Cross-layer queuing analysis on multihop relaying networks with adaptive modulation and coding

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Abstract: Multihop relaying is one of the promising techniques in future generation wireless networks. The adaptive modulation and coding (AMC) mechanisms can be applied in order to increase the spectral efficiency of wireless multihop networks. However, most of these mechanisms concentrate on the physical layer without taking the queuing effects at the data link layer into account, whose performances are overestimated. Therefore the cross-layer analytical framework is presented in analysing the quality-of-service (QoS) performances of the decode-and-forward (DF) relaying wireless networks, where the AMC is employed at the physical layer under the conditions of unsaturated traffic and finite-length queue at the data link layer. Considering the characteristics of DF relaying protocol at the physical layer, the authors first propose modelling a two-hop DF relaying wireless channel with AMC as an equivalent Finite State Markov Chain (FSMC) in queuing analysis. Then, the performances in terms of queuing delay, packet loss rate and average throughput are derived. The numerical results show that the proposed analytical method can be efficiently applied for studying the issues including the relay deployment and the cross-layer design in the multihop relaying networks.

1 Introduction

Multihop relaying is one of the promising techniques in future generation wireless networks [1]. It reduces the transmission distance and increases the amount of users under more favourable channel conditions, allowing for better channel quality and higher throughput [2]. Several repetition-based cooperative relaying schemes such as amplify-and-forward (AF), decode-and-forward (DF) have been already developed to fully exploit the spectral diversity for reducing the outage probability [3]. However, these schemes usually decrease the spectral efficiency of the system because of their repetition-based structure.

On the other hand, by adjusting the transmission parameters to the instantaneous link quality, adaptive modulation and coding (AMC) technique aim at improving both spectral efficiency and link reliability. Consequently, the applications of AMC in multihop relaying networks can provide high throughput [4–6]. Most of the literatures only concentrate on the physical layer to maximise the data throughput of the individual link with the constraint of packet error rate (PER), where the queuing effects at the link layer are not taken into account. In fact, because of the dynamic behaviour of packet arrivals, the queues may be empty even though the wireless channel can provide the transmission rate that is required by the system. Besides the transmission error, the overflow due to finite-length buffer causes the packet loss. In addition, the service process of the queue with AMC is not deterministic as that with non-adaptive modulation, especially in the wireless networks with cooperative relaying schemes.

Recently, Liu proposed a cross-layer analytical framework for single-antenna cellular systems, where the AMC scheme with finite-length queue is applied to provide
quality-of-service (QoS) supports [7]. This framework was then applied in multiple-input multiple-output (MIMO) systems to analyse the queuing model with AMC, especially on the delay constrained traffic [8]. Zhou et al. [9] further proposed a cross-layer design of diversity-multiplexing switching algorithm to optimise the QoS performance of MIMO systems. Also, Liu’s framework was extended directly into two-hop wireless relay network without considering the characteristics of relaying behaviour at the physical layer [10]. Furthermore, in order to support more than one class of traffic in a physical frame, a physical and application layer cross-layer adaptation mechanism is proposed in [11]. However, in our knowledge, there is almost no work on queuing performance analysis of multihop DF relaying networks so far, which still remains open.

In this paper, we analyse the queuing behaviour of DF relaying wireless networks with AMC under the conditions of unsaturated traffic and finite-length queue. For the sake of implementation, the common modulation and coding scheme (MCS) is assumed in both hops and its selection can be based on the equivalent signal-to-noise ratio (SNR) in DF relaying networks. Then, a two-hop DF relaying wireless channel can be modelled as an equivalent Finite State Markov Chain (FSMC). In other words, the AMC with common MCS in both hops yields an equivalent varying-rate queue server. Correspondingly, an analytical method is presented to evaluate the QoS performance including packet loss rate, queuing delay and average throughput in a two-hop DF relaying network. Finally, in order to demonstrate its effectiveness, the proposed analytical method is applied in studying the issues including the relay deployment and the cross-layer design.

