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PERFORMANCE ANALYSIS OF COGNITIVE STOP-AND-WAIT HARQ SYSTEM BASED ON DOUBLE THRESHOLD ENERGY DETECTION TECHNIQUE

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Cognitive radio is considered to be one of the most promising technologies to solve the spectrum shortage problem. Under the condition of not interference to the primary user, cognitive user uses spectrum holes for reliable transmission. It is very important that the cognitive system understand the behavior of the primary user accessing the licensed spectrum. In this paper, a mathematical model for evaluating Cognitive Stop-and-Wait Hybrid Automatic Repeat reQuest (CSW-HARQ) protocol in single cluster head sensor networks is established. Based on Double Threshold Energy Detection (DTED) technique, the outage probability under Nakagami-m fading channel is used to approximately replace packet error probability, which can be used to present the relationship between transmission distance and performance indexes. The relationship between the probability of primary users accessing channels and the arrival rate of data packets is defined by establishing the M/M/1/S queuing model. Under the condition of constant buffer capacity and combined with theoretical derivation, it can be confirmed that the probability of primary users accessing channels is positively correlated with the data packet arrival rate. In addition, the average delay and throughput of CSW-HARQ protocol are derived. The numerical results show that the influence of transmission distance on average packet delay and throughput is consistent with theoretical analysis.

Keywords: cognitive stop-and-wait HARQ; single cluster head sensor network; double threshold energy sensing; average packet delay; throughput

1. Introduction

Cognitive radio technology is considered as one of the technologies to solve the shortage of spectrum resources in the future. The main idea of cognitive radio is to divide users into cognitive users and primary users, who share the same spectrum resources [1]. Spectrum sharing can be divided into two paradigms: in the first paradigm, primary users and cognitive users can share the same spectrum resources at the same time, but cognitive users are not allowed to interfere with the communication of primary users; while in the second paradigm, cognitive users access and use the spectrum resources which are authorized to primary users opportunistically. The interference temperature of cognitive users to primary users

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is zero in the second paradigm. Since this paradigm has the lowest interference to primary users, it is adopted in the first cognitive radio standard, IEEE 802.22 [2].

Wireless sensor networks have been widely used in numerous of applications, such as environmental monitoring, forest fire prevention and battlefield monitoring [3]. Generally, there are no authorized spectrum bands for wireless sensor networks, data transmission between nodes must rely on the spectrum bands that are licensed to the primary users, so wireless sensor nodes play the role of cognitive users. Perhaps there is no shortage of spectrum resources in desert and forest environment, but in densely populated environment, it is easy to face the shortage of spectrum resources, strong interference and other problems restricting the work of wireless sensor networks. In order to minimize the interference to the primary users, cognitive users usually adopt the second paradigm to communicate. In wireless sensor networks, data are collected and fused in the form of clustering. In each cluster, the cluster head with strong communication ability is responsible for establishing communication links with member nodes, detecting spectrum holes and broadcasting messages containing the actual state of the primary channel to member nodes. In cognitive scenarios, signal transmission is affected not only by the fading of wireless channel, but also by the behavior of the primary users [4]. In order to achieve high reliability, low delay and energy-saving data transmission between cluster heads and member nodes, we need to design appropriate link error control protocols to reduce the number of data packet retransmissions.

For wireless sensor networks without cognitive function, reliable data transmission protocols mainly include Stop-and-Wait ARQ, Go-Back-N ARQ and Selective-Repeat ARQ, which are relatively easy to implement [5-7]. However, when nodes are deployed in poor wireless channel conditions, the performance of the three types of Automatic Repeat reQuest (ARQ) protocols will deteriorate dramatically, the effective throughput of the protocols will be reduced, and the delay will be increased. In this case, the number of retransmissions required for a packet will increase. In order to achieve efficient and reliable data transmission in poor wireless channel conditions, researchers developed Hybrid Automatic Repeat reQuest (HARQ) protocol by combining error correction function with classical ARQ. The main idea of HARQ is to add Forward Error Correction function at the destination node, which reduces the number of data packets retransmitted and thus increases the effective throughput. Therefore, HARQ protocol should also be used in cognitive sensor networks to achieve high reliability and low latency data transmission. In order to effectively integrate cognitive function with HARQ protocol, many researchers have explored it from different perspectives. The Cognitive Stop-and-Wait Hybrid Automatic Repeat reQuest (CSW-HARQ) protocol was designed. Their performance was evaluated by using mathematical tools such as discrete Markov chain and probability theory

[8-10]. In terms of the number of cognitive nodes involved in the system, the algorithm flow of the CSW-HARQ is given in the scenario of only a pair of cognitive users, so the algorithm is not suitable for reliable data transmission in multi-cognitive user scenarios [8,9]. Then, a CSW-HARQ protocol is designed for wireless sensor networks with only one cluster head (i.e. one destination node and multiple member nodes) [10]. This attempt extends the application of CSW-HARQ. Obviously, the former the CSW-HARQ protocol is a special case of the latter.

