A Perceptual Spectrum-Hole Proportional Fairness Scheduling Algorithm Integrated with CR

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Abstract. In order to improve the utilization of spectrum resources and solve the problem of unscheduled users in the downlink transmission process in LTE system, we propose a new proportional Fairness scheduling algorithm. The algorithm integrates cognitive radio (CR) technology into proportional Fairness scheduling algorithm, and derives the expression of system throughput under the new algorithm, so that unscheduled users can perceive “spectral-holes” and use the idle spectrum that is not used by the primary user (PU) for data transmission. To achieve maximum resource utilization efficiency. In addition, two secondary user (SU) management schemes for continuing to wait and finding new subcarriers are given, and the delays under the two schemes are calculated. A new decision method is proposed to solve the problem of SU reconstruction. Numerical analysis shows that the new algorithm can ensure the fairness of users, effectively reduce system delay and improve system efficiency.

Keywords: CR; Proportional fairness algorithm; Spectrum-hole; Secondary user; Throughput.

1. Introduction

At present, the demand for communication services is growing rapidly, and spectrum resources are scarce. However, some frequency bands are not used by users for most of the time, and some frequency bands are only occasionally used, and the use of the remaining frequency bands is fiercely competitive. Therefore, how to fully utilize the idle frequency band in different time and space and improve the utilization rate has become a problem of great concern. The proposed cognitive radio (CR) provides a new way to improve spectrum utilization [1]. Its core idea is to perceive "spectral holes" (spectral resources that have been allocated to a user but not used for a certain period) and make reasonable use of it [2]. In the past, research on CR was mainly limited to CR itself. Study its transmission protocol to study the throughput problems of primary user (PU) and secondary user (SU) under the system [3][4]. The current research focuses on how to enable SU and PUs to collaborate in data transmission. For example, the Ref. [4] proposes to cooperate with the PU and SU in the CR network, that is, the SU as the PU relay for data transmission to maximize network efficiency. With the deepening research on cognitive wireless, people have gradually applied cognitive technology to other networks in recent years. The Ref. [5] applies cognitive technology to sensor networks to study system congestion. Thereby achieving the purpose of improving the quality of service and real-time reliable application. In addition, an effective resource allocation method is also an effective way to solve the lack of spectrum resources. The Ref. [6] studies the proportional fair scheduling algorithm, which is an effective resource allocation method considering system performance and user fairness [7]. This paper proposes to incorporate cognitive technology into the proportional fair scheduling algorithm in solving the problem of unscheduled users. So unscheduled users can perceive "spectral holes" and use the idle spectrum that is not used by the PU for data transmission. (Such unscheduled users can perceive "spectral holes" and use the idle spectrum that is not used by the PU for data transmission.) To achieve maximum resource utilization efficiency. In addition, this paper also considers the problem that the channel available time
is less than the SU transmission time, and proposes a new decision method to solve the problem of how to reconstruct the SU. This method of decision can effectively reduce system delay and improve system efficiency.

2. Proportional Fair Scheduling Algorithm
The proportional fair scheduling algorithm is a compromise between providing fairness and overall system throughput [8]. When the user needs to transmit information, it sends a request data rate to the base station, and then the base station tracks the user's window length to \( n_t \). For the moving average throughput of each resource block \( n \), in time slot \( t \), the proportional fair scheduling gives the user who satisfies the following formula in the \( t \)th time slot and the \( n \)th resource block a maximum priority[9][10]:

\[
M^* = \arg \max_{n=1,2,\cdots,N} \frac{R_{n,t}(t)}{T_{n,t}(t)}
\]

where \( R_{n,t}(t) \), \( n = 1,2,\cdots,N \) is the instantaneous rate of the \( m \)th user at the \( n \)th resource block at the \( n \)th transmission time interval[11]. \( T_{n,t}(t) \) is the user \( m \) in each resource block \( n \) in the \( t \)-slot window length is \( t_e \). Average mobile throughput.

The instantaneous rate of the \( m \)th user on the \( n \)th subcarrier can be obtained by the following equation[12]:

\[
R_{n,m}(t) = \frac{B}{N \log_2(1 + SNR)}
\]

where \( R_{n,m}(t) \) is the transmission rate of the \( m \)th user in the \( n \)th time slot, and \( B \) is the total bandwidth \( N \) is the number of subcarriers. The \( SNR \) is the signal to noise ratio and its expression is as follows [13]:

\[
SNR_{n,m}(t) = \frac{S_{n,m}(t) H_{n,m}(t)}{N_0 B/N}
\]

where \( S_{n,m}(t) \), \( H_{n,m}(t) \) are the transmission power and channel gain of the \( n \)th transmission time interval, respectively. \( N_0 \) is the power spectral density of additive white Gaussian noise, \( B \) is the total bandwidth, and \( N \) is the number of subcarriers.