The rest of this paper is organised as follows. Section 2 gives a brief description of the system model. The performances of wireless networks with DF relaying are analysed in Section 3. In Section 4, the numerical results are presented and discussed. Finally, Section 5 gives the conclusion.

Notations: A circularly symmetric complex Gaussian variance \( x \) with mean \( m \) and covariance \( R \) is denoted \( x \sim \mathcal{CN}(m, R) \). \( \mathbb{E}[x] \) denotes the expectation of the random process \( x \).

2 System model

Fig. 1 illustrates a simple two-hop wireless cooperative communication network, where a relay (R) node cooperates with a source (S) node to transmit information to a destination (D) node. All the channels including source to relay (S-to-R) and relay to the destination (R-to-D) are independent to each other and are assumed to be flat Rayleigh fading for the sake of simplification. There is also independent, zero-mean additive white Gaussian noise with unit variance at each receiver. In our analysis, we normalise the distance between the \( S \) and the \( D \), and assume that \( R \) is located between the \( S \) and the \( D \), on the straight line connecting \( S \) and \( D \). We denote the \( S \)-to-\( R \) distance as \( d \) and the \( R \)-to-\( D \) distance as \( 1-d \), respectively, where \( 0<d<1 \).

One frame for two-hop transmission with the duration of \( T_f \) consists of two successive time slots. In the first time slot, the link layer packets are buffered in a queue at the source node, and merged into physical layer frames for the first hop transmission. Then, the relay node detects and decodes the received signal from the source. The packets which pass cyclic redundancy check will be re-encoded and re-modulated for the second hop transmission in the second time slot. The outputs from \( S \) and from \( R \) are denoted as \( x_1 \) and \( x_2 \), respectively. We assume that \( \mathbb{E}[|x_1|^2]=P_1 \) and \( \mathbb{E}[|x_2|^2]=P_2 \) are the long-term average transmit power from \( S \) and \( R \) respectively. For a fixed pathloss exponent \( \alpha \), the average received power is dependent on the distance between the transmitter and receiver [12]. Usually the pathloss exponent depends on the environmental factors and its value is normally in the range of 2–4. The corresponding signals received by \( R \) and \( D \) are expressed as

\[
\begin{align*}
y_1 &= d^{-\alpha} \beta_1 x_1 + z_1 \\
y_2 &= (1-d)^{-\alpha} \beta_2 x_2 + z_2
\end{align*}
\]

where \( \beta \) denotes the independent complex fading channel gain of the \( i \)th hop transmission, modelled as \( \beta_i \sim \mathcal{CN}(0, \sigma_i^2) \) with \( \sigma_i^2 = \mathbb{E}[|\beta_i|^2], i \in \{1, 2\} \). For slow fading (quasi-static) cases, the fading coefficients are constant within the transmission of the entire hop. Without loss of generality, we assume that the noise term \( z_i \) has equal variance \( \sigma_N^2 \) and is modelled as \( z_i \sim \mathcal{CN}(0, \sigma_N^2) \). The instantaneous SNR at \( R \) and \( D \) can be calculated as \( \gamma^{(1)} = d^{-2\alpha}|\beta_1|^2(P_1/\sigma_N^2) \) and \( \gamma^{(2)} = (1-d)^{-2\alpha}|\beta_2|^2(P_2/\sigma_N^2) \), respectively.

2.1 FSMC channel model per hop

Assume that there are \( L \) MCS modes available for AMC transmission in the system. Then, an FSMC \( S = \{s_1^{(0)}, s_2^{(0)}, \ldots, s_L^{(0)}\}, i \in \{1, 2\}, \) with \( L \) states is used to reflect the fading channel in the \( i \)th hop transmission [13]. We denote the state transition probability from \( s_j \) to \( s_{j'} \) and steady-state probability of state \( s_j \) as \( P_{j_{(i)}}^{(0)} \) and \( \pi_{j_{(i)}}^{(0)} \), respectively. Then, \( \pi_{j_{(i)}}^{(0)} = [\pi_1^{(0)}, \pi_2^{(0)}, \ldots, \pi_L^{(0)}] \) is the...
stationary state distribution vector, and $P^{(i)}$ represents the transition probability matrix with $P^{(i)}_{l,m}$, $l, m \in \{1, 2, \ldots, L\}$ in the $i$th hop transmission. Furthermore, the transitions are assumed to only happen between adjacent states, that is

$$p^{(i)}_{l,m} = 0, \forall |l - m| > 1, \ l, m \in \{1, 2, \ldots, L\} \quad (2)$$