The average packet delay and throughput were used to measure the performance of the proposed CSW-HARQ protocols [8-10]. The analysis results show that the main factors affecting the performance of the protocol include the behavior characteristics of the licensed spectrum occupied by the primary user, the wireless channel conditions and the accuracy of the cognitive user sense the primary user’s activity. The two-state discrete Markov chain is used to describe the behavior of primary users occupying licensed spectrum [8]. On this basis, the analytic expressions of the CSW-HARQ performance under perfect and imperfect sensing environments are given respectively [8,9]. Although the above research clarifies the characteristics of primary users occupying licensed spectrum, it does not discuss specific data traffic stream. For primary users, the behavior of occupying the licensed spectrum will only be triggered if the data packet arrived. Therefore, data stream is the main factor determining whether the primary user occupies the licensed spectrum, while existing work does not consider the impact of actual arrival rate of data packet on the behavior of the primary user. The false alarm probability and miss-detection probability are utilized to analyze the accuracy of cognitive user perception but ignore specific signal detection techniques [8,9]. Unfortunately, the performance calculation formulas are given under the condition of perfect sensing, and the condition of imperfect sensing is not discussed. In addition, when exploring the impact of wireless channel quality on CSW-HARQ performance, specific physical parameter (such as fading type, transmission distance, fading scale, etc.) is not used in [10]. In addition, the performance of CSW-HARQ is analyzed only from the perspective of signal detection, and a mathematical model is not established from the perspective of the data packet arrival rules of the primary user in Ref. [8-10]. However, the characteristic of this study is to analyze the performance of the CSW-HARQ by combining the physical layer parameters (such as the communication distance between nodes) and the arrival rule of the primary user data packet. To the best of our knowledge, existing research does not consider these two factors in a comprehensive manner. All in all, existing analytical formulas cannot accurately describe the impact of physical parameter on the performance of the protocol.

Based on the above work, this paper evaluates the performance of CSW-HARQ in single cluster head wireless sensor networks by using DTED technique. The contributions are as follows

- Compared with the results of Ref. [8-10], this paper presents a simple model to describe cognitive decision types. Next, the M/M/1/S queuing model is used to describe the relationship between the probability of the primary user access the primary channel and the packet arrival rate and the buffer capacity. It is found that the probability of accessing the channel increases as the arrival rate of the data packet increases, and the size of the primary user's buffer capacity has no effect on the probability of the primary user accessing the channel. In particular, when the cache capacity tends to infinity, the probability of the primary user access channel at this time is numerically equal to the data packet arrival rate.
- Under the premise of selecting Double Threshold Energy Detection (DTED) technique, the false alarm and miss-detection probability are given, and the packet error probability replaced by the Nakagami-m fading channel's outage probability approximation. Based on this, the formula for calculating the average packet delay and throughput of CSW-HARQ in a single cluster head sensor network is given.
- The numerical simulation shows that the average packet delay and throughput vary with the communication distance, and when the communication distance is large, the cognitive cluster head should actively give up the communication link with the member node.

The structure of this paper is organized as follows. In the Section 2, the basic working principle of the CSW-HARQ protocol is introduced. In the Section 3, a mathematical model of cognitive system behavior is established. In the Section 4, an expression describing the performance of the system is given. In the Section 5, numerical simulations were carried out. Finally, the conclusions and future work are given.

2. System model

2.1 Working principle of CSW-HARQ

In this paper, the problem of reliable transmission was studied in a single cluster head cognitive scene. The cognitive system consists of a cluster head and multiple member nodes. The cognitive system and the primary user (i.e., licensed user) system occupy the same channel to transmit data, which is called the primary channel. When the primary user uses the primary channel, the cognitive user actively interrupts the transmission, otherwise the cognitive user continues to transmit, and the reliable transmission protocol adopted by the cognitive system is the CSW-HARQ. In order to reduce the interference to primary user, it is assumed that the cluster head does not establish transmission links with any member nodes in the cluster as long as the cluster head sense that the primary channel state is "busy".

In order to reduce the complexity of cognitive system design, each time slot includes two parts of sensing and transmission. This time slot division way is the same as that of Ref. [9] and the structure of the time slot is shown in Fig. 1. The cognitive cluster head senses the state of the primary channel at the beginning of each time slot. If it senses that the primary channel is in the "idle" state, it communicates with member nodes in the cluster. Otherwise, it keeps sleeping in order to save energy. We assume that the primary user decides whether to access the primary channel at the beginning of each slot, which ensures that the cognitive cluster head can correctly sense the state of the primary channel during the sensing period. In other words, time slot synchronization needs to be achieved before user communication, that is, the secondary user and the primary user will try to occupy the primary channel at the beginning of each time slot. and this concept has been adopted in Ref. [11]. Let a time slot size be $T = T_s + T_d$ and we can see from Fig. 1 that the time for cognitive cluster head to perform spectrum sensing in each time slot is T_s. When the primary channel is sensed as being "idle'', the data packet transmission time of the cognitive system in each time slot is $T_d = T - T_s$, otherwise $T_d = 0$.

