to the data packets, the frame error of the non-data packets is considered neglected. Moreover, the scheme as proposed in Fig. 2 will be utilized for the evaluation of the saturated network throughput. Other contention-based MAC protocol with cooperative diversity can also be designed and analyzed in the similar manner.

Similar to the work presented in [19], the saturation throughput is defined as the fraction of time utilized to successfully transmit the payloads. In order to facilitate the computation of the network throughput, three associated probabilities are introduced as follows: (a) p_{tr}: the probability of at least one transmission is occurred in the considered time slot; (b) p_{wc}: the probability of a transmission without collisions on the condition that at least one node is transmitting; and (c) p_r: the ratio of the direct transmission to the cooperative and direct communications considering at least one transmission happens. The three probabilities can be obtained as

$$p_{tr}=1-(1-\tau)^n \tag{9}$$

$$p_{wc}=\frac{n\tau(1-\tau)^{n-1}}{p_{tr}}=\frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n} \tag{10}$$

$$\begin{aligned} p_r&=\frac{\sum_{j=0}^{\ell-1}\pi_{j,0}}{\sum_{i=0}^{m+r}\pi_{i,0}} \\ &=\frac{(1-p_{dir}^{\ell})(1-p_{coop})}{(1-p_{dir}^{\ell})(1-p_{coop})+p_{dir}^{\ell}(1-p_{coop}^{m+r-\ell+1})(1-p_{dir})} \end{aligned} \tag{11}$$

Furthermore, the saturation throughput S, which is defined as a function of ℓ, $p_{fe(dir)}$, and $p_{fe(coop)}$, can be expressed as

$$S(\ell,p_{fe(dir)},p_{fe(coop)})=\frac{E[T_P]}{E[T_B]+E[T_S]+E[T_C]+E[T_E]} \tag{12}$$

The expected values within (12) are obtained as follows. $E[T_B]=(1-p_{tr})\sigma$ indicates the average length of the non-frozen backoff time in a time slot, where σ is defined as the slot time size [19]. The average duration of the successful transmission in a time slot is acquired as

$$\begin{aligned} E[T_S] &= p_r p_{tr} p_{wc}(1-p_{fe(dir)})T_{s(dir)} \\ &\quad +(1-p_r)p_{tr}p_{wc}(1-p_{fe(coop)})T_{s(coop)} \end{aligned} \tag{13}$$

where $T_{s(dir)}$ and $T_{s(coop)}$ are the required time intervals for a successful transmission via the direct and the cooperative communications respectively. These two parameters are obtained as

$$\begin{aligned} T_{s(dir)} &= T_{RTS}+T_{CTS}+T_{Header}+T_{Payload}+T_{ACK} \\ &\quad +3T_{SIFS}+4\rho+T_{DIFS} \end{aligned} \tag{14}$$

$$\begin{aligned} T_{s(coop)} &= T_{s(dir)}+(T_{CRTS}-T_{RTS})+T_{Header} \\ &\quad +T_{Payload}+T_{SIFS}+\rho \end{aligned} \tag{15}$$

where ρ is denoted as the propagation time. It is noted that the meanings of the other parameters are revealed by their corresponding subscripts, e.g. T_{Header} indicates the time interval for transmitting the packet header, and T_{DIFS} corresponds to the time duration of a distributed inter-frame space. Moreover, $E[T_C]$ represents the average time duration for the transmission with collisions in a time slot. The mean length of a failure transmission caused by the channel noises is denoted as $E[T_E]$.

Both $E[T_C]$ and $E[T_E]$ are obtained as

$$\begin{aligned} E[T_C] &= p_r p_{tr}(1-p_{wc})T_{c(dir)} \\ &\quad +(1-p_r)p_{tr}(1-p_{wc})T_{c(coop)} \qquad (16) \\ E[T_E] &= p_r p_{tr} p_{wc} p_{fe(dir)} T_{e(dir)} \\ &\quad +(1-p_r)p_{tr} p_{wc} p_{fe(coop)} T_{e(coop)} \qquad (17) \end{aligned}$$

where $T_{c(dir)}$ and $T_{c(coop)}$ are the time intervals for the packet collision by adopting the direct and the cooperative schemes respectively, i.e.

$$\begin{aligned} T_{c(dir)} &= T_{RTS} + \rho + T_{DIFS} \qquad (18) \\ T_{c(coop)} &= T_{c(dir)} + (T_{CRTS} - T_{RTS}) \qquad (19) \end{aligned}$$