Let $\Gamma = [\Gamma_1, \Gamma_2, \ldots, \Gamma_{L+1}]$ be the region boundary of the received SNR, by which the entire SNR region is partitioned into $L + 1$ parts. For simplicity, the SNR threshold values for MCS selection in AMC are set as the region boundary in this paper. These threshold values are in the ascending order with $\Gamma_1 = 0$ and $\Gamma_{L+1} = \infty$. Since the radio channels of two hops are assumed to be independent and statistically identical, the same set of boundary can be used for both hops so that the index $i$ of the hop is omitted.

The channel is in state $s_i$ if the instantaneous SNR $\gamma^{(i)}$ is between $\Gamma_i$ and $\Gamma_{i+1}$. The adjacent-state transition probability over one frame period $T_i$ can be calculated as

$$p^{(i)}_{l+1} = \frac{\chi(\Gamma_{i+1})T_i}{\pi_i}, \ l = 1, \ldots, L - 1 \quad (3)$$

$$p^{(i)}_{l-1} = \frac{\chi(\Gamma_i)T_i}{\pi_i}, \ l = 2, \ldots, L \quad (4)$$

Here, $\chi(\Gamma_i)$ denotes the level cross rate at an instantaneous SNR in the $i$th hop transmission. Since the wireless channel is assumed to be Rayleigh fading, the received instantaneous SNR $\gamma^{(i)}$ is distributed exponentially with probability density function

$$f(\gamma^{(i)}) = \frac{1}{\overline{\gamma}^{(i)}} \exp\left(-\frac{\gamma^{(i)}}{\overline{\gamma}^{(i)}}\right), \ i \in \{1, 2\} \quad (5)$$

where $\overline{\gamma}^{(i)} = E[\gamma^{(i)}]$ is the average received SNR. Then, $\chi(\Gamma_i)$ can be expressed as

$$\chi(\Gamma_i) = \frac{2\pi T_i}{\overline{\gamma}^{(i)}} \left(1 - \exp\left(-\frac{\Gamma_i}{\overline{\gamma}^{(i)}}\right)\right), \ i \in \{1, 2\} \quad (6)$$

where $f_{\gamma}^{(i)}$ denotes the mobility-induced Doppler spread in the channel of the $i$th hop transmission. Finally, $p^{(i)}_{l,m}$ can be derived from the normalising condition $\sum_{m=1}^{L} p^{(i)}_{l,m} = 1$ as

$$p^{(i)}_{l,m} = \begin{cases} 1 - p^{(i)}_{l+1,m} - p^{(i)}_{l-1,m}, & (l = 2, \ldots, L - 1) \\ 1 - p^{(i)}_{l+1,m}, & (l = 1) \\ 1 - p^{(i)}_{l-1,m}, & (l = L) \end{cases} \quad (7)$$

Meanwhile, the stationary probability $\pi_i^{(i)}$ that the Markov chain is in state $s_i$ can be given by [13]

$$\pi_i^{(i)} = \int_{T_i}^{T_{i+1}} f(\gamma^{(i)}) d\gamma^{(i)} = \exp(\Gamma_i/\overline{\gamma}^{(i)}) - \exp(\Gamma_{i+1}/\overline{\gamma}^{(i)}) \quad (8)$$

### 3 Performance analysis

#### 3.1 Arrival process

Let $A_i$ denote the number of packets arriving from the upper layer at the source in frame $i$. This arrival process $A_i$ is stationary with the mean of $E[A_i] = \lambda T_i$ and independent of the queue state as well as the service process. Usually $A_i$ is assumed to be Poisson distributed with parameter of $\lambda T_i$ for simplicity

$$P(A_i = a) = \frac{(\lambda T_i)^a e^{-\lambda T_i}}{a!}, \ a \in \{0, 1, \ldots, \infty\} \quad (9)$$

The value of the random variable $A_i$ is the non-negative integer, that is $A_i \in A = \{0, 1, \ldots, \infty\}$.

