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Queuing analysis of cooperative GBN-ARQ in wireless networks with peers contending for a common helper

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ABSTRACT

This paper presents a new queuing model for performance analysis of go-back-N automatic repeat request (GBN-ARQ) protocol in cooperative wireless networks. In the model, cooperative medium access control (CoopMAC) protocol and dynamic radio link adaptation are taken into consideration. We analyze the probability distribution of the total delay witnessed by packets at the source side. Multi-rate transmissions are considered for all links with link adaptation. An enhanced Markov model is introduced in our model, which encompasses the following aspects: CoopMAC protocol at the MAC sub-layer; GBN-ARQ protocol at the logical link control sub-layer and the transmission using decode-and-forward cooperative diversity at the physical layer. The stochastic process of random feedback delay because of peers contending for a common helper is analyzed. The queuing system is modeled as a GI/M/1 Markov chain to acquire statistics of the exact queue length and the total delay. We analyze the effects of Doppler frequency shift and packet arrival rate on the total delay. The analysis is validated by simulation.

1. Introduction

1.1. Cooperative transmission

IEEE 802.11 protocol is widely used in today's wireless networks like wireless LANs and hotspots. With increasing usage, tractable analytical models that estimate the performance of 802.11 protocols accurately gain more importance. A significant amount of research opened up by [1] on cooperative communication techniques is being developed to allow stations to cooperate in their transmissions in order to improve the overall performance of the network. As shown in Fig. 1, since a transmission in the wireless channel is overheard by neighboring stations, these neighboring stations can process these signals and re-transmit them in order to facilitate better reception. The destination combines the signals received from the source and the helper, thus creating spatial diversity and robustness against channel variations due to fading [2].

In recent researches, cooperative communication not only at the physical layer but also at higher layers of the protocol stack, e.g., the medium access control (MAC), or network layer, is proposed [3]. At the physical layer, adaptive modulation and coding (AMC) technique is being used in most of the 3G wireless networks to increase the transmission rate by exploiting the wireless channel variations [4]. With the aid of channel state information, AMC tries to make full use of the dynamic capacity of the time-varying channel with the aim to increase the average transmission rate [5]. ARQ protocol is an error-control method of the link layer, which guarantees reliable transferring of packets by retransmitting packets after negative acknowledgments (NACK's) being reported on the feedback channel. There are three basic ARQ protocols: stop-and-wait (SW) ARQ, go-back-N (GBN) ARQ, and selective-repeat (SR) ARQ protocols. SR-ARQ is the most efficient one in terms of throughput, however, GBN-ARQ is superior to the SR-ARQ protocol in terms of implementation simplicity. In a multi-rate wireless network, the partitioning of signal-to-noise ratio (SNR) for different transmission modes can be chosen such that the packet error rate is kept under some expected level, and the performances of these two protocols become very close to each other. Therefore, the GBN-ARQ protocol can be used to eliminate residual error in the link layer when the implementation simplicity of the radio link protocol is a major concern as in [6].

This paper focuses on queuing analysis for go-back-N automatic retransmission request (GBN-ARQ) protocol in cooperative wireless networks. Due to the fading channel in wireless links, we take into account link adaptation in the physical layer and the stochastic nature of the feedback delay of ARQ protocols because of the contention resolution in the MAC sub-layer of the common helper.

1.2. Related work

Cooperative communication plays an important role in automatic repeat request (ARQ) scheme extending that of legacy IEEE

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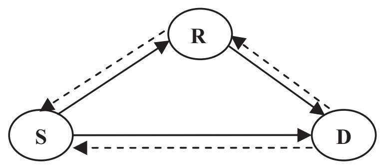

Fig. 1. Cooperative transmission scene.

802.11. Cooperative ARQ scheme aims at reducing packet transmission delay with improved reliability through relaying, and increasing network throughput [7].

The basic idea of cooperative diversity is that a wireless station with low data rate can be assisted by neighboring stations with higher data rates for its transmissions. These assisting nodes are referred to as relay nodes or helper stations. With such assistance available, the source station will be able to transmit data with a higher rate to the relay node which in turn will forward the data to the destination with a higher rate. This achieves an overall higher performance than that the source station transmit the data directly to the destination [8]. But the retransmission of data by a helper may introduce extra interference or collision with communications between other adjacent nodes. An optional Collision Avoidance (CA) mechanism is defined in the 802.11 MAC protocol by which a Request-to-Send/Clear-to-Send (RTS/CTS) handshake is established between source and destination prior to the data transmission [9], which is employed in this paper.

Liu and Tao demonstrated that cooperation among stations in a wireless network can achieve both higher throughput and lower interference in [2]. They presented a design for a medium access control protocol called CoopMAC, in which high data rate stations assist low data rate stations in their transmission by forwarding their traffic. A distributed, threshold based MAC protocol was developed in [10] for cooperative multi-input multi-output (MIMO) transmissions in distributed wireless systems. The protocol uses a threshold scheme that is updated dynamically based on the queue length at the sending node to achieve low power transmissions while ensuring stability of the transmission queues at the nodes. In paper [11], a novel protocol called vehicular cooperative media access control (VC-MAC) was proposed, which leverages the broadcast nature of the wireless medium to maximize the system throughput.

Ma and Yang presented a novel contention-based medium access control (MAC) protocol, namely, the channel reservation MAC (CR-MAC) protocol in [12]. The CR-MAC protocol takes advantage of the overhearing feature of the shared wireless channel to exchange channel reservation information with little extra overhead. Each node can reserve the channel for the next packet waiting in the transmission queue during the current transmission. By analytically deriving the CW sizes optimized for achieving the maximum throughput under both saturated and non-saturated conditions, literature [13] proposed a distributed algorithm that enables each station to dynamically adapt its CW size according to the channel status. In [14], an analytical model for IEEE 802.11 DCF protocol has been presented to accurately predict the performance for a wide range of scenario parameters in single hop networks. In fact, it is of interest to study the impacts on queuing delay by the packet arrival rate in the case of non-saturation loads, as presented in this paper.