The average throughput can be updated with an exponentially weighted low pass filter:

\[
T_{n,m}(t+1) = \begin{cases} 
  \left(1 - \frac{1}{t_e}\right) T_{n,m}(t) + \frac{1}{t_e} R_{n,m}(t) & \text{the user is scheduled at time } t \\
  \left(1 - \frac{1}{t_e}\right) T_{n,m}(t) & \text{the user is not scheduled at time } t 
\end{cases}
\]

where \( t_e \) is the window size length.

3. New Algorithm with CR Technology
Different from the previous proportional fairness algorithm, this algorithm is mainly for unscheduled users in the proportional fair scheduling algorithm [14]. The steps of the new algorithm are as follows:
Algorithm 1. New algorithm with CR.

**Input:** $R_{m,n}(t)$

**Output:** SU

According to the requested data rate $R_{m,n}(t)$ get channel quality information.

**while** $(R_{m,n}(t)/T_{n,a}(t) = \max(R_{m,n}(t))$ and SU==PU **do**

{}\]

Dispatch this user;

if Until the next user satisfies

block Step 2, this user will have no permissions to be scheduled;

else

{Schedule those users in these resource blocks;
SU perceive spectrum holes;
Assign the perceived free subcarriers to SU;
}

Repeat this cycle;

This paper assumes that the free subcarriers perceived by the SU are all correct, that is, there is no missed detection. Then, at time $t$, the throughput of user $r$ in subcarrier $k$ is:

$$C_{r,k}(t) = \Delta f \log_2 (1 + SNR_{r,k}(t))$$

(5)

where $\Delta f$ is the band width of the free subcarrier accessed by the SU, $SNR_{r,k}(t)$ is the SNR of user $r$ on subcarrier $k$ at time $t$. Combined Eq. (5), the total perceived throughput of the user at time $t$ can be expressed as:

$$T_r(t) = \sum_r \sum_k \theta_{r,k} C_{r,k}(t)$$

(6)

$\theta_{r,k} = 1$ indicates that subcarrier $k$ is occupied by SU $r$, and $\theta_{r,k} = 0$ indicates that subcarrier $k$ is not occupied by SU $r$. Similarly, $\theta_{m,n} = 1$ indicates that the $n$th resource block is occupied by user $m$, and $\theta_{m,n} = 0$ indicates that the $n$th resource block is not occupied by user $m$. Combine Eq. (1)–(5) with cognitive technology $t+1$ the throughput of the system at the moment is expressed as:

$$T(t+1) = \sum_m \sum_n \theta_{m,n} \left[ \left( 1 - \frac{1}{T_c} \right) T_{m,n}(t) + \frac{1}{T_c} R_{m,n}(t) \right] + \sum_k \sum_r \theta_{r,k} C_{r,k}(t+1)$$

(7)

According to the Ref. [6], if the cognitive technology is not added, the throughput of the system at $t+1$ is expressed as:

$$T(t+1) = \sum_m \sum_n \theta_{m,n} \left[ \left( 1 - \frac{1}{T_c} \right) T_{m,n}(t) + \frac{1}{T_c} R_{m,n}(t) \right]$$

(8)

where $\theta_{r,k}, \theta_{m,n}$ is 0 or 1. From the comparison of Eq.(7) and Eq.(8), it can be seen that as long as the SU successfully accesses the free subcarrier, the system throughput under the algorithm will be improved.

4. Management of SU

On the basis of the new algorithm, the management of SU is realized. The management of the SU is to quickly find new available spectrum or continue to wait after the SU withdraws from the subcarrier of the PU. Waiting for the spectrum to become idle again to continue data transmission. The specific process is shown in Fig.1.
The meaning expressed in Fig.1(a) is that when the PU arrives during the SU transmission, the SU immediately withdraws, waiting for the PU to transmit the data, and continues to transmit the remaining data on the atomic carrier. The meaning expressed in Fig.1(b) is that when the PU occupies the subcarrier, the SU immediately withdraws, looks for a new subcarrier, and then retransmits all the data on the new subcarrier. Suppose the PU and SU have a packet size of \( L_{PU} \) and \( L_{SU} \), the transmission rate are \( C_{PU} \) and \( C_{SU} \), respectively. Then, in the case of Fig. 1(a), the time required for the SU to successfully transmit a data packet (ignoring the switching time) is

\[
T_S = k_p L_{SU} / C_{SU} + L_{SU} / C_{SU} ,
\]

where \( k_p \) represents the number of times the PU arrives. Suppose that in the transmission process of SU in \((0,L_{SU}/C_{SU})\), PU reaches uniform distribution at any time in time period \((0,L_{SU}/C_{SU})\).

![Figure 1. Schematic diagram of SU data transmission for two reconstruction schemes.](image)

(a) Interrupt waiting. (b) Finding new subcarriers.