#### 3.2 Queue service process

Considering the characteristics of DF relaying scheme, the transmission over a two-hop DF relaying channel can be regarded as a dynamic server. The multirate transmission is achieved by AMC schemes, where the transmitted data rate can be adjusted depending on the channel conditions of both hops.

##### 3.2.1 Adaptive modulation and coding:

For the relay with simple functions, the common MCS scheme is adopted in different hops with the knowledge of the channel qualities of both hops. In this way, the packets received at the relay can be forwarded immediately with no need of buffering. In DF relaying networks, the equivalent instantaneous SNR of two-hop transmission can be given by [3]

$$\gamma^{DF} = \min\{\gamma^{(1)}, \gamma^{(2)}\} \quad (10)$$

Then, the MCS selection can be made according to this equivalent SNR. The objective of AMC is to maximise the system throughput by adjusting the transmission parameters like modulation order and coding rate according to the available channel state information (CSI), while maintaining the required PER of $P_0$. The $\theta$th MCS mode is chosen when the equivalent SNR of DF relaying channel enters the range as [14]

$$\text{Mode } \theta \text{ is chosen when } \gamma^{DF} \in [\Gamma_{i}, \Gamma_{i+1}) \quad (11)$$

with the corresponding rate of $R_{i}, \ i \in \{1, \ldots, L\}$. When the deep channel fading occurs, that is $\Gamma_1 \leq \gamma^{DF} < \Gamma_2$, no data...
transmission is allowed, which corresponds to the mode 0 with rate $R_1 = 0$ bits/symbol. Assuming that $b$ radio resource units are allocated to one user by the system, the number of packets transmitted per frame is denoted as $c_t = bR_t$. Then, let $C_t$ denote the number of packets transmitted using AMC scheme in frame $t$, which is a random variable with the non-negative integer values taken from the set $C = \{c_1, c_2, \ldots, c_L\}$.

3.2.2 Equivalent FSMC of DF relaying: In DF relaying networks, the AMC with common MCS in both hop yields an equivalent varying-rate queue server. Owing to the Poisson arrivals, this queue server is the one with vacations. Correspondingly, we define a new equivalent FSM $\mathcal{H} = \{h_1, h_2, \ldots, h_L\}$ with $L$ states for DF relaying transmission, which considers the effects of both channel varying character and DF relaying scheme. In this newly defined FSMC, a user is regarded to be in the state $h_i \in \mathcal{H}$ only when the worse link of two hops is in channel state $s_i \in \mathcal{S}$, $1 \leq i \leq L$. The corresponding data rate in state $h_i$ is the same as $s_i$ in the FSMC per hop.

Next, let us discuss the stationary state distribution vector $\tilde{\pi} = [\tilde{\pi}_0, \tilde{\pi}_1, \ldots, \tilde{\pi}_L]$ and the transition probability matrix $P$ of the equivalent FSMC, where $P$ is formed by $P_{l,m}$ with $l, m \in \{1, 2, \ldots, L\}$. Under the assumption that the channels in both hops are independently, the steady-state probability of a user in DF relaying channel can be first computed by

$$
\tilde{\pi}_l = \pi_l^{(1)} \sum_{m=1}^{L} \pi_m^{(2)} + \pi_l^{(2)} \sum_{m=1}^{L} \pi_m^{(1)} + \pi_l^{(1)} \pi_l^{(2)}
$$

(12)

Similar to the single-hop channel, the transitions of the DF relaying channel are assumed to happen only between adjacent states, that is

$$
\tilde{P}_{l,m} = 0, \forall|l-m| > 1, \quad l, m \in \{1, 2, \ldots, L\}
$$

(13)

There are several possibilities that the state of a user may change from $h_l$ to $h_{l+1}$ in the DF relaying channel, that is

- **Case 1:** The first hop is in state $s_l$ while the second hop is in state $s_m$, $m \in \{l+1, \ldots, L\}$ at the current time. Then, at the next time, the former is in state $s_{l+1}$ while the latter is in state $s_m$, $m \in \{l+1, \ldots, L\}$.