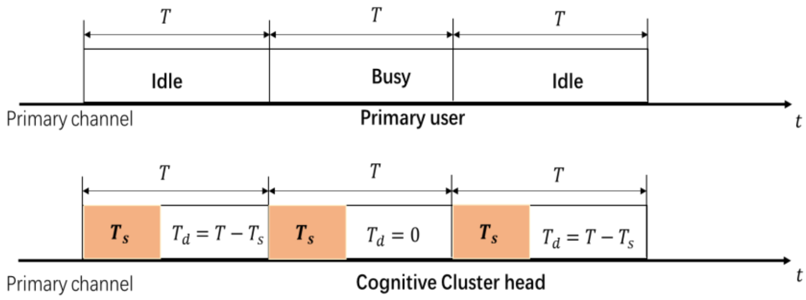

Fig. 1. Cognitive system's time slot structure division

The algorithm of reliable transmission protocol used in single cluster head sensor networks can be described as follows:

Step 1: At the beginning of each time slot, the cognitive cluster head senses whether the primary channel is idle. If the sensed result is idle, the Clear To Send (CTS) message is broadcast to all member nodes in the cluster, otherwise, it waits for the next time slot to start.

Step 2: When a member node receives a CTS message, it generates a corresponding Request to send (RTS) message. The cognitive cluster head establishes a communication link with the member nodes according to the order of arrival of the RTS, and then uses the CSW-HARQ for reliable data transmission.

Step 3: After the cognitive cluster head performs error correction and error detection on the received data packet, if there is no error, a corresponding Acknowledgement (ACK) message is returned, otherwise, No Acknowledgement (NACK) is returned.

The algorithm flow of the CSW-HARQ is shown in Fig. 2. For the rationality of subsequent analysis, here are some key assumptions

- The feedback message ACK/NACK of the cognitive system does not go wrong, that is, the member node can receive the feedback message correctly and without error.
- Only one packet is transmitted in each slot, and the length of the packet is fixed.
- The ratio between the duration of sensed slots and the duration of transmitted data is constant in each time slot.
- Only one-member node in each time slot establishes a transmission link with cluster head, that is to say, the problem of competing primary channels among member nodes is not considered here.

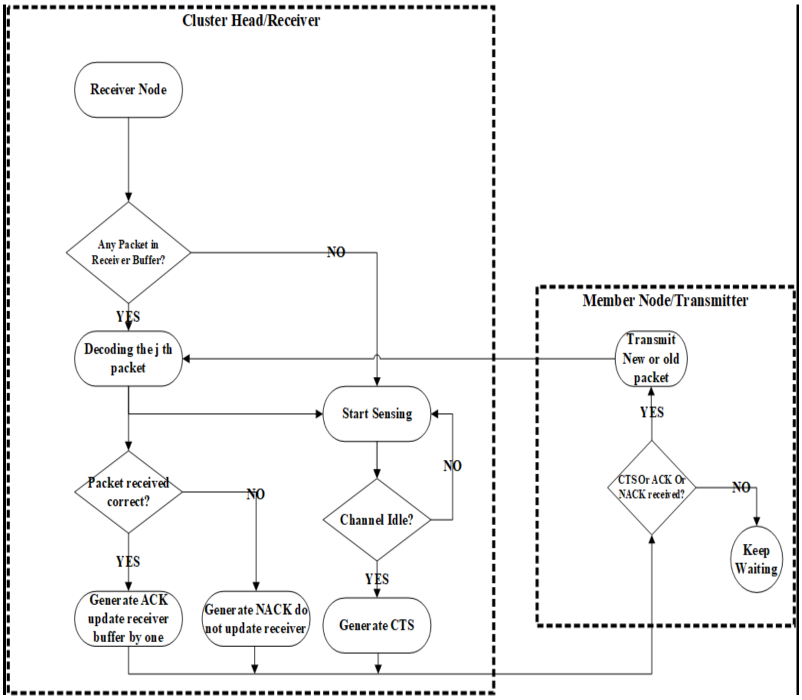

Fig. 2. The algorithm of Cognitive Stop-and-Wait HARQ

2.2 Outage probability of communication link

The Nakagami-m fading channel is choose to describe the characteristics of wireless channel. Wireless channels with different physical characteristics can be simulated by adjusting the scale parameter m. When $m = 1$, the communication between nodes has the characteristics of non-line of sight (NLOS); If $m = 2$, it has the characteristics of line-of-sight (LOS). It is assumed here that the wireless channel is quasi-static fading, that is, the parameter used to describe channel characteristics remain constant in each slot.