The delay statistics for GBN-ARQ with non-instantaneous feedback delay was early discussed in [15]. It used a two-state Markov channel model, which could not capture the multi-rate transmission feature of currently deployed wireless networks. The model in [16] was extended in [17] for channels with more states. However, the transmission rate was assumed to be constant (i.e., for all channel states only one packet is transmitted in one time slot);

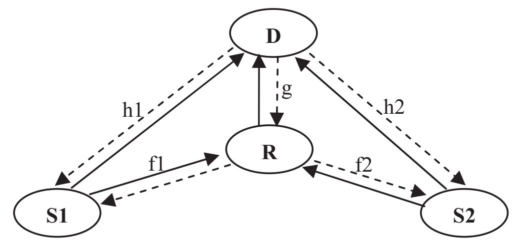

Fig. 2. Cooperative transmission system model.

therefore, the model did not truly take the multi-rate transmission or link adaptation technique into account. The statistics of total delay for GBN-ARQ with non-instantaneous feedback was further studied in [18], which capture the multi-rate transmission feature of currently deployed wireless networks. However, it is limited to cases that the feedback delay is constant for different packets. Delay for cooperative ARQ protocols is also studied in [19], which evaluates the delay experienced by Poisson arriving frames in slotted radio networks.

The authors of [6] presented a queuing model for performance analysis of cooperative GBN-ARQ protocols in wireless networks using dynamic radio link adaptation. The stochastic nature of the feedback delay in the cooperative GBN-ARQ was investigated. The queuing problem for GBN-ARQ is formulated as a four-dimensional GI/M/1 Markov chain, the solution of which is then obtained by the classical matrix geometric method [20]. However, it was assumed that the source is the sole node to ask the help of the relay. However, in real cooperative networks, there is a great probability that a good relay may be chosen simultaneously by several sources. Contentions among these sources occur because they share a common helper. The process of contention resolution is stochastic. This leads to a new type of random round trip delay or feedback delay in cooperative GBN-ARQ protocols. Research on performance analysis of ARQ protocols taking such factor into consideration has not been reported yet.

In summarize, among the published work on performance analysis of ARQ protocols in the literature, no one is fit for GBN-ARQ protocols in wireless networks which integrate cooperative diversity and link adaptation together with different sources share a common helper. With the aim of crossing this barrier, this paper studies the stochastic nature of the delay of peers contending for a common relay and then develops a method to evaluate the statistics of the total delay of packets under the control of GBN-ARQ protocols.

The rest of this paper is organized as follows. Section 2 presents the system model and analyzes the randomly variable delay for channel accessing. Then, we formulate the queuing problem and obtain the performance metrics for GBN-ARQ protocol in the cooperative wireless system with CoopMAC in Section 3. Model validation and numerical results are provided in Section 4. Finally, Section 5 concludes the paper.

2. System model and assumptions

2.1. System description

As illustrated in Fig. 2, we consider a cooperative wireless system composed of two source nodes ($S1$ and $S2$), a relay node (R) and a destination node (D), where the relay node R functions as a partner to help the sources transmitting packets to the destination. In order to transmit packets to the relay node (R), the two source nodes become competing nodes when attempting to access the channel. At the source node ($S1$ or $S2$), input packets from higher layers of protocol stack are stored in a buffer regarded as infinite before being

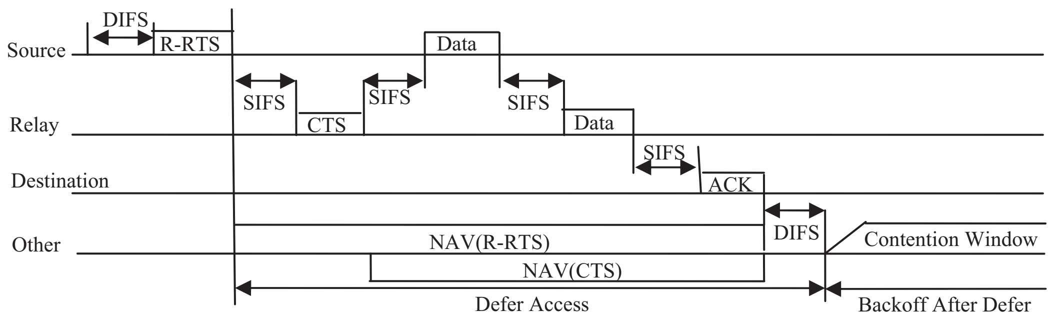

Fig. 3. R-RTS/CTS/data/ACK timing diagram.

transmitted. $S1$ and $S2$ communicate with R over a channel with a flat Nakagami-m fading coefficient $f1$, $f2$ respectively. R relays the signal to the destination. The channel coefficients between $S1$, $S2$ and D are $h1$ and $h2$ respectively, and that between R and D is g and it is also a flat Nakagami-m fading coefficient.

As the two source nodes are assumed identical, it is sufficient to analyze the behavior of one of them to predict the behavior of the other. We consider the source using adaptive modulation and coding at the physical layer and contention-based IEEE 802.11 RTS/CTS mode at the MAC sub-layer to communicate with the relay node over a wireless channel in cooperative wireless network.

Before explaining the details of the system model, we introduce an additional control message as in [12], termed as reservation RTS (R-RTS), which is used to reserve the channel between the source and the relay. R-RTS has the same fields as the basic RTS message except the helper address. In order to differentiate the new message R-RTS from the existing ones, a different code is put in the control field for the new frame type. Besides this new message, all other messages are kept unchanged as in IEEE 802.11. Fig. 3 shows the timing of CoopMAC.

The data transmissions after the reservation process occur in time slots (STs) where the number of packets transmitted during each ST depends on the chosen transmission mode. Note that the unit ST is different from the SlotTime specified in IEEE 802.11 DCF scheme [21]. The length of one ST in this paper is presumed to contain fifty DCF SlotTimes reflecting the corresponding PHY characteristics.