- **Case 2:** The second hop is in state $s_l$, while the first hop is in state $s_{m}$, $m \in \{l+1, \ldots, L\}$ at the current time. Then, at the next time, the former is in state $s_{l+1}$ while the latter is in state $s_m$, $m \in \{l+1, \ldots, L\}$.

- **Case 3:** Both the first hop and the second hop are in state $s_l$ at the current time. Then, at the next time, both of them are in state $s_{l+1}$.

Similar cases will happen when the state of a user switches from $h_l$ to $h_{l-1}$. Therefore the adjacent-state transition probability in the DF relaying channel is calculated by

$$
\tilde{P}_{l,l+1} = \frac{1}{\tilde{\pi}_l} \left( \pi_l^{(1)} \tilde{\pi}_l^{(2)} \sum_{m=1}^{L} \pi_m^{(2)} \sum_{l=1}^{L} \pi_m^{(2)} \tilde{\pi}_m^{(2)} + \pi_l^{(2)} \tilde{\pi}_l^{(1)} \sum_{m=1}^{L} \pi_m^{(1)} \sum_{l=1}^{L} \pi_m^{(1)} \tilde{\pi}_m^{(1)} + \pi_l^{(1)} \pi_l^{(2)} \right)
$$

$$
+ \pi_l^{(2)} \tilde{\pi}_l^{(2)} \sum_{m=1}^{L} \pi_m^{(1)} \sum_{l=1}^{L} \pi_m^{(1)} \tilde{\pi}_m^{(1)} + \pi_l^{(1)} \pi_l^{(2)} \right)
$$

(14)

Finally, $\tilde{P}_{l,m}$ can be derived from the normalising condition $\sum_{m=1}^{L} \tilde{P}_{l,m} = 1$ as

$$
\tilde{P}_{l,m} = \begin{cases} 
1 - \tilde{P}_{l,l+1} - \tilde{P}_{l,l-1}, & (l = 2, \ldots, L - 1) \\
1 - \tilde{P}_{l,l+1}, & (l = 1) \\
1 - \tilde{P}_{l,l-1}, & (l = L)
\end{cases}
$$

(15)

3.3 Queue state transition

According to the analytical framework in [7], not only the queue service process but also the queue state have to be considered to analyse the system performances. The queue state $Q_t$ is described as the number of packets in the queue at the end of frame $t$, or equivalently, at the beginning of frame $t+1$. Its value region is denoted as $Q_t \in \mathcal{Q} = \{0, 1, \ldots, K\}$ with the queue buffer length of $K$.

Depending on the current channel state, the transmitter at the source moves at most $C_t$ packets out of the queue to the physical layer at the beginning of frame $t$. Thus, the number of free slots in the queue at the beginning of frame $t$ is

$$
F_t = K - \max[0, Q_{t-1} - C_t]
$$

(16)

Then, the $A_t$ arriving packets are tried to be placed in the queue throughout frame $t$. If $A_t > F_t$, only $F_t$ packets can be put into the queue and $A_t - F_t$ packets are dropped due to finite-length queuing. Otherwise, all $A_t$ packets are accepted by the queue. Therefore the queue transition can be given by

$$
Q_t = \min[K, \max[0, Q_{t-1} - C_t] + A_t]
$$

(17)

Next, an joint queuing and serve-rate FSMC with a state pair $(Q_{t-1}, C_t)$ is constructed in order to analyse the system behaviour. Its state transition matrix $P$ can be obtained with the entry $P_{(u,c),(v,m)}$ defined as the transition probability from $(Q_{t-1} = u, C_t = c)$ to $(Q_t = v, C_{t+1} = m)$.  

