Energy-Efficient Scheduling for Buffer-Aided Relaying with Opportunistic Spectral Access

(Invited Paper)

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***Abstract*—In this paper, we propose a cross-layer design framework for transmitting Markov modulated Poisson process (MMPP) traffic over cognitive cooperative networks, which considers the energy efficient transmissions for different delay-aware packets. The adaptive modulation and coding (AMC) is used in the cooperative transmission system. The queueing process is considered in the buffer aided relay and source. We obtain an optimum strategy of power and time allocation to maximize the energy efficiency of the relay assisted cooperative system. With the stationary distribution of the system state, we derive the closed-form expression of the delay and the energy efficient transmission policy with AMC. Then, we derive the energy efficient strategy for packet transmission with different delay requirements, which can make the cooperative transmissions energy efficient.**

I. Introduction

DUE to the rapid growth of mobile data traffic over the last decades, cognitive radio has been proposed as a revolutionary technology to solve the conflict between spectrum scarcity and the spectrum under-utilization [1]. Under the condition of opportunistic spectrum access, the secondary users could utilize the unoccupied free bands in a discontinuous manner to perform their own transmission, because the primary user share the licensed bands with the secondary users [2]. Thus far, in the multiuser environment, each secondary user has a probability to be chosen by the base station to transmit data over the free bands. Meanwhile, energy efficiency, which is measured by bits-per-joule, has emerged as a key figure of merit and become the most widely adopted design metric for green wireless communication systems [3], [4]. In this case, how to schedule the transmission to ensure the energy efficiency needs to be considered. Furthermore, to enable multimedia applications with different delay requirements over the cognitive cooperative network has become a critical issue and received much attention.

Many existing works on cooperative communications were based on throughput optimization under delay constraint [5], [6]. However, all these works do not consider the energy efficient communication, which have attracted much research attention in wireless networks recently. In [7], [8], delay constrained energy-efficient problem in cooperative wireless networks is studied. However, the adaptive modulation and coding (AMC) is not considered. In [9], [10], the authors have studied the AMC scheduling for the cooperative wireless system. However, the scheduling strategy for the energy efficiency is not considered. The scheduling strategy with direct transmission and relay assisted transmission for cognitive radio network has been studied in [1], where the traffic delay is not considered. On the other hand, considering the deterministic delay performance of the cooperative communication, the multipath fading and channel noise disturbance make it impracticable to be analysed. Therefore, in the cooperative network with opportunistic spectrum access, it is practical to provide statistical delay guarantee, which is an ultimate goal.

In this work, we consider the energy efficient design approach in the cooperative network with opportunistic spectrum access, which aims at taking the physical layer transmission and delay-aware service into account, the influence of spectrum utilization probability also can be obtained. This approach enables the energy efficient scheduling strategy while achieves the QoS requirements. In this research direction, there are some works on cross-layer designs considered in [1], [9], [11], [12], where a similar system model is considered.

Our contribution can be summarized as follows: We obtain the closed-form delay for the cooperative transmission system, which considers both the transmission delay and the queueing delay in the relay-buffer and the source-buffer. Then we obtain the closed-form expression for the system throughput by taking into account the packet drop caused by both the channel transmission error and buffer overflow. Correspondingly, the average energy consumption of the cooperative system is also obtained. Considering the opportunistic spectrum access, we reveal the intrinsic relationship between the energy efficient scheduling strategy and different delay requirements. At last, we obtain the energy efficient transmission policies for the source to the relay transmission as well as the relay to the destination transmission.