On the other hand, the parameters $T_{e(dir)}$ and $T_{e(coop)}$ are the required time durations to receive and detect the error packet caused from the channel noises. Both values are considered the same as that for successful transmissions, i.e. $T_{e(dir)} = T_{s(dir)}$ and $T_{e(coop)} = T_{s(coop)}$. Finally, the parameter $E[T_p]$ represents the average time of the payload information that is successfully transmitted in a time slot, which can be acquired as

$$\begin{aligned} E[T_p] &= p_r p_{tr} p_{wc}(1-p_{fe(dir)})T_{Payload} \\ &\quad +(1-p_r)p_{tr} p_{wc}(1-p_{fe(coop)})T_{Payload} \qquad (20) \end{aligned}$$

Two special cases for the saturation throughput S are considered as follows. S_{dir} represents the saturation throughput if only the direct transmission scheme is utilized for all the backoff stages; while S_{coop} indicates the case that the cooperative algorithm is adopted for the entire communication process. These two special cases are defined as

$$\begin{aligned} S_{dir}(p_{fe(dir)}) &\triangleq S(\ell{=}m{+}r{+}1, p_{fe(dir)}, p_{fe(coop)}{=}0) \qquad (21) \\ S_{coop}(p_{fe(coop)}) &\triangleq S(\ell{=}0, p_{fe(dir)}{=}0, p_{fe(coop)}) \qquad (22) \end{aligned}$$

Whether it is suitable to adopt the cooperative schemes can be intuitively observed from the two extreme cases as described in (21) and (22). In general, the cooperative algorithms can improve the FER with the cooperation of the RN, i.e. $p_{fe(coop)} < p_{fe(dir)}$. However, the successful transmission time via the cooperative link is inherently longer than that from the original direct communication, i.e. $T_{s(coop)} > T_{s(dir)}$. Due to the tradeoff between the FER and the required transmission time, there is no guarantee that the saturation throughput from the cooperative communication (S_{coop}) will be higher than that from the direct link (S_{dir}). The analytical models derived in this section will be utilized to determine the suitable occasions to exploit the cooperative algorithms, as will be presented in the next section.

IV. NUMERICAL EVALUATION

Numerical results are performed to evaluate the suitability of the cooperative algorithms. The parameters utilized in this paper are selected to be the same as that in [19] except the following: (a) the total number of interfering neighbors is $n = 10$; (b) the number of backoff stages after the maximum window size has been achieved is selected as $r = 4$; (c) the CRTS packet is designed to be six bytes more compared to the conventional RTS packet.

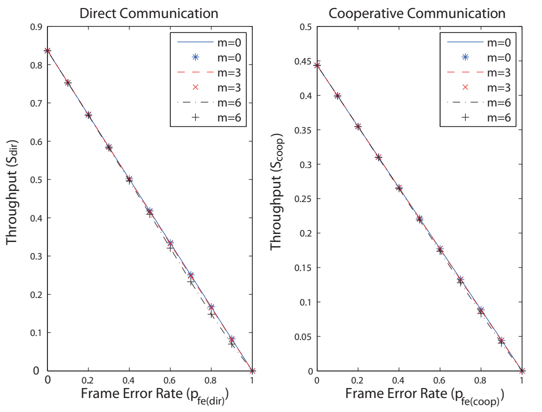

Fig. 3. Throughput versus frame error rate (Line segment: analytical result; Symbol: simulation result)

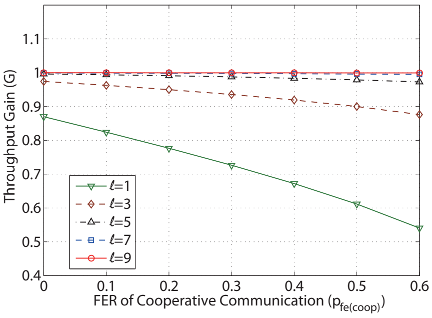

Fig. 4. Throughput gain versus frame error rate for cooperative communication (with $p_{fe(dir)} = 0.3$).

The model for the saturation throughput as derived in the previous section is validated with simulations. Fig. 3 illustrates the validation of the throughput versus the FER (with $W = 32$ and $m = 0, 3, 6$), i.e. left plot: S_{dir} vs. $p_{fe(dir)}$; and right plot: S_{coop} vs. $p_{fe(coop)}$. It is observed that the analytical and the simulation results closely coincide with each other, which confirm the correctness of the proposed model. It is also shown in both plots of Fig. 3 that the dependency between the throughput and the parameter m is negligible.