Then, in the case of Fig. 1(b), In CSMA/CA mechanism, when a cognitive node has data packets to send, it will select a random double back-off time \( BT \) in the \([0, BT_{max}]\) range, where \( BT_{min} \) is the minimum back-off time. When the back-off attempt is the \( i \)th time, a random back-off time is selected from the range of \([0,2^i BT_{min}]\) having a continuous uniform distribution, and the back-off time is expressed as

\[
D_{op} = \sum_{i=0}^{k-1} 2^i BT ,
\]

where \( BT \sim U(0, 2^i BT_{min}) \) is a random variable, \( P_b \) is the probability that the channel is busy in the carrier sensing, that is, the back-off probability, and \( k \) is the maximum number of back-offs. Then the time required for the SU to successfully transmit a data packet is expressed as

\[
T_C = L_{SU} / 2C_{SU} + D_{op} + L_{SU} / C_{SU} .
\]

5. **Numerical Analysis**

In this part, we will show the change of system throughput before and after adding cognitive technology, the value of \( T_S \) under different \( k_p \), and the relationship between \( T_C \) and back-off times \( k \) when SU transmit a data packet under different back-off probability. We will compare the size of \( T_S \) and \( T_C \), and then give the decision basis when SU face the problem of reconfiguration. Take the following analysis \( L_{PU} = 60 \) bytes, \( C_{PU} = 60k \) bps, \( L_{SU} = 30 \) bytes, \( C_{SU} = 30k \) bps, \( B = 5M \) Hz, \( N = 300 \), \( \Delta f = 2.5 \times 10^3 \) Hz.

Fig.2 shows the relationship between the number of PUs \( m \), throughput \( T \) and \( SNR_{n,a} \) without adding cognitive technology. It can be seen from the figure that the system throughput increases with the increase of the number of users. When the number of users is constant, the larger the \( SNR_{n,a} \), the greater the throughput of the system, indicating that the better the channel quality, the better the performance of the system.
Figure 2. The relationship between throughput $T$ and number of users $m$ under different $\text{SNR}_{n,\alpha}$.

Fig.3 shows the change of system throughput after adding cognitive technology. It can be seen from the figure that when the number of PUs is fixed, the cognitive technology is added to make the unassigned users become SU, and the "spectrum holes" are perceived to be used for data transmission. Obviously, as the number of SU increases, the throughput of the system also increases.

Figure 3. The relationship between system Throughput $T$ and $r$ under different $m$, $\text{SNR}_{n,\alpha} = 40$, $\text{SNR}_{\beta} = 20$.

It can be seen from Fig.2 that the system throughput is about 0.3 at the time of 5 PUs without adding cognitive technology. Fig.3 shows that when the cognitive technology is added, when there are 5 PUs, when a SU successfully accesses the free subcarrier, the throughput of the system is about 0.4. It can also be seen from the comparison between Fig.2 and Fig.3, in the case that the number of PUs is constant, the more the number of SUs successfully accessing subcarriers, the greater the throughput of the system. Therefore, it is explained that as long as there is a successful access subcarrier for the SU, the new algorithm proposed by the cognitive technology can improve the system throughput.

Figure 4. The relationship between back-off times $k$ and $T_c$ under different $P_b$.

Fig.4 shows the relationship between the number of back-off $k$ and $T_c$ for different $P_b$, and also shows the size of $T_c$ when $k_p$ is 1 and 2 respectively. It can be seen from the figure that the $T_c$ increases with the increase of the number of back-off $k$, indicating that the more back-offs, the longer the waiting...
time. (It can be seen from the figure that the $T_C$ increases with the increase of the number of back-off $k$, indicating that the more the number of back-off, the longer the waiting time.) When the number of back-off $k$ is constant, the larger the probability of evasion, the larger the $T_C$ will be. It can also be seen that when $k_p = 1$, the value of $T_S$ is always below $T_C$, indicating that when the SU is transmitting data, when the PU arrives once, the SU only needs to wait for the subcarrier to change. For data transmission for idle, a small delay can be obtained without re-finding new subcarriers. When $k_p = 2$, it can be seen that the value of $T_S$ is always above the $T_C$, indicating that if the PU arrives twice when the SU performs data transmission, the SU needs to search for a new subcarrier for data transmission to reduce Small system delays. In practice, the frequency of arrival of the PU can be monitored, which provides a reference for the two reconstruction schemes of the SU.

6. Conclusion

In order to further improve the throughput of the system, we propose to incorporate CR technology into the proportional fair scheduling algorithm, and derive the expression of the system throughput under the new algorithm, to ensure the fairness of the user and the throughput of the system. Improvement, this is also verified in numerical analysis. At the same time, it also considers the management problem of SU, that is, how to reconstruct users. In the article, two reconstruction schemes are given, and the delays under the two schemes are calculated. Finally, through numerical analysis, it is concluded that if the PU only arrives once when the SU performs data transmission, then to reduce the system delay, the SU only needs to wait for the PU to transmit the data, that is, wait for the child. (it is concluded that if the PU only arrives once when the SU performs data transmission, then in order to reduce the system delay, the SU only needs to wait for the PU to transmit the data, that is, wait for the child.) Data transmission may be performed when the carrier is idle again. Otherwise, new subcarriers need to be searched for data transmission.

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