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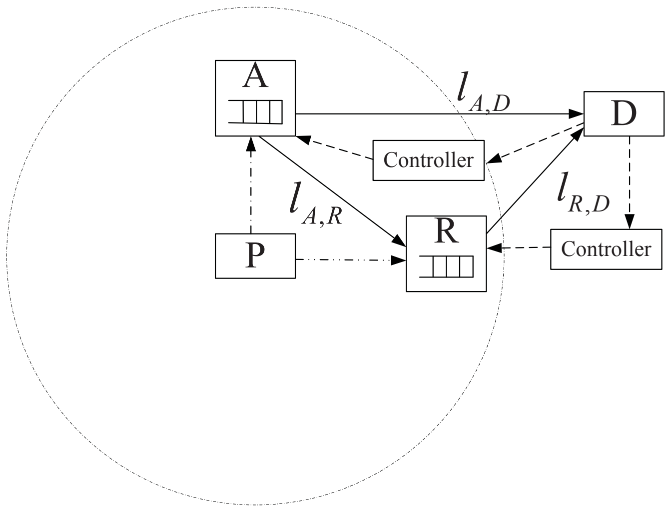

Fig. 1. System model.

II. System Model and Problem Statement

A. Network Model

As shown in Fig. 1, we consider a cooperative secondary system which consists of node A, node R, and node D, shares the same wireless spectrum with the legal primary system (PS) node P. Node A has traffics to transmit to node D. Packets can be transmitted via the direct path composed of link $l_{A,D}$, or via the relay path composed of links $l_{A,R}$ and $l_{R,D}$ as shown in Fig. 1. On each link of $l_{A,D}$, $l_{A,R}$, or $l_{R,D}$, the secondary system will terminate the transmission if one of the following situation occurs: 1) the PS has transmissions, 2) a deep fading occurs such that the packet error rate (PER) exceeds a maximum tolerable level.

B. Traffic and Queueing Models

We assume that the incoming traffic of source A is random and can be modeled as a Markov modulated Poisson process (MMPP), The MMPP model can represent multimedia traffic [13]. The incoming traffic from MMPP is Poisson distributed and the transitions between the states are governed by an Markov chain.

Denote the set of states of the arriving traffic as $\mathbb{F} = \{f_1, f_2, \cdots, f_K\}$ and denote the probability of transition from state f_i to state f_j as P_{f_i,f_j}. Each state follows Poisson distribution with average arrival rate λ_i. The stationary distribution of the incoming traffic is $\pi^f = [\pi_1^f, \pi_2^f, \cdots, \pi_K^f]$, and it satisfies $\pi^f = \pi^f \mathbf{P}^f$. By the stationary distribution π^f, we can get the average arrival rate as $\bar{\lambda} = \sum_{i=1}^{K} \pi_i^f \lambda_i$.

It is assumed that for the source node A, packet streams with the packet size of L bits arrive in a first-in-first-out (FIFO) buffer at the average arrival rate $\bar{\lambda}$. The buffers of the source and the relay have finite capacity in each of which, denoted as M. Let χ_n be the service rate at the physical layer corresponding to channel state n. Thus, the service state χ_n is in the set of $\Psi = \{\chi_1, \cdots, \chi_N\}$.

C. Channel Model

All inter-node wireless channels are assumed to have Nakagami-m fading with the same fading parameter m, and are block fading with additive white Gaussian noise (AWGN) by zero mean and variance σ^2.

For transmit power constant at $\bar{e}$, the channel quality can be captured by the received signal to noise ratio (SNR) γ. The received SNR γ per frame follows a Gamma distribution with probability density function (PDF):

$$f_{\bar{\gamma}}(\gamma) = \frac{m^m \gamma^{m-1}}{\bar{\gamma}^m \Gamma(m)} \exp\left(-\frac{m\gamma}{\bar{\gamma}}\right), \tag{1}$$

where $\bar{\gamma} \triangleq E\{\gamma\}$ is the average received SNR, and $\Gamma(m) \triangleq \int_0^\infty t^{m-1} e^{-t} dt$ is the Gamma function. Assume that all inter-node channels are $i.i.d$ with the same average SNR $\bar{\gamma}$, and the average SNR of the direct link $l_{A,D}$, denoted by $\bar{\gamma}_D$, is 10 dB lower than $\bar{\gamma}$.