The destination decodes the received packets and sends a feedback packet containing acknowledgment (ACK) or negative acknowledgment (NACK) information to the source. In case of decoding failure of one or more packets transmitted during a ST, error recovery based on GBN-ARQ protocol is initiated. The source continuously transmits packets from the buffer in sequence until it detects a transmission error through NACK in the feedback packet. If NACK is received, the source retransmits all the packets starting from the erroneous packet reported by the NACK.

The flowchart of transmitting a packet at the source is shown in Fig. 4.

This paper analyzes the packet queuing delay at the source node. The cooperating node (i.e., the relay node R) only forwards packets to the destination. The feedback packet (i.e., the ACK/NACK information) is supposed to arrive at the source node n STs (n is a random variant) after the first attempt to initiate a transmission at the beginning of the corresponding slot. The feedback delay of a transmission of the packets in the source includes the R-RTS feedback delay and data frame feedback delay. The randomly changing feedback delay of data frames not concerning the contention resolution process has been analyzed in paper [6]. In order to investigate the total feedback delay values here, it is essential to focus on the analysis of random R-RTS feedback delay values and deduce the corresponding transition probability matrix.

Next, we are to analyze the R-RTS/CTS procedure for channel reservation. Packet arrivals are assumed to follow a Bernoulli process. The following seven cases are considered which may occur in the cooperative transmission process:

I. If the source node $S1$ has data packets to transmit, it will first sense the medium to determine if there were any transmissions over the channel currently. If the medium is not determined to be busy and after duration of DIFS, $S1$ will broadcast a control message R-RTS. Upon the reception of R-RTS, the helper R will respond a control frame CTS to $S1$. When $S1$ receives the CTS frame, it waits for a SIFS and then begins to transmit its data packets to R which will forward the packet to the destination.

II. Since not all nodes can hear each other, even if the channel is sensed to be free, a collision may occur, that is, $S1$ and $S2$ broadcast R-RTS frames during the same time slot. The binary exponential backoff mechanism of DCF protocol is invoked to resolve the collision. $S1$ and $S2$ then generates a random backoff period, respectively. After the medium is sensed idle for a duration time of DIFS, the backoff procedure shall decrement its backoff timer by a unit if no medium activity is indicated for a SlotTime. When the Backoff Timer of $S1$ reaches zero prior to $S2$, $S1$ will broadcast the control frame R-RTS in a time slot.

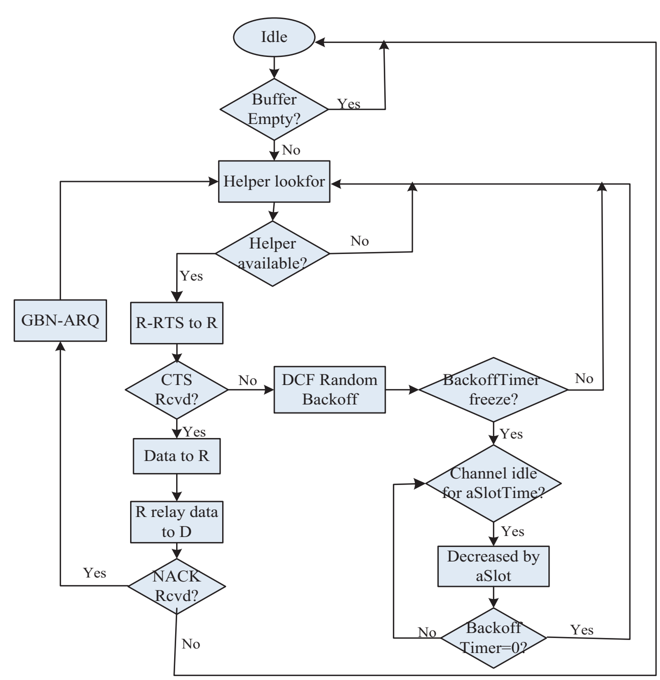

Fig. 4. Flow chart of transmitting a packet at the source node S.

As $S2$ does not broadcast frames during the same time slot, no further collision will occur and R receives R-RTS from $S1$ successfully. Then, R gives a feedback frame CTS to $S1$. $S2$ will accept the CTS message as well and be informed that it has to stay quiet for duration of NAV specified in CTS. Upon the reception of feedback message CTS at node $S1$, it suggests that $S1$ has grabbed the channel and can start transmitting data packets to R after duration of SIFS.

III. As stated in case II, if the backoff timer of $S1$ reaches zero behind $S2$, $S2$ will reserve the channel successfully. After $S2$ completes its transmission, $S1$ reserves the channel and starts to deliver its packets to R.
IV. There is a branch situation in case III: $S2$ obtains the channel again after its first transmission procedure. Then $S1$ has to wait to initiate its reservation process unless the medium is determined to be idle (i.e. when $S2$ finishes its second transmission).
V. If the second collision occurs and after the subsequent backoff process, $S1$ obtains the channel successfully.
VI. In case V, if $S2$ reserves the channel after the second collision, $S1$ will wait to initiate a transmission after the medium is determined to be idle without interruption for a period of time equal to DIFS.
VII. There is another case derived from case III: A collision appears following the completion of the packet transmission of $S2$. $S1$ grabs the channel after a random backoff interval.

Compared with the probabilities of the above mentioned procedures, the probability of the third collision is so small that it can be negligible.

2.2. Feedback delay transition probability

From [21], we are aware of Backoff Time = Random () × aSlotTime, where Random () is a pseudo-random integer drawn from a uniform distribution over the interval [0, CW]. CW is an integer within the range of values of the PHY characteristics aCWmin and aCWmax, namely aCWmin ≤ CW ≤ aCWmax. The CW shall increase exponentially in the contention resolution process every time an unsuccessful attempt to transmit packets occurs, until the CW reaches the value of aCWmax.

Unlike [6], the transmission of a data frame is assumed to be finished in one ST in this paper. Compared with the ST length, the feedback time duration from the destination back to the source is assumed to be negligible due to the small amount information bits of the feedback message in the high-speed cooperative wireless networks.