The scenario explored in this paper is a single cluster head cognitive sensor network, in which the communication between a cluster head and its members is carried out in single hop way. The signal received by cognitive cluster head is

$$Y = \sqrt{P_{SH}\gamma_{SD}}h_{SD}X + n_{SD}$$

where P_{SH} is the transmission power of the member node, γ_{SD} is the path loss, and h_{SD} is the fading scale of the Nakagami-m quasi-static channel; X is the signal transmitted by the member node; n_{SD} is the Additive White Gaussian Noise with variance $\frac{N_0}{2}$ and N_0 is the power spectral density of the noise. The path loss can be determined by the results given [12]. The calculation equation is as follows

$$\gamma_{SD} = \frac{G\kappa^2}{(4\pi)^2 d_{SD}^{\alpha} M_l N_f} \quad (1)$$

where d_{SD} represents the distance between source node and destination node; α is path loss index; R is the total gain of the receiving and transmitting antennas; κ is the wavelength; M_l is the limit of loss; N_f is the received noise value.

According to Eq. (1), the signal-to-noise ratio (SNR) of the link between source node and destination node can be found as $SNR = |h_{SD}|^2 \gamma_{SD} \cdot P_{SH}/N$, the noise power $N = N_0 \cdot B$, B is the system bandwidth.

The main causes of packet errors can be attributed to the unreliability of the wireless channel and the behavior of the primary user accessing the channel. By replacing the packet error probability P_e with outage probability P_{out}, so that we can describe the impact of wireless channel on performance of CSW-HARQ. This operation was also verified [13]. The packet error probability after error correction is $P_e \approx P_{out}$, so the packet error probability is

$$P_e \approx P_{out} = P\{SNR < \beta\} = \frac{\Gamma(m, \frac{P_{SH}\gamma_{SD}}{mN\beta})}{\Gamma(m)} \tag{2}$$

where decision threshold $\beta = 2^{\Delta} - 1$, Δ represents the spectral efficiency of cognitive system. $\Gamma(a,b) = \int_0^b t^{a-1}\exp(t)dt$ is an Incomplete Gamma Function $\Gamma(a) = \int_0^{\infty} t^{a-1}\exp(-t)dt$ is a Gamma Function.

In particular, when SNR is relatively large, we can get $\Gamma(a,b)\,;\ {}^{1}\!/_{a}\cdot b^{a}$ [14], then Eq. (2) can be simplified to

$$P_e \approx P_{out} = P\{SNR < \beta\}\,;\ \frac{1}{\Gamma(m+1)}\left(\frac{mNB}{P_{SH}\gamma_{SD}}\right)^{m} \tag{3}$$

3. Analysis of cognitive system behavior

In this section, the sensing techniques used by the cognitive system and the probability of false-alarms and miss-detection are given. On this basis, the cognitive system sense the primary channel state sensing result and gives the probability of occurrence. Next, the M/M/1/S model is used to characterize the relationship between the probability of the primary user access channel and the packet arrival rate of the primary user.

3.1 Double threshold energy detection technique

If cognitive system is unclear about the characteristics of primary user signal, then cognitive cluster head needs DTED technique to sense the state of primary channel [15]. This technique is developed from traditional energy detection technique. It can solve the problem of selecting the optimal decision threshold in traditional energy detection technique. For the convenience of following analysis, two symbols H_0 and H_1 are introduced to represent the idle and busy states of primary channel respectively. So the signal $r(n)$ received by cognitive cluster head is as follows

$$r(n) = \begin{cases} s(n) + \omega(n), & H_1 \\ \omega(n), & H_0 \end{cases} \tag{4}$$

where $s(n)$ is the signal transmitted by primary user; $\omega(n)$ is Additive White Gaussian Noise with zero mean and unit variance, namely, $\omega(n):\ N(0,1)$.

Assuming that the number of samples in each sensing slot is N, the average energy of signals sensed by cognitive cluster head can be expressed as

$e = \frac{1}{N} \cdot \sum_{n=1}^{N} |r(n)|^2$. We set two thresholds e_1 and e_2 in the double threshold energy detection technique, and satisfy $0 < e_1 \le e_2$. The decision principle of cognitive cluster head is given as

$$LD = \begin{cases} 1, & e \ge e_2 \\ \infty, & e_1 < e < e_2 \\ 0, & e \le e_1 \end{cases} \tag{5}$$

where $LD = 1$ and $LD = 0$ indicate the channel is idle and busy respectively; $LD = \infty$ means no decision is made.

From the literature [15], the miss-detection probability P_m and the false alarm probability P_f are

$$\begin{cases} P_m = 1 - Q_N(\sqrt{SNR}, \sqrt{e_2}) \\ P_f = \dfrac{\Gamma(N, \frac{e_1}{2})}{\Gamma(N)} \end{cases} \tag{6}$$

For the convenience of following analysis, we introduce two indicative variables F and G to indicate whether false alarm and miss-detection events occur. If $F = 1$, the false alarm event occurs, otherwise $F = 0$; similarly, $G = 1$ means the miss-detection event occurs and $G = 0$ means not.