We consider AMC for transmission at each inter-node link, let N denote the total available number of AMC transmission modes. The entire SNR range is divided into $N+1$ nonoverlapping consecutive intervals, and the channel is said to be in state n when $\gamma \in [\gamma_n, \gamma_{n+1})$. With (1), the probability that the channel is in state n is given by

$$P_r(n) = \int_{\gamma_n}^{\gamma_{n+1}} f_{\bar{\gamma}}(\gamma) d\gamma. \tag{2}$$

Let the transmission rate corresponding to the channel state n denote as b_n bits per channel use.

D. Medium Access of the System

In general, the spectrum occupancy of the PS and other SSs can be modeled as a continuous-time Markov chain with available and unavailable states [14], [15]. The channel holding times of the PS and other SSs are independent and exponentially distributed with aggregated parameter $q_{i,j}^{-1}$ for the available state and $u_{i,j}^{-1}$ for the unavailable state on link $l_{i,j}$ $(i, j \in \{A, R, D\})$. Under this model, the stationary distribution of the available and unavailable states are respectively given by [14] as

$$a_{i,j}^1 = \frac{q_{i,j}}{q_{i,j} + u_{i,j}}, \tag{3}$$

$$a_{i,j}^0 = \frac{u_{i,j}}{q_{i,j} + u_{i,j}}. \tag{4}$$

E. Problem Statement

Let $\mathcal{P}_{(T)}$ denote the total power consumption in the secondary cooperative network. The resulting system throughput can be denoted as $\mathcal{R}$. We define the energy efficiency as the ratio of average throughput to its power consumption, i.e.,

$$f_{ee} \triangleq \frac{\mathcal{R}}{\mathcal{P}_{(T)}} \text{packets/joule}, \tag{5}$$

which measures the number of reliable packets that are transmitted per joule of energy consumed.

In this paper, we are interested in in getting the rate adaption policies maximizing the energy efficiency by taking into account the maximum tolerable packet delay $\mathcal{D}_0$. In particular, the rate adaption policy μ represents the probability distribution of transmission rate b_n, $n = 1, \cdots, N$. Mathematically, the problem is given by

$$\max_{\{P_r(n)\}} \left\{ f_{ee} | \mathcal{D}_{(T)} \leq \mathcal{D}_0, \right\}, \tag{6}$$

Based on (2), the problem is equivalent to $\max_{\bar{\gamma}} \left\{ f_{ee} | \mathcal{D}_{(T)} \leq \mathcal{D}_0 \right\}$.

III. Energy Efficient Scheduling

We denote the total time duration of each transmission period as $T \triangleq T_1 + T_2$ and denote the ratio of the time allocation in the phase of source to relay over the whole period as $\alpha \triangleq T_1/T \in (0, 1)$, where T_1 and T_2 are the transmission time duration from source to relay and from relay to the destination respectively.

A. Throughput Analysis

1) Service Rate: The source node selects transmission modulation b_n, which is also adopted by the relay node. Intuitively, due to the long distance between transmitter and receiver or limited power at the transmitter, the packets transmission is assisted by a relay. At the destination, the receiver attempts to decode frames from the source or the relay. Regarding the successfully receiving packets, an ACK packet will be transmitted to notify the source node at the end of the time slot. Once the source node receives the ACK packet, the corresponding packet is removed from the source buffer.

Now, with the packet error rate PER_n at channel state n, we can derive the average packet error rate of the direct transmission link as

$$P_{LD} = \frac{\sum_{n=1}^{N} \frac{R_s b_n^{l_{A,D}}}{L} P_r(n) PER_n}{\sum_{n=1}^{N} \frac{R_s b_n^{l_{A,D}}}{L} P_r(n)},$$

where R_s is the symbol rate. Similarly, the average packet error rate of the other internode link can be derived as

$$P_L = \frac{\sum_{n=1}^{N} \frac{R_s b_n^{l_{A,R}}}{L} P_r(n) PER_n}{\sum_{n=1}^{N} \frac{R_s b_n^{l_{A,R}}}{L} P_r(n)},$$