According to the assumption that the duration of one ST contains fifty mini-slots in the previous section and the DCF access procedure in this paper, we can now decide the R-RTS feedback delay of the seven cases stated in Section 2.1. The R-RTS feedback delays of case I, II, V are classified into one ST and the R-RTS feedback delays of case III, VI, VII are classified into two STs, while case IV's R-RTS feedback delay is sorted out as three STs.

The whole feedback delay is obtained by adding the above discussed time of contention resolution to one ST for data frame retransmission at the relay. Thus, there are three values of feedback delay in the above model (i.e. 2, 3, 4), in which the feedback delay of case I, II, V is 2 STs, case III, VI, VII corresponding to 3 STs and case IV with 4 STs.

b_i is imposed to represent the feedback delay of the transmitted R-RTS for packet i, and d_j represents the feedback delay of packet j for the whole transmission process, where $1 \le b_i \le 3, 2 \le d_j \le 4$. Packet arrivals follow a Bernoulli process with arrival probability λ. The value of b_i can influence the probability distribution of b_{i+1}, but b_{i+1} has nothing to do with $b_0, b_1, \ldots, b_{i-1}$. Thus $\{b_i, 0, 1, 2, \ldots\}$ is a Markov chain:

$$P(b_{i+1} = \beta | b_0, b_1, \ldots, b_i = \alpha) = P(b_{i+1} = \beta | b_i = \alpha) \quad \alpha, \beta \in S = \{1, 2, \ldots, 7\} \tag{1}$$

And $\{d_j, j = 0, 1, 2, \ldots\}$ is a Markov chain as well [18]:

$$P(d_{j+1} = n | d_0, d_1, \ldots, d_j = m) = P(d_{j+1} = n | d_j = m) \quad m, n \in Z = \{2, 3, 4\} \tag{2}$$

The following transitions are defined:

$$P(b_{i+1} = \beta | b_i = \alpha) = \bar{q}_{(\alpha)(\beta)} \quad \alpha, \beta \in S, \bar{q}_{(\alpha)(\beta)} \ge 0 \text{ and } \sum_{\beta=1}^{7} \bar{q}_{(\alpha)(\beta)} = 1 \tag{3}$$

$$P(d_{j+1} = n | d_j = m) = q_{(m)(n)}$$
$$m, n \in Z, q_{(m)(n)} \ge 0 \text{ and } \sum_{n=2}^{4} q_{(m)(n)} = 1 \tag{4}$$

Assume that ρ_i is the probability of the occurrence of case i and μ_j represents the probability of the total feedback delay being j STs. According to the cases stated in Section 2.1, μ_2, μ_3, μ_4 can be expressed as follows:

$$\mu_2 = \sum_{i \in I_2} \rho_i, \quad i \in I_2 = \{1, 2, 5\} \tag{5}$$

$$\mu_3 = \sum_{i \in I_3} \rho_i, \quad i \in I_3 = \{3, 6, 7\} \tag{6}$$

$$\mu_4 = \rho_i, \quad i \in I_4 = \{4\} \tag{7}$$

In fact, according to the DCF access procedure discussed in Section 2.1, $\rho_i, i \in \{1, 2, \ldots, 7\}$ can be calculated as follows:

$$\rho_1 = 1 - \lambda, \quad \rho_2 = \lambda \cdot \frac{W_1}{2(W_1 + 1)}, \quad \rho_3 = \rho_2 \cdot \frac{2(W_1 - 1)}{3(W_1 + 1)},$$
$$\rho_4 = \lambda \cdot \frac{W_1(W_1 + 2)}{6(W_1 + 1)^2}, \quad \rho_5 = \rho_6 = \lambda \cdot \frac{W_2}{2(W_1 + 1)(W_2 + 1)},$$
$$\rho_7 = \rho_2 \cdot \frac{1}{W_1 + 1} \tag{8}$$

where W_1 is the size of initial contention window and $W_i = 2^{i+2} - 1$, $i = 1, 2, \ldots$. Then the elements of state transition matrix $\bar{q}$ can be calculated as follows:

As the packet state will go back to the initial state when the case I's transmission finished, case I is independent of the other ones and can be written as:

$$\bar{q}_{1j} = \rho_j \quad j = 1, 2, \ldots, 7, \tag{9}$$

The remainder elements of matrix $\bar{q}$ can be obtained due to the correlation between the seven cases discussed in Section 2.1, as follows:

$$\bar{q}_{21} = 1 - \sum_{j=2}^{7} \bar{q}_{2j}, \quad \bar{q}_{22} = \frac{W_1 + 2}{3(W_1 + 1)}, \quad \bar{q}_{23} = \frac{2f_1}{W_1(W_1 + 1)^3},$$
$$\bar{q}_{24} = \frac{2f_2}{W_1(W_1 + 1)^3}, \quad \bar{q}_{25} = \bar{q}_{26} = \frac{W_2}{2(W_1 + 1)(W_2 + 1)},$$
$$\bar{q}_{27} = \frac{2(W_1 - 1)}{3(W_1 + 1)^2} \tag{10}$$

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where $f_1 = \sum_{i=1}^{W_1-1}\left(i(W_1-i)+\sum_{j=1}^{W_1-i}j\right)\cdot(W_1-i)$, $f_2 = \sum_{i=1}^{W_1-1}\left(i(W_1-i)+\sum_{j=1}^{W_1-i}j\right)\cdot i$.

$$\bar{q}_{31} = 1-\sum_{j=2}^{7}\bar{q}_{3j},\quad \bar{q}_{32} = \frac{f_3}{f_4},\quad \bar{q}_{33} = \left(\frac{f_5}{f_4}\right)^2,\quad \bar{q}_{34} = \frac{f_5\cdot f_3}{f_4{}^2},$$
$$\bar{q}_{35} = \bar{q}_{36} = \frac{W_2}{2(W_1+1)(W_2+1)},\quad \bar{q}_{37} = \frac{f_5}{f_4\cdot(W_1+1)} \tag{11}$$

where, $f_3 = \sum_{i=1}^{W_1-1}(W_1-i)\cdot i$, $f_4 = \left(\sum_{i=1}^{W_1-1}i\right)\cdot(W_1+1)$, $f_5 = \sum_{i=1}^{W_1-1}i^2$.