Then, the average packet drop rate

\[ \hat{P}_{(u,v)} = P(Q_t = v, C_{t+1} = m|Q_{t-1} = u, C_t = c) \]

\[ = P(C_{t+1} = m|C_t = c)P(Q_t = v|Q_{t-1} = u, C_t = c) \]

(18)

where \( P(C_{t+1} = m|C_t = c) \) can be found from the entries of \( \hat{P} \), and \( P(Q_t = v|Q_{t-1} = u, C_t = c) \) is calculated as

\[ P(Q_t = v|Q_{t-1} = u, C_t = c) = \begin{cases} \frac{P(A_t = v - \max(0, u - c))}{1 - \sum_{0 \leq \nu < K} P(Q_t = \nu|Q_{t-1} = u, C_t = c)}, & \text{if } 0 \leq v < K \\ \frac{C_t}{uP(Q_t = \nu|Q_{t-1} = u, C_t = c)}, & \text{if } v = K \end{cases} \]

(19)

The stationary distribution vector \( \hat{\pi} \) of this FSMC \((Q_{t-1}, C_t)\) can be computed by

\[ \hat{\pi} = \hat{\alpha} \sum_{\nu \in \mathbb{N}} \hat{\pi}_{(u, \nu)} = 1 \]

(20)

where \( \hat{\pi}_{(u, \nu)} = \lim_{t \to \infty} P(Q_{t-1} = u, C_t = \nu) \) is the entry of \( \hat{\pi} \), which is proved to exist and be unique in [7].

### 3.4 System performance

Corresponding to the number of free slots in frame \( t \) in (16), the number of packets dropped at frame \( t \) can be easily given by

\[ D_t = \max\{0, A_t - K + \max\{0, Q_{t-1} - C_t\}\} \]

(21)

Since the limit distribution of the stationary \( A_t \) exists when \( t \to \infty \), we define \( A = \lim_{t \to \infty} A_t \) and obtain

\[ P(A = a) = P(A_t = a) \]

(22)

Then, with the similar method in [7], the average number of packets dropped per frame can be calculated by

\[ \bar{D} = E[\lim_{T \to \infty} D_t] \]

\[ = \sum_{a \in \mathbb{N}, a \leq Q \leq C} \max\{0, a - K + \max\{0, u - c\}\} P(A_t = a)P(Q_t = u, C_t = c) \]

(23)

Next, the average packet drop rate \( P_d \) can be computed by

\[ P_d = \lim_{T \to \infty} \frac{\sum_{t=1}^{T} D_t}{\sum_{t=1}^{T} A_t} = \frac{\bar{D}}{\bar{A}} \]

(24)

So, the packet loss rate and average throughput of DF relaying systems can be obtained as follows, respectively

\[ \xi = 1 - (1 - P_d)(1 - P_o) \]

(25)

\[ \eta = (\lambda T_f)(1 - \xi) \]

(26)

Also, the average queuing delay is computed according to Little’s law [15]

\[ \tau = \frac{\bar{Q}}{(1 - P_d)\lambda T_f} \]

(27)

where the average queue length \( \bar{Q} = E[\lim_{t \to \infty} Q_t] \) is given by

\[ \bar{Q} = \sum_{u \in \mathbb{Q}, c \in \mathbb{C}} uP(Q_t = u, C_t = c) \]

(28)

### 4 Numerical results and analysis

In this section, the performances of two-hop DF relaying wireless networks are evaluated by the numerical analysis. We also study the performances of the direct transmission (DT) between the source and destination as the reference. Most of the common parameters are summarised in Table 1. Define the long-term transmit power difference between from \( R \) and from \( S \) as \( \Delta P = 10 \log P_t/P_o \). The related applications of the proposed analytical method are given to demonstrate its effectiveness in DF relaying wireless networks.