3.2 Probability description of cognitive decision types

In cognitive scenario, the detection of the states of primary channel by cognitive cluster head is imperfect, mainly because of the unreliable and constantly changing wireless channel. Assuming that the probability of primary user accessing the primary channel is ρ, then the decision types of cognitive cluster heads and their probabilities can be derived as

- The primary channel is busy, and sensing result is busy.
- The primary channel is busy, but sensing result is idle.
- The primary channel is idle, but sensing result is busy.
- The primary channel is idle, and sensing result is also idle.

If the above events occur with the probability of p_1, p_2, p_3 and p_4 respectively. The equations are as follows

$$\begin{cases} P_1 = P\{S \ne 0 \,\&\, G = 0\} = \rho(1 - P_m) \\ P_2 = P\{S \ne 0 \,\&\, G = 1\} = \rho P_m \\ P_3 = P\{S = 0 \,\&\, F = 1\} = (1-\rho)P_f \\ P_4 = P\{S = 0 \,\&\, F = 0\}(1-\rho)(1 - P_f) \end{cases} \tag{7}$$

where S represents the cache capacity of the primary user, and $p_1 + p_2 + p_3 + p_4 = 1$.

As long as a packet arrives, primary user must access the primary channel. That is to say, whether primary user accesses the primary channel is determined by the packet arrival rate, and the greater the packet arrival rate, the greater the probability that the primary user accesses the channel. It is further assumed that packet arrival rate of primary user's obeys Poisson distribution with intensity λ, the packet transmission rate obeys exponential distribution with parameter μ, and the buffer capacity is S. When $S \neq 0$, the primary user will definitely attempt to access the primary channel, which can be described by M/M/1/S model with a single servers and limited buffer capacity. Let the service rate of the primary channel μ is 1, and in order to study the system performance under steady state conditions, it is necessary to ensure $\lambda \leq 1$. So we can say that the probability of primary user accessing primary channel is equal to the probability that the primary user buffer is not empty. The formula for non-empty probability of the buffer from Ref. [5] is

$$\rho = P\{S \neq 0\} = 1 - P\{S = 0\} = 1 - \frac{1 - \frac{\lambda}{\mu}}{1 - \left(\frac{\lambda}{\mu}\right)^{S+1}} = 1 - \frac{1-\lambda}{1-\lambda^{S+1}} \tag{8}$$

From the above formula, when $\rho \to \infty$, that is, $\rho = \lim_{S \to +\infty}\left(1 - \frac{1-\lambda}{1-\lambda^{S+1}}\right) = \lambda$ this indicates that when the buffer capacity tends to be infinite, the probability of primary user accessing the channel is fixed, which is equal to the packet arrival rate numerically. Under the premise that primary user buffer capacity S remains unchanged, the probability ρ of primary user accessing channel can be regarded as a unary function of packet arrival rate, that is, $\rho = f(\lambda),\ \lambda \in [0,1]$. In order to carry out the relationship between probability of primary user accessing channel and the packet arrival rate λ, let's calculate the first derivative of access probability with respect to variable λ, as follows

$$f^{'}(\lambda) = \frac{1-(1-\lambda)(S+1)\lambda^{S}}{(1\text{-}\lambda^{S+1})^2} \geq 0 \tag{9}$$

4. Performance analysis

This section mainly analyses the performance of CSW-HARQ. Only two metrics, average packet delay and throughput are considered here. The average packet delay is defined as the number of slots required to successfully transmit a packet, and throughput is defined as the average number of packets successfully transmitted in a unit time slot.

4.1 Average packet delay

In cognitive scenarios, the two factors contributing to the average packet delay are: (1) the average delay it takes to sense the primary channel is in the "idle" state, it can be recorded as T_{busy}; (2) the average delay of successful data packet transmission can be recorded as T_D.

When we analyze the average packet delay caused by the first factor, we assume that the probability of cognitive cluster head sensing primary channel is in the "busy" state is P_{busy}, which can be determined by the following equation

$$P_{busy} = P\{LD=1\} = P\{e>e_2 \mid H_0\} + P\{e>e_2 \mid H_1\} = P_1 + P_3 = \rho(1-P_m-P_f)+P_f \quad (10)$$

Similarly, the probability P_{idle} that cognitive cluster head senses that primary channel is "idle" is as follows

$$P_{free} = P\{LD=0\} = P\{e<e_1 \mid H_0\} + P\{e<e_1 \mid H_1\} = P_2 + P_4 = 1-P_f-\rho(1-P_m-P_f) \quad (11)$$