$$\bar{q}_{41} = 1-\sum_{j=2}^{7}\bar{q}_{4j},\quad \bar{q}_{42} = \frac{f_6}{f_8},\quad \bar{q}_{43} = \frac{f_7\cdot f_6}{f_8{}^2},\quad \bar{q}_{44} = \left(\frac{f_7}{f_8}\right)^2,$$
$$\bar{q}_{45} = \bar{q}_{46} = \frac{W_2}{2(W_1+1)(W_2+1)},\quad \bar{q}_{47} = \frac{f_7}{f_8\cdot(W_1+1)} \tag{12}$$

where $f_6 = \sum_{i=1}^{W_1-1}i\cdot(i+1)$, $f_7 = \sum_{i=1}^{W_1}i\cdot(W_1-i+1)$, $f_8 = \left(\sum_{i=1}^{W_1-1}i\right)\cdot(W_1+1)$.

$$\bar{q}_{51} = 1-\sum_{j=2}^{7}\bar{q}_{5j},\quad \bar{q}_{52} = \frac{f_9+f_{10}}{f_{11}},\quad \bar{q}_{53} = \frac{f_{12}}{f_{11}}\cdot\frac{f_5}{f_4},$$
$$\bar{q}_{54} = \frac{f_{12}}{f_{11}}\cdot\frac{f_3}{f_4},\quad \bar{q}_{55} = \frac{f_{13}}{f_{11}}\cdot\frac{f_{15}}{(W_2+1)(W_3+1)},$$
$$\bar{q}_{56} = \frac{f_{13}}{f_{11}}\cdot\frac{f_{14}}{(W_2+1)(W_3+1)},\quad \bar{q}_{57} = \frac{f_{12}}{f_{11}}\cdot\frac{1}{(W_1+1)} \tag{13}$$

where $f_9 = \sum_{i=1}^{W_1}i\cdot(W_2-i+1)$, $f_{10} = \left(\sum_{i=1}^{W_2-W_1}i\right)\cdot(W_1+1)$, $f_{11} = \left(\sum_{i=1}^{W_2}i\right)\cdot(W_1+1)$, $f_{12} = \sum_{i=1}^{W_1-1}(W_2-i+1)\cdot(W_1-i)$, $f_{13} = \sum_{i=W_2-W_1+1}^{W_2}i$, $f_{14} = \sum_{i=1}^{W_2}i$, $f_{15} = \sum_{i=W_3-W_2}^{W_3}i$.

$$\bar{q}_{61} = 1-\sum_{j=2}^{7}\bar{q}_{6j},\quad \bar{q}_{62} = \frac{f_{12}}{f_{11}},$$
$$\bar{q}_{63} = \frac{f_9+f_{16}}{f_{11}\cdot(W_1+1)}\cdot\frac{f_4}{f_{14}+(W_1+1)(W_2-W_1)},$$
$$\bar{q}_{64} = \frac{f_9+f_{16}}{f_{11}}\cdot\left[1+f_{14\_2}\cdot\left(\frac{1}{f_{14}}+\frac{f_{14}}{(W_1+1)^2}\right)\right],$$
$$\bar{q}_{65} = \frac{f_{13}}{f_{11}}\cdot\frac{f_{14}}{(W_2+1)(W_3+1)},\quad \bar{q}_{66} = \frac{f_{13}}{f_{11}}\cdot\frac{f_{15}}{(W_2+1)(W_3+1)},$$
$$\bar{q}_{67} = \frac{f_{9\_1}}{f_{11}}\cdot\frac{W_1}{f_{14}+(W_1+1)(W_2-W_1)} \tag{14}$$

where $f_{9\_1} = \sum_{i=1}^{W_1}i\cdot(W_2-i+1)+\left(\sum_{i=1}^{W_2-W_1}i\right)\cdot(W_1+1)$, $f_{16} = \left(\sum_{i=1}^{W_1}i\right)\cdot(W_1+1)$, $f_{14\_2} = \sum_{i=1}^{W_1+1}i$.

$$\bar{q}_{71} = 1-\sum_{j=2}^{7}\bar{q}_{7j},\quad \bar{q}_{72} = \frac{f_{14}}{(W_3+1)(W_2+1)},$$
$$\bar{q}_{73} = \frac{f_{17}}{(W_3+1)(W_2+1)(W_1+1)},$$
$$\bar{q}_{74} = \frac{1}{W_3+1}\left[\frac{\sum_{i=1}^{W_1}i}{W_1+1}+f_{14}+(W_2+1)(W_3-W_2-W_1)\right],$$
$$\bar{q}_{75} = \frac{\sum_{i=1}^{W_3}i}{(W_3+1)^2(W_4+1)},\quad \bar{q}_{76} = \frac{f_{15\_1}}{(W_3+1)^2(W_4+1)},$$
$$\bar{q}_{77} = \frac{W_1}{(W_3+1)(W_1+1)} \tag{15}$$

where $f_{15\_1} = \sum_{i=W_4-W_3}^{W_4}i$, $f_{17} = (W_2+1)\sum_{i=1}^{W_1-1}i$.