In order to observe the benefits acquired by adopting the cooperative schemes, a new metrics throughput gain G is utilized, i.e. $G(\ell, p_{fe(dir)}, p_{fe(coop)}) \triangleq (S/S_{dir})$ where S and S_{dir} are obtained from (12) and (21). Figs. 4 and 5 (with $m = 6$ and $W = 32$) illustrate the relationships between the throughput gain (G) and the FER for cooperative communication ($p_{fe(coop)}$) under a pre-defined FER for the direct link, i.e. $p_{fe(dir)} = 0.3$ in Fig. 4 and $p_{fe(dir)} = 0.6$ in Fig. 5. Both figures illustrate different trials (ℓ) of the direct transmissions that are conducted before the activation of the cooperative communication. Under the case of $p_{fe(dir)} = 0.3$, it is observed from Fig. 4 that the cooperative scheme possesses inferior performance, i.e. $G < 1$. The reason is attributed to its comparably longer transmission time, which can not be compensated even with lowered FER value $p_{fe(coop)}$. However, considering the case with $p_{fe(dir)} = 0.6$ as in Fig. 5, it is found that all the lines roughly intersect at a point where $p_{fe(coop)} \approx 0.3$. The cooperative mechanism outperforms the direct communication as $p_{fe(coop)} < 0.3$. In other words, it is shown in Fig. 5 that certain types of cooperative algorithms (which can achieve

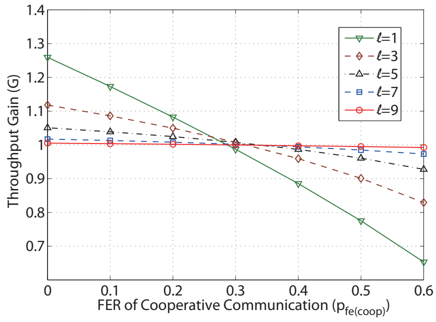

Fig. 5. Throughput gain versus frame error rate for cooperative communication (with $p_{fe(dir)} = 0.6$).

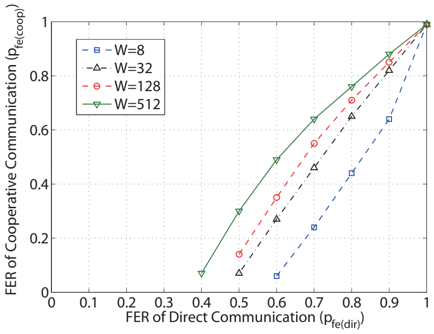

Fig. 6. FER of cooperative communication versus FER of direct communication.

$p_{fe(coop)} < 0.3$) are suggested to be exploited under the case while the FER from the direction link is equal to 0.6. It is also noticeable to observe that whether to adopt the cooperative scheme is independent to the backoff stage ℓ.

Based on the results acquired from Fig. 5, either S_{dir} or S_{coop} will achieve the maximum throughput performance while both $p_{fe(dir)}$ and $p_{fe(coop)}$ are given. These two cases will be further investigated to explore the suitability for cooperative schemes. Fig. 6 shows the occasions for the cooperative mechanism to have a better performance than the direct communication under different contention window W. For each specific $p_{fe(dir)}$, each point on the lines represents the value of $p_{fe(coop)}$ that satisfies the following condition:

$$\sup\left\{p_{fe(coop)} : S_{coop}(p_{fe(coop)}) \geq S_{dir}(p_{fe(dir)})\right\} \qquad (23)$$

For example, as $W = 512$ and $p_{fe(dir)} = 0.5$, the cooperative scheme with $p_{fe(coop)} < 0.3$ can outperform the conventional direct communication in network throughput. Each line in Fig. 6 can also be explained as the case while $S_{coop} = S_{dir}$ for a specific initial contention window size. The region below the line represents the situations of $S_{coop} > S_{dir}$. Fig. 6 can be utilized as a reference plot to determine the suitability for adopting the cooperative schemes as opposed to the direct communication.

V. CONCLUSION

This paper presents the performance analysis of the cooperative communication from the medium access control (MAC) perspectives. An analytical model which consists of both the conventional direct communication and the cooperative mechanism is proposed to evaluate the suitability for adopting the cooperative scheme. Simulations are also performed to validate the effectiveness of the proposed analytical model. In order to enhance the network throughput, it is suggested in this paper that not only the cooperative diversity (with the resulting frame error rate) but also the transmission delay should be considered in the design of cooperative communications.

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