The time taken by the cognitive cluster head to find that the primary channel is the "idle" state, denoted as T_{busy}. This formula indicates that the channel is the "busy" state in the first $i-1$ time slot, and the sensing result in the i time slot is "idle", that is, $T_{busy} = (i-1)T$. The average delay of the cognitive cluster head sensing that the primary channel is in the "idle" state can be calculated by the following equation

$$T_{busy} = E[T_{busy}(i)] = \sum_{i=1}^{\infty}(i-1)TP_{busy}^{i-1}P_{free} = \frac{P_{busy}}{1-P_{busy}} \cdot T = \frac{\rho(1-P_m-P_f)+P_f}{1-\rho(1-P_m-P_f)-P_f} \cdot T \quad (12)$$

Using Eq. (12), the average delay required for cognitive cluster head sensing channel to be in the "idle" state can be calculated. As previously analyzed, the wireless channel conditions are constantly changing, and the signal is prone to fading during transmission, which in turn causes data packets to be transmitted incorrectly. Data packets must be retransmitted if errors occur. When cognitive cluster head senses actual channel states, there will be miss-detection and false alarm. Therefore, under the condition that cognitive cluster head senses the primary channel state is "idle", while the probability that the primary channel is actually in the "idle" and "busy" states are as follows respectively.

$$P_A = P\{S=0 \,\&\, F=0 \mid LD=0\} = \frac{P_4}{P_{free}} = \frac{(1-\rho)(1-P_f)}{1-P_f-\rho(1-P_m-P_f)} \quad (13)$$

$$P_B = P\{S \neq 0 \,\&\, G = 1 \mid LD = 0\} = \frac{P_2}{P_{free}} = \frac{\rho P_m}{1 - P_f - \rho(1 - P_m - P_f)} \quad (14)$$

Suppose that when cognitive cluster head miss-detects the state of the primary channel, the packet error probability of the transmitted packets after error correction is 1, that is to say, $P_e = 1$, and it must be retransmitted. If the number of times a packet is correctly transmitted is i, the average packet delay of is $T_D(i) = i(T_{busy} + T)$. A packet is transmitted i times, and the probability of having j times of transmission failure is

$$P\{j \mid i\} = \binom{i-1}{j} P_B^j \cdot P_A^{i-j-1} P_e^{i-j-1} \quad (15)$$

The average packet delay for each packet is

$$T_D = E[T_D(i)] = \sum_{i=1}^{\infty} i(T_{busy} + T) \sum_{j=0}^{i-1} \binom{i-1}{j} P_B^j P_A^{i-j-1} P_e^{i-j-1} (1 - P_e) \quad (16)$$

Let $\Xi = T_{busy} \cdot \frac{1}{T}$, then use it to simplify Eq. (16), we can get

$$T_D = \frac{P_A(1-P_e)(1+\Xi)}{(P_B + P_A P_e - 1)^2} \cdot T = \frac{[(1-\rho)(1-P_f) + \rho P_m](1+\Xi)}{(1-\rho)(1-P_f)(1-P_e)} \cdot T \quad (16)$$

According to previous analysis, the average packet delay is given in Eq.(17). So the normalized throughput is

$$\eta = \frac{1}{T_D} = \frac{(P_B + P_A P_e - 1)^2}{P_A(1-P_e)(1+N_{DP})} \cdot \frac{1}{T} = \frac{(1-\rho)(1-P_f)(1-P_e)}{[(1-\rho)(1-P_f) + \rho P_m](1+\Xi)} \cdot \frac{1}{T} \quad (17)$$

5. Numerical simulation and analysis

In this section, the validity of the proposed model will be verified by numerical methods, and the parameters are shown in Table 1 [13].

Table 1

Physical layer parameter value

Parameter	Value	Parameter	Value
Path loss index α	2.5	Power spectral density of nois N_0	-174 dBm
Total antenna gain G	5 dBi	Discriminant threshold of outage probability β	3 b/s/Hz
Wavelength κ	0.12 m	System bandwidth B	10 KHZ
Spectral efficiency Δ	2 b/s/Hz	Noise value at the destination N_f	10 dB

Transmission power P_{SH}	97.9 mW	Link margin M_l	40 dB
Upper threshold for energy sensing e_2	8 mW	Lower threshold for energy sensing e_1	5 mW

Based on Eq. (2), we get the relationship between the outage probability and the distance of communication, as is shown in Fig. 3.