The state transition matrix $\bar{Q}$ can be written as follows:

$$\bar{Q}_{(7)(7)} = \begin{pmatrix} \bar{q}_{11} & \cdots & \bar{q}_{17} \\ \vdots & \ddots & \vdots \\ \bar{q}_{71} & \cdots & \bar{q}_{77} \end{pmatrix} \tag{16}$$

On the basis of Eqs. (5)–(15), the state transition matrix Q can be expressed as follows:

$$Q_{(3)(3)} = \begin{pmatrix} q_{22} & q_{23} & q_{24} \\ q_{32} & q_{33} & q_{34} \\ q_{42} & q_{43} & q_{44} \end{pmatrix} \tag{17}$$

where

$$q_{mn} = \sum_{i\in I_m}\left((\rho_i/\mu_m)\cdot\sum_{i'\in I_n}\bar{q}_{ii'}\right),$$
$$m, n\in\{2,3,4\},\ i\in\{1,2,\ldots,7\} \tag{18}$$

2.3. FSMC channel model

For each link in the cooperative network, we consider a general discrete time channel model. Take the *S–D* link as an example, it has flat Nakagami-m fading captured by an FSMC channel model [22]. According to the channel model for adaptive modulation and coding, stochastic capacity can be obtained based on their corresponding channel state information (CSI) at the physical layer. The approximation $\mathrm{PER}_k(\gamma)$ is used to calculate the packet error rate (PER) for mode k.

$$\mathrm{PER}_k(\gamma) \approx \begin{cases} 1, & 0<\gamma<\gamma_{pk} \\ a_k\exp(-g_k\gamma), & \gamma>\gamma_{pk} \end{cases} \tag{19}$$

where the parameters $\{\alpha_k, g_k, \gamma_{pk}\}$ are determined by curve fitting to the exact PER of mode k. The average PER for mode k can be written as follows:

$$\overline{\mathrm{PER}} = \frac{1}{P_r(k)}\int_{\gamma_k}^{\gamma_{k+1}} a_k\exp(-g_k\gamma)p_\gamma(\gamma)d\gamma$$
$$= \frac{1}{P_r(k)}\cdot\frac{a_k}{\Gamma(m)}\cdot\left(\frac{m}{\bar{\gamma}}\right)^m\frac{\Gamma(m,b_k\gamma_k)-\Gamma(m,b_k\gamma_{k+1})}{(b_k)^m} \tag{20}$$

where k is the mode index and $\bar{\gamma}$ is the average received SNR, $b_k = m/\bar{\gamma}+g_k(k=1,2,\ldots,K)$. $\Gamma(m,x) = \int_x^\infty t^{m-1}\exp(-t)dt$ is the complementary incomplete Gamma function, and $P_r(k)$ is the probability of channel being in state k, which can be calculated as:

$$P_r(k) = \frac{\Gamma(m, m\gamma_k/\bar{\gamma}) - \Gamma(m, m\gamma_{k+1}/\bar{\gamma})}{\Gamma(m)} \quad (21)$$

3. Queuing model and analysis

We build a 4-dimensional Markov chain model to analyze the queuing process of a packet at S, under the control of the protocols including GBN-ARQ, CoopMAC and PHY. The system can be described as $X(t) = \{x(t), n(t), s(t), c(t)\}$. Here t denotes the time which has a unit ST. $x(t)$ denotes the number of packets in the queue, $n(t)$ is the feedback delay of a packet transmitted in the past and its feedback message ACK/NACK just arrives at t, $s(t)$ denotes if the current ST is a useful slot and $c(t)$ is the channel capacity of the current ST. These symbols have the same meanings as in [6]. Because all elements of $X(t)$ are only related to elements of $X(t-1)$, $X(t)$ is a 4-dimensional Markov process. Let (i, n, j, k) be the generic system state. In order to calculate the steady state probability for the 4-dimensional Markov chain, we need to establish the transition probability matrix P for such a system.

Although the work in this paper shares some common basis with that of [6], the major improvements here are two folds. The first one is that in this paper we analyze a different cause of random feedback delay related to the contention resolution process for peers selecting a common good helper, as shown in Section 2. The second one is that the ARQ protocol itself has some difference: the work in [6] did not care about signal combining at the destination, but now in this paper, we take the benefits of signal combining into consideration.

Because the transition probability matrix P of the system here has similar structure to that in [6], we use similar symbols as [6], and the above mentioned two differences leads to different expressions of blocks $C_{i,j}$ (see Eq. (22) below).

We assume $Q_{n,n'}$ denotes feedback delay transition probability from state n to state n', which can be drawn from Eqs. (17) and (18).

The feedback delay values are changing among 2, 3, 4 STs, as having been discussed in Section 2.1. Therefore, $C_{i,j}$ can be expressed as

$$C_{i,j} = \begin{pmatrix} q_{2,2} \times C_{i,j}^{2,2} & q_{2,3} \times C_{i,j}^{2,3} & q_{2,4} \times C_{i,j}^{2,4} \\ q_{3,2} \times C_{i,j}^{3,2} & q_{3,3} \times C_{i,j}^{3,3} & q_{3,4} \times C_{i,j}^{3,4} \\ q_{4,2} \times C_{i,j}^{4,2} & q_{4,3} \times C_{i,j}^{4,3} & q_{4,4} \times C_{i,j}^{4,4} \end{pmatrix} \quad (22)$$

Similar to [6], the sub-blocks $C_{i,j}^{k,l}$ contains the contribution of the FSMC model for a single Nakagami-m fading channel. For wireless cooperative networks, if the helper adopts decode-and-forward and the destination plays maximum ratio combining, the communication between S and D can be looked upon as an equivalent channel as shown in [5]. So in this work we have incorporated the equivalent channel model of [5] in calculating $C_{i,j}$ according to Eq. (22). The transition probability matrix P describes a GI/M/1 Markov chain, where the solution can be found by the method of matrix geometry proposed by Neuts [20]. The steady-state probability $x = (x_0x_1x_2\ldots)$ can be achieved as follows:

$$xP = x, \quad \sum_{i=0}^{\infty} x_i e = 1 \quad (23)$$

where e is a column vector of all ones with the same dimension as x_i which is $n(K+1)$.