All of the channels are modelled as five-state independent and identically distributed (i.i.d) FSMC with the same Doppler frequency. Correspondingly, the MCS modes for transmission are pre-defined in Table 2, referred as Mode 1–Mode 5. Although there is no exact closed-form PER for coded modulations, we can use the equivalent closed-form PER expression for MCS selection. Therefore for the sake of simplification, the PER performance of each MCS can be approximatively expressed as [16]

\[ \text{PER}_i(\gamma) \approx \begin{cases} 1, & \text{if } 0 \leq \gamma < \eta_i \\ a_i \exp(-g_i \gamma), & \text{if } \gamma \geq \eta_i \end{cases} \]

(29)

where \( \gamma \) is the received SNR and the coefficients of \( a_i, g_i, \eta_i \) are mode dependent as shown in Table 2. These coefficients are generated by fitting and comparing curves to the simulated PER according to the Monte-Carlo simulations with parameters given by 3G long-term evolution (LTE) specification [17]. For various MCS modes on the assumption of target PER \( 10^{-2} \), the SNR boundaries can be found in Table 2.

### 4.1 Relay deployment

In Fig. 2, we study the variation of the average throughput with respect to relay location characterised by \( d_r \), where different \( \Delta P \) is assumed. For simplicity, the average received SNR with DT is set to be 8 dB. When the relay is
close to the middle between the source and destination, the throughput is increased because of the improvement of the equivalent SNR with DF relaying. We can find that the optimal location of the relay is the point where the average SNR of the first hop equals that of the second hop. For example, in the case of $\Delta P = 0 \text{ dB}$, the relay is optimally deployed at $d = 0.5$ with $\gamma^{(1)} = \gamma^{(2)} = 20 \text{ dB}$. Moreover, only when the location of relay is within the given range, for example, $d \in [0.2, 0.8]$ in case of $\Delta P = 0 \text{ dB}$, the throughput performance of two-hop transmission with DF relaying is better than that of direction transmission. Furthermore, with less transmit power from $R$, that is $\Delta P > 0$, the throughput becomes smaller because of the lower received SNR at the destination. Correspondingly, the queuing delay performances with the different location of relay and $\Delta P$ are also given in Fig. 3, where the similar conclusion can be drawn.

Then, we compare the analytical and simulation results of the throughput performances with the different packet arrival rate in Fig. 4, where the relay is deployed at the optimal location. With the increase of the packet arrival rate, the throughput gain with DF relaying transmission becomes larger compared with the DT. However, it is floor in the region of the large packet arrival rate because the data rate that provided by the networks is limited by the wireless channel. It is noted that the analytical results are in line with those simulation ones, which demonstrates the effectiveness of our analytical method.

4.2 Cross-layer design

The proposed framework can also be used in various cross-layer optimisation schemes in DF relaying cooperative networks, example to find the optimal $P_0$ on the physical layer to minimise the packet loss rate on the data link layer. For simplicity, the average transmit power from $S$ is assumed to be equal to that from $R$, for example $P_1 = P_2$. So the corresponding optimal location of the relay is in the middle of the source and destination. Then, Figs. 6 and 7 show the packet loss rate performances with the different queue length

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>frame length ($T_f$)</td>
<td>2 ms</td>
</tr>
<tr>
<td>doppler frequency ($f_D$)</td>
<td>20 Hz</td>
</tr>
<tr>
<td>resource unit per frame ($b$)</td>
<td>1</td>
</tr>
<tr>
<td>queue buffer length ($K$)</td>
<td>50</td>
</tr>
<tr>
<td>packet arrival rate ($\lambda$)</td>
<td>2</td>
</tr>
<tr>
<td>pathloss exponent ($\alpha$)</td>
<td>4</td>
</tr>
</tbody>
</table>