Note, the two metrics are defined by the ratio of the average number of packets cannot be successfully transmitted over the total average number of transmitted packets, and the packet error rate PER_n is denoted as [9, Eq. (5)]

$$PER_n = \begin{cases} \alpha_n \exp(-g_n \gamma), & \gamma \geq \gamma_{pn} \\ 1, & \gamma < \gamma_{pn} \end{cases} \tag{7}$$

and α_n, g_n and γ_{pn} are mode dependent parameters. Considering the single packet transmission with two phases, the probability that the destination node and the relay node fail to decode the source packet in the first phase of a time slot is given by $P_1 = P_{LD} \cdot P_L$. On the other hand, if we assume that the relay node successfully received the packet in the first phase, but the direct source to destination transmission failed in the first phase, then the packet cannot be successfully received at the destination with probability $P_2 = P_{LD}(1 - P_L)P_L$. Thus, the overall probability that a single packet cannot be successfully transmitted to the destination over the cooperative wireless communication link is given by $P_0 = P_1 + P_2 = P_{LD} \cdot P_L + P_{LD}(1 - P_L)P_L$.

Based on the maximum retransmission times N_r^{max}, we can derive the packet's service rate χ_n at channel state n for the source-to-relay transmission as

$$\chi_n = \frac{\alpha(1 - P_0)}{\tau_n} \left[1 - P_0^{N_r^{\max}} \left(1 + N_r^{\max}(1 - P_0)\right) \right]^{-1},$$

where τ_n represents the packet transmission time when the channel is in state n, shown in [16].

At the same time, the packet's service rate $\chi_n^{'}$ at channel state n for the relay-to-destination transmission can be derived as

$$\chi_n^{'} = \frac{(1 - \alpha)(1 - P_L)}{\tau_n^{'}} \left[1 - P_L^{N_r^{\max}} \left(1 + N_r^{\max}(1 - P_L)\right) \right]^{-1},$$

where $\tau_n^{'} = \frac{L}{T_u b_n^{l_{R,D}} R_s a_{R,D}^1}$ represents the relay-to-destination packet transmission time. Then we can get the set of service rate as $\Psi^{'} = \left\{ \chi_1^{'}, \cdots, \chi_N^{'} \right\}$.

2) Packet Dropping Rate: Due to the burst service, the packet can be dropped from the buffer. Now, the packet dropping rate at the source node A and the relay node R can be written as P_d^A and P_d^R, respectively. Intuitively, when the number of packet arrivals is larger than the remaining space of the buffer, some packets will be dropped. At time t, assumed that the current service rate is $\chi_t^{'}$ at relay node R, and the service rate is $\chi_{t-1}^{'}$ at previous time. Then, the remaining space of node R can be obtained as $r_t^R = M - (\chi_{t-1}^{'} - \chi_t^{'})$. As a result, the buffer for the relay node can accommodate r_t^R arriving packets in the current time slot. Now, under the condition that the number of arriving packets a_t^R for relay node is larger than r_t^R, there will be $a_t^R - r_t^R$ packets to be dropped.

Theorem 1. *Under the condition that $\bar{\chi}_n > M - (S_{t-1}^R - \chi_t^{'})$, the packet dropping rate at relay node R is $P_d^R = \frac{E\{D^R\}}{\bar{\chi}}$, where*

$$\begin{aligned} E\left\{\Delta^R\right\} &= \sum_{s^{'} \in \mathbb{S}, \chi^{'} \in \Psi^{'}} DP(\bar{\chi}_n | S_{t-1}^R = s^{'}, \chi_t^{'} = \chi^{'}) \\ &= \sum_{s^{'} \in \mathbb{S}, \chi^{'} \in \Psi^{'}} \left[(\bar{\chi}_n - (M - (S_{t-1}^R - \chi_t^{'}))) \times \pi_{s^{'}, \chi^{'}}^{'} \right] \end{aligned}$$

is the average number of dropped packets at node R and $\pi_{s^{'}, \chi^{'}}$ is the stationary distribution of the buffer state and service state for the relay to the destination transmission system.