Afterwards, we derive the distribution of the total delay of a packet arriving at the queue of the source node in the system model proposed in the paper. The total delay is the time for all the packets ahead of the target packet and itself successfully leaving the queue of the source and being correctly received by the destination D. Similar to [6], the probability that the total delay is D STs (not including the arrival ST) can therefore be written as follow:

$$P_d(D) = \sum_{h=0}^{DL-1} y_h \Phi_{h+1,D} e_{\sum_{n=2}^{4} n(K+1)} \quad (24)$$

The quantities appeared on the right side of the above equation have similar definitions as in [6] and all of them can be calculated out based on the solution of Eq. (23).

The surplus accumulative probability distribution of the queuing delay at the source can be written as:

$$P_r(\text{delay} > d) = 1 - \sum_{D=1}^{d} P_d(D) \quad (25)$$

Table 1
Transmission modes with convolutionally coded modulation.

	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
Modulation	BPSK	QPSK	QPSK	16-QAM	64-QAM
Coding rate	1/2	1/2	3/4	3/4	3/4
R_k(bits/sym)	0.5	1.0	1.5	3.0	4.5
α_k	274.7229	90.2514	67.6181	53.3987	35.3508
g_k	7.9932	3.4998	1.6883	0.3756	0.0900
γ_{pk}	−1.5331	1.0942	3.9722	10.2488	15.9784

4. Model validation and numerical results

In this section, we present the numerical results based on our expressions derived in Section 3. Owing to its advantages in matrix operations, we write the programs for theoretical calculations on the platform Matlab R2009b. Also, extensive simulations are carried out to verify the accuracy of queuing analysis by measuring the stationary distribution. The simulation program is written in C language and we choose Dev C++ as the compiler. In the simulation, the cooperative system is composed of two source nodes, a relay node and a destination node. The source is set to transmit N_P data packets. N_P is adequately large. 10,000 packets are sent to the destination during each loop. The loop is repeated 100 times, so that a sum of 1,000,000 packets is sent. Packets arrivals follow a Bernoulli process. We use the PER fitting values of α_k and g_k in Table 1 of [23] to obtain the SNR thresholds of the FSMC model such that $\text{PER}_k = P_0$ for all the transmission modes, where P_0 is a certain target packet error rate.

The division of different modes is shown in Table 1 as follows.

The channel is considered using adaptive modulation where $h_k = k$ (i.e., the source transmits k packets/ST in channel state k). Five transmission modes is taken into consideration (i.e., $K = 5$). The ST interval T_s is set to be 1 ms, while SlotTime is 20 μs. $CW_{\min} = 7$, $CW_{\max} = 255$. Arrival rate $\lambda = 0.2$ is set to compare with results of [6], all the channel state transmission error rate $\theta = 0.1$. For each link, Nakagami parameter $m = 1$, Doppler frequency shift $FD = 20$ Hz for the Figs. 5–7 and 9. Simulation process is mainly to keep track of the state of each packet, and record the delay duration. The queuing delay is considered at the source node. The statistics of the delay probabilities distribution of each packet is achieved at last.

The numerical evaluation and analysis of the model reveals the following results. The surplus accumulative delay distributions i.e. $P_r(\text{delay} > d)$ obtained from both the simulation and the framework for GBN-ARQ protocol taking MAC level contention into consideration is shown in Fig. 5. As can be seen, the curve of numerical results fits the one of simulation very closely. In fact, the delay statistics for GBN-ARQ protocol obtained here is suitable for general system model which takes the DCF access mechanism in MAC

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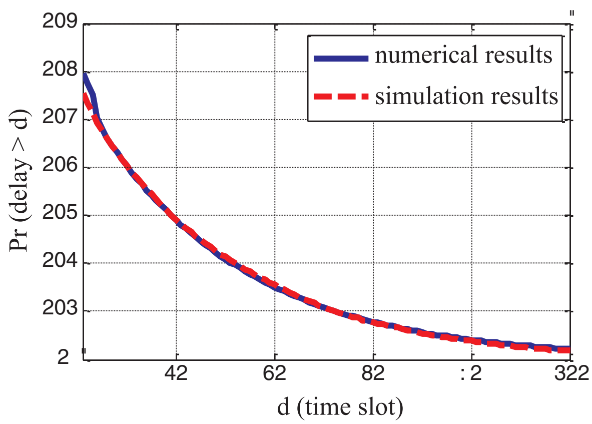

Fig. 5. Comparison of simulation results and numerical results of accumulative delay distributions in DCF cooperative wireless networks with random feedback delay (for arrival rate λ = 0.2, average SNR = 10 dB, P_0 = 0.1, m = 1 and FD = 20 Hz).

layer and the dynamic radio link adaptation in physical layer into account.

Typical variations of numerical results in the surplus accumulative delay distributions are shown in Fig. 6 for both different fixed feedback delay values and randomly changed feedback delay value for DCF in contending the helper. It can be drawn from the plot that the increasing feedback delay value degrades the queuing delay performance. When $0 < d < 65$, it can be seen that the delay distributions of our new model (black line) is close to the case that feedback delay is fixed in 2 STs. When $d > 70$, it is becoming closer to the case fixed in 3 STs till it reaches 90. With d surpassing 90, the delay distribution of the new model is approaching parallel to the cases of fixed feedback delays.

Typical numerical results of the surplus accumulative delay distribution for the cooperative system are compared with that without cooperation, which is shown in Fig. 7. It can be drawn from the plot that the slopes of the curves are substantially alike when $0 < d < 10$ and the delay performance of the cooperative link where CoopSNR (i.e. the SNR after combining) = 20, 18, 16 beats that of the direct link (without cooperation), due to either higher transfer rate or lower packet error rate brought about by the cooperative transmission, which in turn improves the performance of the GBN-ARQ protocol. The curves for CoopSNR = 12, 14, 16 are higher than the curve for the Direct Link when $d > 10$, 17 respectively and their decreasing trend displays more gentle than the case for the Direct Link.