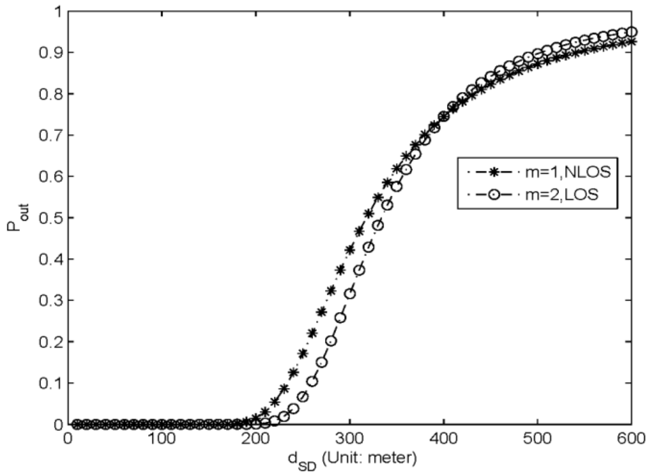

Fig. 3. The relationship between the outrage probability and the communication distance

It can be seen from the figure that the outage probability increases with the increase of the distance of communication, which is in line with reality. This is mainly because the farther the member nodes are from the cognitive cluster head, the faster the signals are attenuated in transmission, and the cognitive cluster head can't correctly decode the received data packets. It can also be found that in single cluster head cognitive sensor network, when the communication distance between member nodes and cognitive cluster heads is less than 400 m, the outage probability of communication links with line-of-sight feature is less than that of communication links with non-line-of-sight feature, but when the distance between member nodes and cognitive cluster heads is greater than 400 m, the outage probability of communication links with line-of-sight feature is greater than the links with the non-line-of-sight feature, but the overall trend is same. In the following numerical verification, only the case of non-line-of-sight communication is considered. Since $P_e \approx P_{out}$, the packet error probability has a similar conclusion to the outage probability.

From Eq. (8), the relationship between the probability of primary user accessing channels and the buffer capacity of primary user is obtained, as shown in Fig. 4.

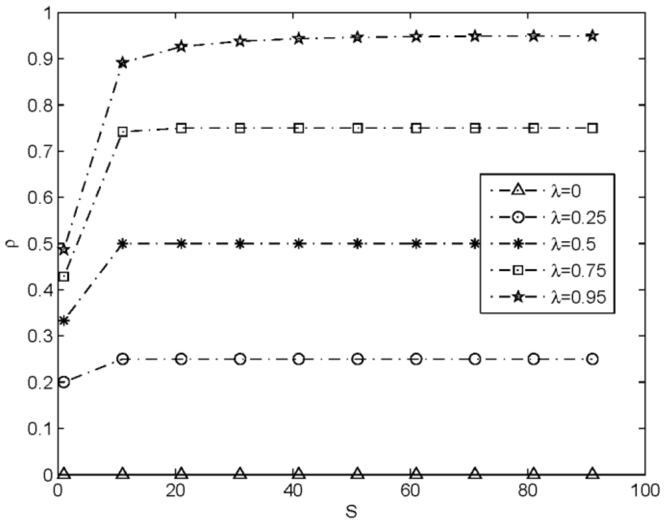

Fig. 4. Primary user access channel probability varies with cache capacity

It illustrates that the size of buffer capacity has no effect on the probability of primary user accessing channels for S larger than 10. When the buffer capacity increases, the probability of primary user accessing channels is approximately equal to the packet arrival rate. When the packet arrival rate is zero, it indicates that primary user does not access the channel, but only the communication between cognitive users, which is consistent with the theoretical analysis. Under the same buffer capacity, the probability of primary user accessing channel increases with the increase of packet arrival rate for S less than 10, and in the case of a relatively large buffer capacity, the probability of accessing the channel is numerically approximately equal to the packet arrival rate. Therefore, in the subsequent analysis, the packet arrival rate can be considered as the probability that primary user accesses channel.

According to Eqs. (2), (17) and (18), we simulate the average packet delay and throughput under various distances between nodes, as shown in Fig. 5 and Fig. 6 respectively.

In Fig. 5, it is obvious that the average packet delay becomes larger when communication distance between nodes is increasing. It is suggested that the cognitive cluster head should establish communication links with closer nodes when collecting data. When the probability of primary user accessing the channel becomes zero (that is, packet arrival rate is zero), the average delay required is the smallest, mainly because the primary user no longer occupies the primary channel, and the average packet delay is mainly caused by the unreliability of the wireless channel. With the increasing probability of primary user accessing channel, the probability of primary user accessing channel and the unreliability of channel on average packet delay have a greater impact on the average packet delay. When the communication distance is less than 250 m, the average packet delay is almost independent of the communication distance between nodes, but only affected by the packet arrival probability of primary user.