Proof: We only need to prove the existence of the stationary distribution for the relay system, the proof is omitted due to limited space. ■

With P_d^A and P_d^R available, we can get the average traffic rate and the system throughput. By consider the influences of both the source-queueing and the relay-queueing, we will analyse the packet delay in the next subsection.

$$\tau_n = \tau_n^{l_{A,D}}(1-P_{LD}) + \tau_n^{l_{A,R},l_{R,D}} P_{LD} = \frac{L}{T_u b_n^{l_{A,D}} R_s a_{A,D}^1}(1-P_{LD}) + P_{LD}\left(\frac{L}{T_u b_n^{l_{A,R}} R_s a_{A,R}^1} + \frac{L}{T_u b_n^{l_{R,D}} R_s a_{R,D}^1}\right) \quad (8)$$

3) Network Throughput: To analyze the performance of the network throughput, we need to consider how the packets are successfully transmitted to the destination from the cooperative network. During the packet transmission, the packet dropping rate from the source and relay queueing and packet violation from the channel with $N_r^{\max}$ retransmissions are influencing the successfully transmission. This means that the system average throughput is related to not only the packet dropping rate P_d^A and P_d^R, but also the average overall packet error rate P_0. Then, for an average packet arrival rate of $\bar{\lambda}$, we can obtain the system average throughput $\mathcal{R}$ as

$$\mathcal{R} = \bar{\lambda}(1-P_d^A)(1-P_d^R)(1-P_0^{N_r^{\max}}). \quad (9)$$

B. Delay Analysis

We can get the average queue length of source node A for channel state n as $\bar{Q}_{(q,A)}^n = \sum_{s\in\mathbb{S}}\sum_{f\in\mathbb{F},\chi=\chi_n}\pi_{(s,f,\chi)}\cdot s$. At the same time, based on the stationary distribution $\pi_{(s',\chi')}$, we can get the average queue length of relay node R for channel state n as $\bar{Q}_{(q,R)}^n = \sum_{s'\in\mathbb{S},\chi'=\chi_n'}\pi_{(s',\chi')}\cdot s'$.

With the M/G/1 queue model, we know that the average delay of a packet consists of queueing time and service time. For the purpose of analyzing queueing time, we adopt the Little's formula in [17]. Then, we can obtain the queuing delay as $\bar{D}_q = \frac{\bar{Q}_q}{r}$. Then, we can get the average packet delay $\bar{\mathcal{D}}_n$ for channel state n given by (10), where $\bar{c} = \sum_{n=1}^{N} P_r(n)\chi_n'$. Thus, we can obtain the average packet delay over the relay-assisted transmission system as

$$\mathcal{D}_{(T)} = \sum_{n=1}^{N} P_r(n)\bar{\mathcal{D}}_n. \quad (11)$$

Substituting (10) into (11), we can get the average delay $\mathcal{D}_{(T)}$.

C. Energy Efficiency

Let $\mathcal{P}$ denote the average transmission power for source-to-relay transmission, and the BER ϑ of the packet can be expressed as a function of the received SNR γ [18]

$$\vartheta \approx 0.2\exp(-\frac{1.5}{2^{b_n}-1}\frac{\mathcal{P}}{\bar{e}}\gamma), \quad (12)$$

where b_n is the modulation size for AMC mode n.

Using (12), we can get the average transmission power $\mathcal{P}$ as a function of the average BER $\bar{\vartheta}$ and $\bar{\gamma}$ as follows:

$$\mathcal{P} = \frac{\bar{e}(2^{\bar{b}}-1)}{1.5\bar{\gamma}}\ln\frac{0.2}{\bar{\vartheta}}. \quad (13)$$

where $\bar{b}$ is the average modulation size with AMC transmission, which is shown in (14)

$$\bar{b} = \sum_{n=1}^{N} P_r(n) b_n. \quad (14)$$

By substituting $\bar{\gamma}$ and $\bar{\gamma}_D$ into (13), we can get the average transmission power of links $l_{A,R}$ and $l_{R,D}$ as $\mathcal{P}_{t,l_{A,R}}$ and $\mathcal{P}_{t,l_{R,D}}$ respectively based on (1) and (2).