**Table 2** Approximate coefficients of MCS modes and SNR boundary

<table>
<thead>
<tr>
<th>Mode $l$</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>modulation</td>
<td>–</td>
<td>QPSK</td>
<td>16QAM</td>
<td>16QAM</td>
<td>64QAM</td>
</tr>
<tr>
<td>coding Rate</td>
<td>–</td>
<td>1/2</td>
<td>1/2</td>
<td>3/4</td>
<td>2/3</td>
</tr>
<tr>
<td>$R_l$</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>$a_l$</td>
<td>–</td>
<td>3709.7</td>
<td>6724.9</td>
<td>11 875</td>
<td>5406.3</td>
</tr>
<tr>
<td>$g_l$</td>
<td>–</td>
<td>5.8513</td>
<td>1.9604</td>
<td>1.1554</td>
<td>0.3253</td>
</tr>
<tr>
<td>$\eta_l$(dB)</td>
<td>–</td>
<td>1.4046</td>
<td>4.4958</td>
<td>8.1202</td>
<td>26.4188</td>
</tr>
<tr>
<td>$\Gamma_l$(dB)</td>
<td>0</td>
<td>2.17</td>
<td>6.82</td>
<td>16.94</td>
<td>40.7</td>
</tr>
</tbody>
</table>

From the view of implementation, less transmit power from $R$ means less cost. So, Fig. 5 compares the average throughput performances between two-hop DF relaying and direction transmission, where the average transmit power from $R$ is changed. It is clear that the throughput gain of two-hop DF relaying transmission become less with the increase of $\Delta P$. When the power difference $\Delta P$ is more than 13 dB, the throughput with two-hop DF relaying transmission is even worse than that with direction transmission. Therefore to determine the transmit power from $R$ is the trade-off between the performance and the implementation cost.

**Table 1** Parameters assumption in a DF relaying networks

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$frame length (T_f)$</td>
<td>2 ms</td>
</tr>
<tr>
<td>$doppler frequency (f_D)$</td>
<td>20 Hz</td>
</tr>
<tr>
<td>$resource unit per frame (b)$</td>
<td>1</td>
</tr>
<tr>
<td>$queue buffer length (K)$</td>
<td>50</td>
</tr>
<tr>
<td>$packet arrival rate (\lambda)$</td>
<td>2</td>
</tr>
<tr>
<td>$pathloss exponent (\alpha)$</td>
<td>4</td>
</tr>
</tbody>
</table>
Figure 3 Delay performances with the different relay location

Figure 4 Throughput performances with the different $\lambda$

Figure 5 Throughput performances with the different $\Delta P$

Figure 6 Packet loss rate performances with the different queuing length

Figure 7 Packet loss rate performances with the different maximum Doppler frequency

$K$ and Doppler frequency $f_D$, where $P_0$ varies from $10^{-4}$ to $10^{-1}$. As shown in (25), the packet loss rate is dependent on the value of $P_0$ directly, that is, the larger $P_0$ leads to the larger packet loss rate if $P_d$ is unchanged. However, with the increase of $P_0$, the mode switching levels of AMC scheme is changed and consequently affects the probability of rate selection. As a result, $P_d$ is affected by $P_0$ indirectly and becomes less, which may decrease the PER. Therefore we observe that the packet loss rate first decreases and then becomes larger with the increase of $P_0$. Then, the optimal $P_0$ can be obtained, that is, the one with the minimum packet loss rate. Furthermore, the performances of packet loss rate can be improved with larger queue length $K$ and Doppler frequency $f_D$.

5 Conclusion

In this paper, we presented a cross-layer analytical framework in studying the queuing behaviour of DF relaying wireless networks with AMC and finite-length buffer. The service process of two-hop DF relaying schemes can be modelled as an equivalent FSMC when taking into account the characters of DF relaying protocol. The QoS performances of DF relaying wireless networks are evaluated in terms of queuing delay, packet loss rate and average throughput.
By using the proposed analytical method, we observe that the two-hop DF relaying transmission do not always outperform the direct transmission, which depends on the location of the relay (R) node. Moreover, the performance gain is related to the transmission power from R. On the other hand, the cross-layer design is also studied by using the proposed analytical framework. Numerical results show that the packet loss rate first decreases and then becomes larger with the increase of PER, where the optimal PER can be obtained, that is, the one with the lowest packet loss rate.

In the next steps, we will extend this work by considering the following issues: the impacts of multiuser scheduling, the relay selection and retransmission schemes in DF relaying wireless networks.

6 Acknowledgments

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7 References


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