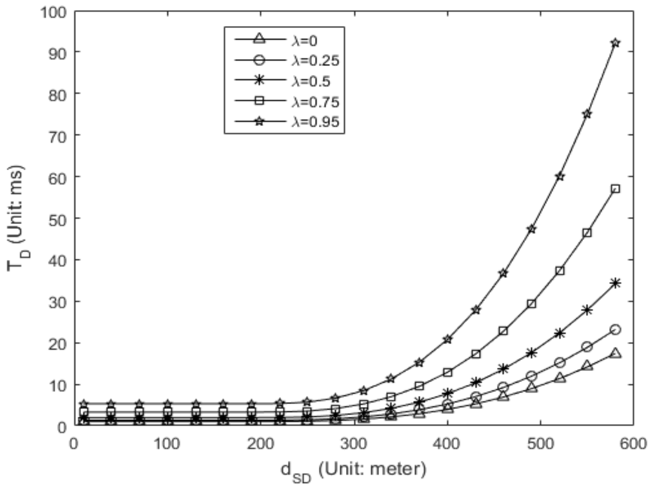

Fig. 5. Average packet delay variation with communication distance

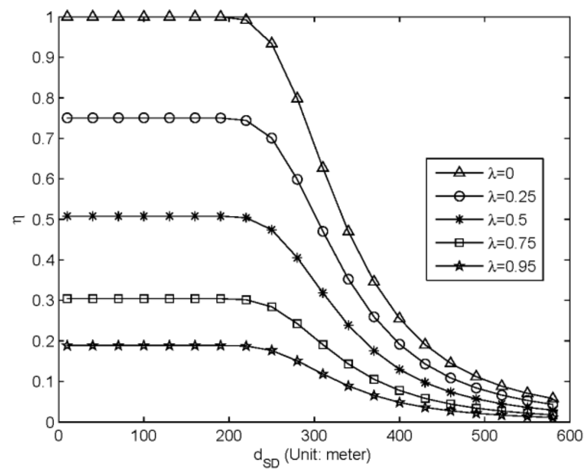

Fig. 6. Throughput variation with communication distance

Fig. 6 shows that throughput decreases with the increase of communication distance in general. The throughput of cognitive system is the largest, if the probability of primary user accessing the channel is zero (i.e., the packet arrival rate of primary user is zero). Similar to Fig. 6, 250 m is a key distance, and when the distance between nodes is less than it, the throughput of cognitive system is only related to the probability of the packet arrival rate of primary user, when the communication distance between nodes is larger than it, the decrease of throughput is mainly attributed to the increase of channel access probability and communication distance of primary user. When the communication distance increases to a certain extent, the throughput almost becomes zero, and due to the excessive cost, the cognitive cluster head abandons the attempt to establish a communication link in this case.

In an opportunistic spectrum-sharing cognitive network, the average packet delay consists of two parts: the delay of sensing idle slots and the delay of retransmitting. Under the condition that buffer capacity of primary user is 5 and probability of miss-detection and false alarm are both zero, the average packet delay and the delay of sensing idle slots are changed with the probability of access channel of primary user, as shown in Fig. 7. As is apparent from the Fig. 7, the average packet delay is larger than the delay of sensing idle slots, which is consistent with the theoretical analysis. When the probability of the primary user accessing the channel is zero, the delay of sensing idle time slots also becomes zero, and the average packet delay is the minimum.

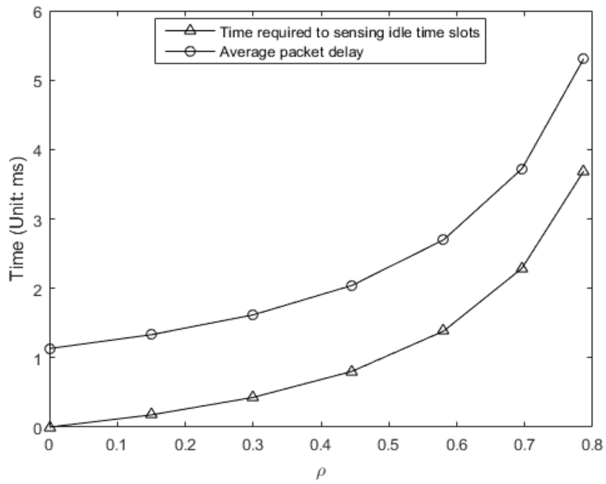

Fig. 7. The relationship between two types of delays and the probability of accessing the channel of the primary user

6. Conclusions

The expressions of throughput and average packet delay from the perspective of signal sensing are given in Ref. [8-10]. The results of Ref. [8-10] can’t describe the impact of the protocol performance of the data packet arrival rule of the primary user. Unlike the works of Ref. [8-10], we evaluate the performance of the CSW-HARQ protocol from the new perspective of data packet arrival rule of the primary user and the parameters of the physical layer are considered. In this paper, based on DTED technique, we derive analytic expressions of average packet delay and throughput for evaluating the performance of CSW-HARQ protocol. The numerical analysis shows that the average delay increases but the throughput decreases with the increase of communication distance. In order to explore the influence of communication distance on protocol performance, the average packet error probability is approximately replaced by the outage probability of communication link. Meanwhile, a simple model is established to describe the cognitive system decision type, and the M/M/1/S queuing model is used to derive the relationship between the probability of the primary user accessing the primary channel and the packet arrival rate. In this paper, we only study the CSW-HARQ performance under the premise of single cluster head sensing the idle spectrum resource. In the future, the performance of HARQ with multiple member nodes participating in sensing will be discussed widely.

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