Proposition 1. *The total energy consumption of the cognitive cooperative network for each transmission period is*

$$\zeta = (a_{A,R}^1\mathcal{P}_{t,l_{A,R}} + a_{A,R}^0 e_0)T_1 + (a_{R,D}^1\mathcal{P}_{t,l_{R,D}} + a_{R,D}^0 e_0)T_2 \quad (15)$$

where e_0 is power consumption for the node at idle state.

Based on the active transmit power and idle power consumption, Proposition 1 comes from the result of substituting the stationary distribution of the link available and unavailable states into the power model.

Based on (9) and Proposition 1, the energy efficiency is

$$f_{ee} = \frac{T\bar{\lambda}(1-P_d^A)(1-P_d^R)(1-P_0^{N_r^{\max}})}{\zeta} = \frac{T\bar{\lambda}(1-P_d^A)(1-P_d^R)(1-P_0^{N_r^{\max}})}{\alpha(a_{A,R}^1\mathcal{P}_{t,l_{A,R}} + a_{A,R}^0 e_0)T_1 + (1-\alpha)(a_{R,D}^1\mathcal{P}_{t,l_{R,D}} + a_{R,D}^0 e_0)T_2}. \quad (16)$$

We would like to jointly optimize the SNR $\bar{\gamma}$ and the time allocations for the cooperative transmission based on the closed-form expression of the energy efficiency. Note that the time allocation ratio α may take any number in the range of $(0,1)$. The optimization problem can be specified as follows:

$$\begin{aligned} \max_{\alpha,\bar{\gamma}} \quad & f_{ee} \\ s.t. \quad & 0<\alpha<1, \quad \bar{\gamma}_{\min}<\bar{\gamma}<\bar{\gamma}_{\max}. \end{aligned} \quad (17)$$

We found that for any given time allocation ratio $\alpha \in (0,1)$, we are able to express the corresponding energy efficient transmit power $\mathcal{P}_{t,l_{A,R}}$ and $\mathcal{P}_{t,l_{R,D}}$ in terms of the time allocation ratio α with closed-form expressions, which are denoted as $\mathcal{P}_{t,l_{A,R}}^*(\alpha)$ and $\mathcal{P}_{t,l_{R,D}}^*(\alpha)$, respectively. Since the variables α and $\bar{\gamma}$ are coupled to the packet dropping rate and the transmit power, it's too complex to solve (17). Then, we provide a suboptimal solution for problem (17) in two stages. In the first stage, we fix α for some value in the interval $(0,1)$. To this end, a numerical search algorithm based on a Golden Section search method [19] can be utilized to get the energy efficient solution $\bar{\gamma}^{\rm opt}$. In the second stage, we still apply numerical search of the single variable α over the interval $(0,1)$ to obtain the energy efficient time allocation ratio α^* that maximizes the energy efficiency f_{ee}. The results are summarized in the following Algorithm 1. The algorithm based on the golden section leads to a linear convergence speed. At the same time, this algorithm can be implemented offline, thus the complexity can be ignored.

$$\bar{\mathcal{D}}_n = \frac{T_u \bar{Q}^n_{(q,A)}}{r} + \frac{T_u \bar{Q}^n_{(q,R)}}{\bar{\chi}} + T_u \mathsf{E}\{S_{T_n}\} = \frac{T_u \bar{Q}^n_{(q,A)}}{r} + \frac{T_u \bar{Q}^n_{(q,R)}}{\bar{\chi}} + \frac{\tau_n T_u}{1-P_0}\left[1 - P_0^{N_r^{max}}\left(1 + N_r^{max}(1-P_0)\right)\right]. \quad (10)$$

Algorithm 1 Energy efficient time allocation ratio and power allocation for the proposed relay assisted transmission.