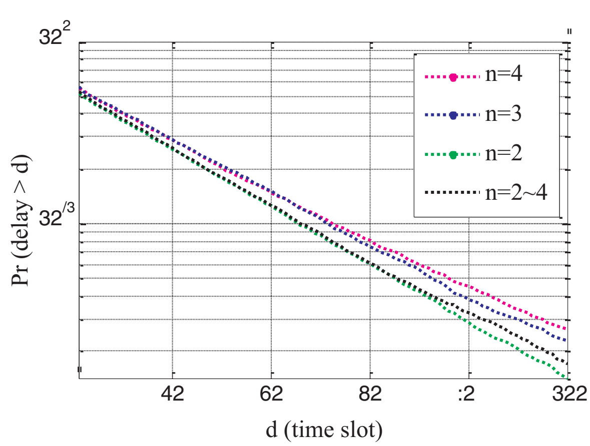

Fig. 6. Numerical results of accumulative delay distributions (for arrival rate λ = 0.2, average SNR = 10 dB, P_0 = 0.1, m = 1 and FD = 20 Hz).

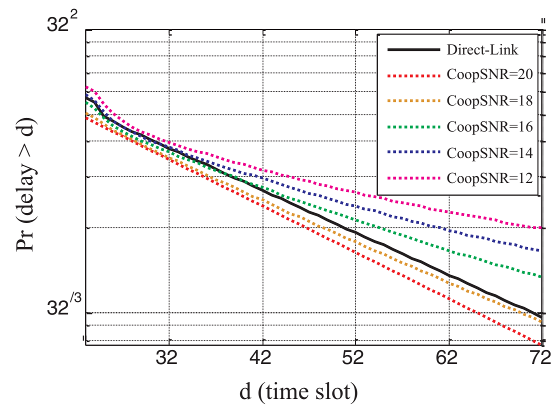

Fig. 7. Numerical results of accumulative delay distributions between Direct-Link and Coop-Link for CoopSNR = {20, 18, 16, 14, 12} (for arrival rate λ = 0.2, average SNR for Direct-Link = 10 dB, n = 2 for Direct-Link and n randomly changes among 2, 3, 4 for Coop-Link, m = 1 and FD = 20 Hz).

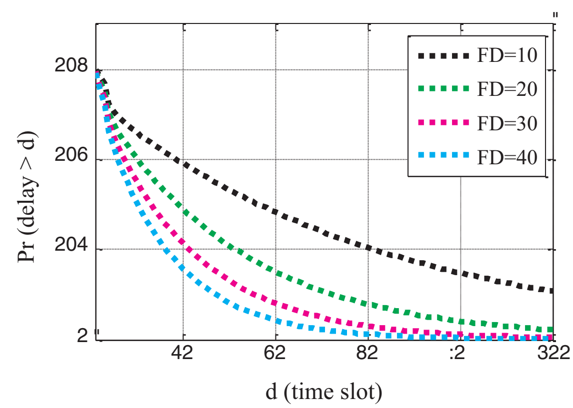

Fig. 8. Accumulative delay distributions for Doppler frequency shift FD = {10, 20, 30, 40} (for arrival rate λ = 0.2, average SNR = 10 dB, P_0 = 0.1, m = 1).

From the figure, it can be concluded that the delay performance of cooperative transmission is not always better than that without cooperation. When the MAC level contention turns serious, the feedback delay of cooperative link increases apparently. If the signal-to-noise ratio is not good enough in cooperative link, the advantage generated by the improved channel quality may fail to compensate for the disadvantage produced by the increasing feedback delay.

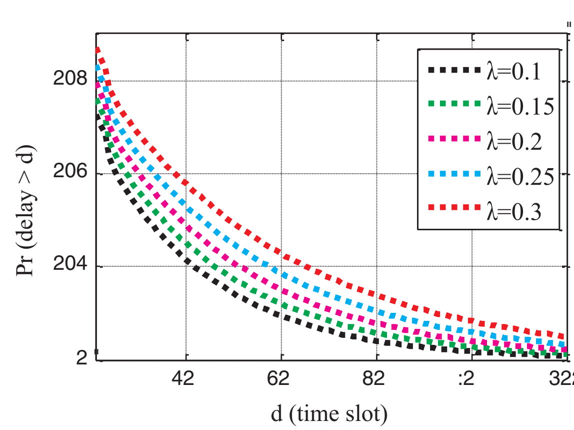

Fig. 9. Accumulative delay distributions for packet arrival probabilities λ = {0.1, 0.15, 0.2, 0.25, 0.3} (for average SNR = 10 dB, P_0 = 0.1, m = 1 and FD = 20 Hz).

The effects on the delay distributions by Doppler frequency shift are illustrated in Fig. 8. It can be seen clearly that the smaller the Doppler frequency shift, the higher the surplus accumulative delay distributions. Fig. 9 plots the surplus accumulative delay distributions for different packet arrival probabilities $\lambda = \{0.1, 0.15, 0.2, 0.25, 0.3\}$. It can be observed that the higher the value of the arrival rate λ, the higher the surplus accumulative delay distributions. This reveals that the total delay has positive correlation with the arrival rate. The model thus enables us to analyze the impact of system parameters on the delay performance. In fact, most delay-sensitive data applications have certain delay limits such that packets received after the delay limit would be useless.

5. Conclusions

An enhanced model which joints cooperative MAC at the MAC sub-layer, GBN-ARQ protocol at the logical link control sub-layer and cooperative diversity at the physical layer is presented in this paper. Queuing model for GBN-ARQ protocol has been developed taking MAC level feature into consideration in cooperative transmission wireless networks. This paper focuses on the queuing delay in the source when the feedback messages reach the source node randomly. A Markov model is put forward to establish the steady state probability of the system. The delay statistics of cooperative wireless networks is obtained by using matrix geometric methods. The queuing delay probability distribution of the model is compared with that feedback delay is fixed and that did not consider the DCF access procedure. The results show that the method to calculate the queuing delay of the cooperative wireless networks is accurate. The queuing delay probability distribution for the cooperative system is compared with that without cooperation. Also, the influences on the delay probability distribution by the packet arrival rate and Doppler frequency shift are analyzed. The method may also be useful to find way to leverage the delay performance and to evaluate the design of cooperative MAC protocol.

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