1: For α=0:1
   Step 1) Initialize the threshold value $\gamma_n = \gamma_n^*$ (see [16]), $\forall n = 1, 2, \cdots, N$.
   Step 2) Repeat:
   calculate f_{ee} using (16);
   update $\bar{\gamma}$ using the Golden Section search method;
   Step 3) Until $\bar{\gamma}$ converge.
2: End.
3: Energy efficient time allocation ratio: α^*=$\arg\max f_{ee}$, and power allocation for the source node and relay node: $\mathcal{P}^*_{t,l_{A,R}}$=$\{\mathcal{P}_{t,l_{A,R}}\}_{\bar{\gamma}=\bar{\gamma}^{\text{opt}}}$, $\mathcal{P}^*_{t,l_{R,D}}$=$\{\mathcal{P}_{t,l_{R,D}}\}_{\bar{\gamma}=\bar{\gamma}^{\text{opt}}}$.

Based on the solutions of our optimization problem, the energy efficient modulation scheduling policy is the same $\mu^{\text{opt}} = \mu(\gamma_n^*, \bar{\gamma}^{\text{opt}}(\mathcal{D}_0))$ for the source node and relay node when $\mathcal{D}_{(T)} < \mathcal{D}^0$. $\bar{\gamma}(\mathcal{D}_0)$ is the average SNR making $\mathcal{D}_0$ be the packet delay from the source-to-relay link and relay-to-destination link.

IV. Numerical Results and Discussion

A. System Parameters

The corresponding simulation parameters are shown as follows: the number of traffic states is $K = 2$, the channel states for the inter-node link and direct link is $N = 7$, and the buffer size is $M + 1 = 51$ for the source node and relay node; The packet size $L = 100$, the maximum retransmission times of packet is $N_r^{\max} = 6$.The maximum number of packet arrivals for source node is set as $A = 15$, with an average arrival rate, $\lambda_1 = 1$ packets/time-unit and $\lambda_2 = 2$ packets/time-unit, the symbol rate $R_s = 100$kHz; The Nakagami parameter $m = 1$, which corresponds to Rayleigh fading channel with no line of sight (LOS) component. Like 3GPP LTE standard, we assume that block (also called frame) length $T_u = 2$ ms.

B. Performance Evaluation

In Fig. 2 and Fig. 3, the two metrics of energy efficiency based on (16) are investigated over different values of time allocation ratio α. For any time allocation ratio $\alpha \in (0, 1)$, we can get the energy efficient SNR as $\bar{\gamma}^{\text{opt}}(\alpha)$, and the corresponding energy efficient power allocation can be calculated based on (13). In each figure, we plot the energy efficiency based on energy efficient partition method (EEP) as well as the minimum SNR required to acheive P_{target} (MSRE) method for comparison (see [16]). These two figures show that the energy efficiency of EEP is better than that of MSRE, since we use the energy efficient threshold values for choosing the

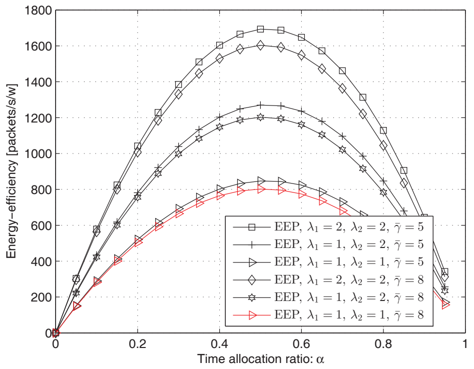

Fig. 2. The average energy efficiency versus the time allocation ratio α for relay assisted transmission under the energy efficient partition method (EEP).

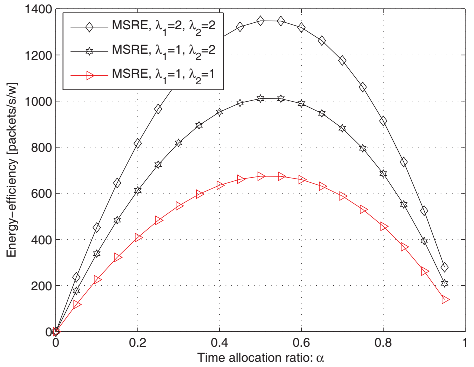

Fig. 3. The average energy efficiency versus the time allocation ratio α for relay assisted transmission under the minimum SNR required to acheive P_{target} (MSRE) method, where $P_{\text{target}} = 0.001^{\frac{1}{N_{\max}^r+1}}$.

modulation. In the case of average SNR $\bar{\gamma} = 5$ dB, Fig. 2 shows that the optimal time allocation ratio is $\alpha^* = 0.53$. In the case of $\bar{\gamma} = 8$ dB, the optimal time allocation ratio is the same, since we assume that the average SNR for the source to the relay is the same with that of the relay to the destination.

In Fig. 4, we show the packet dropping rate of source node A, P_d^A, for the proposed relay assisted transmission. We can see in Fig. 4 that the packet dropping rate is decreasing when increasing the SNR, since the service rate for the source node is increasing when increasing the SNR. Moreover, we can observe that when the ratio of the source-relay time allocation over the relay-destination time allocation becomes larger, the packet dropping rate for source node A becomes smaller. When the source-relay time allocation is increasing, the dropped number of packets for the source node during each

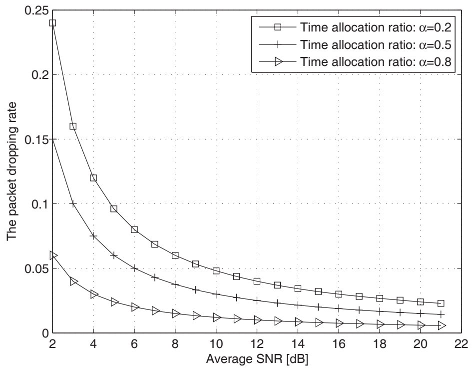

Fig. 4. The analysis results of the packet dropping rate versus average SNR for relay assisted transmission with different time allocation ratio.

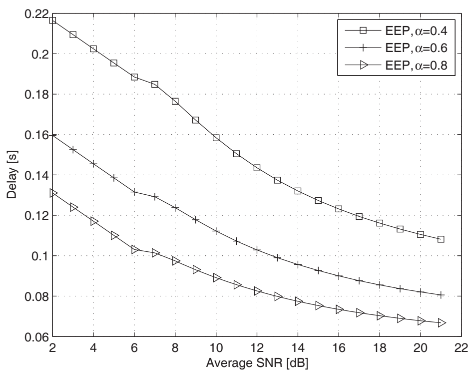

Fig. 5. The analysis results of the delay for relay assisted transmission with different time allocation ratio.

transmission period is decreasing. Then the packet dropping rate becomes smaller. In Fig. 5, we show the delay performance for the relay assisted transmission system when the average packet arrival rate $\bar{\lambda} = 2$. From this figure we can see that the delay is smaller when the time allocation ratio is larger. This phenomenon can be understood as follows: when the packet arrival rate is larger, the packet dropping rate of the source node is in dominant place. Then the delay can be smaller when increasing the source-destination time allocation.

V. Conclusion

In this paper, we have presented a cross-layer framework in the cognitive cooperative network that determines the energy efficient transmission policy based on both the physical and the upper-layer information. We derive the closed-form expression of delay for the relay-assisted transmission system, which considers the queueing delay of the relay-buffer and source-buffer. For the relay assisted transmission, we derive the energy efficient time allocation ratio and transmission policy with AMC. With the optimal scheduling strategy, the buffer-aided relay system can achieve the energy efficient transmissions.

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