An Adaptive Wireless Resource Allocation Scheme with QoS Guaranteed in Smart Grid

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***Abstract*—Data transmission via wireless communication is crucial for smart grid. Wireless resource allocation is applied to provide different levels of Quality-of-Service (QoS) in wireless communication systems. In this paper, we propose an Adaptive Wireless Resource Allocation (AWRA) scheme with Quality of Service (QoS) guarantee, which includes channel allocation and time scheduling. According to QoS requirements, packets are assigned one of three different priorities, so that AWRA performs flexible and efficient channel allocation based on packets' priorities, thus satisfying a specific QoS requirement. Given transmission power and Packet Loss Rate (PLR), a mathematical optimization framework is formulated for maximizing the total capacity. Using the channels' quality indicated by Signal Noise Ratio (SNR) of a node, the proposed scheme allocates the channels to the predefined packet types. An adaptive-scheduling scheme based on the Residual Life Time (RLT) of packets is further introduced, where the value of RLT determined by the threshold of packet's tolerable waiting time is updated after each transmission. The proposed method aims to ensure the packets' QoS requirements by transmitting the packets with high priority on the high-quality channels. Simulation results show that the proposed algorithm may considerably reduce the data drop rate and satisfies the packets' QoS requirements of smart grid.**

I. INTRODUCTION

The emergence of the smart grid is based on the development of high-speed communication network. It can apply modern technologies of communication, information, computer and control to meet the user's electrical demand and optimize the resource allocation to ensure the security, reliability and economy of electricity supply. In order to adapt to the development of electricity market, it provides the reliable, economic power supplying and interactive value-added services. Table I depicts the salient features of the smart grid in comparison with the existing grid [1].

TABLE I: The smart grid compared with the existing grid.

the current grid	smart grid
Electromechanical	Digital
Centralized Generation	Centralized or Distributed Generation
Hierarchical	Network
Few Sensors	Sensors Throughout
Blind	Self-Monitoring
Manual Restoration	Self-Healing
Manual Check/Test	Remote Check/Test
Limited Control	Pervasive Control
Few Customer Choices	Many Customer Choices

According to the spectrum defined by State Radio Regulatory Commission (SRRC) in China, the available wireless frequency band for the electrical usage is within 223MHz $\sim$ 231MHz, which is overlapped with other wireless local area networks, such as astronomy systems and radio location systems, resulting in severe performance degradation due to external interference [2]. Our target is to allocate resource adaptively with Quality of Service (QoS) guarantee in whatever situation of interference.

Because of the different varieties of grid data acquisition, there are some periodic data, such as: voltage, current, the requirement of delay is not much strict. But there are some unexpected data, such as: power outages, equipment failures, need to reach instantly. There are some businesses including real-time business and non-real-time business. Real-time business requires low latency and can tolerate a certain amount of packet loss rate, while non-real-time business requires low packet loss rate and less harsh latency requirements. Meanwhile, due to the large number of users in the grid, it is unreality to send those messages together because of insufficient resource. There must exits some data should be sent firstly and other later, therefore, how to allocate resource is worth researching. Resource allocation schemes are necessary to enhance the performance of wireless network in smart grid in order to guarantee successful data transmission and to satisfy the users' requirements [3]. In general, the performance assessment for the scheduling algorithms uses the following parameters:

1) Throughput: it can be understood as a radio resource utilization, including the short-term throughput for the single-user and long-term throughput for the entire system.
2) User fairness: it reflects the user accesses to the wireless

resource, including two facts: short-term fairness of equitable allocates resource for users on high-quality channels; long-term fairness of equitable allocates resource for all users.

3) The maximum packet delay: this parameter is especially important for delay-sensitive services.
4) The complexity of the algorithm: it indicates the total time that the duration of each scheduling adds the computing cycle of a scheduling algorithm.

In this paper, we propose an Adaptive Wireless Resource Allocation (AWRA) algorithm with QoS guarantee in communication network of smart grid. The algorithm not only considers the information of physical layer information, but also takes account of the characteristic of messages from the media access control layer and the QoS requirements to allocate the resources. We allocate wireless resource adaptively based on not only data's priority, but also the Residual Life Time (RLT) of packets in order to satisfy QoS requirements.

The rest of this paper is organized as follows. In Section II we describe related work for smart grid. System model is presented in section III. An AWRA scheme is developed to improve the level of service quality in Section IV. Some mathematical analysis for the proposed system is presented and simulation results are provided in Section V. We conclude with the summary and future work discussion in Section VI.

II. RELATED WORK

Currently, the major wireless resource scheduling algorithms can be divided into two categories: one kind is resource scheduling algorithm which only considers the channel quality information of the physical layer (PHY-layer), the other kind is cross-layer resource scheduling algorithm which combines the channel quality information of the PHY-layer and the buffer queue information from the media access control layer (MAC-layer). There are three classic kinds of algorithm about the resource scheduling of only considering PHY-layer: Round Robin (RR) scheduling algorithm, Max Carrier to interference ratio (C/I) scheduling algorithm, Proportional Fairness (PF) scheduling algorithm [4][5]. In smart grid, there is a common disadvantage about these three kinds of algorithm, they don't consider the data condition in the buffer queue. In this case, when the length of buffer queue is zero, the algorithm may allocate resource for it which may result in resource wasting.

A. RR Scheduling Algorithm

The basic idea is to ensure that the users occupy the radio resources within a certain equal time to communicate with the order recycling in RR algorithm. Each scheduling does not consider the service condition of user in the past, it means that there is no memory. Each user Corresponds to a queue to store the data which is waiting for transmission. Non-empty queue accepts the way of Round Robin to transmit data.

RR algorithm [6] considers that different users have the same priority, it can not only guarantee the long-term fairness among users, but also ensure that the user's short-term fairness, and the complement of RR algorithm is very simple. The RR algorithm always is the most effectively algorithm to protect the fairness among the users. Because of the RR algorithm does not take advantage of the system's effective information, such as, carrier to interference ratio, when the channel conditions of some users which are very bad can also get service that make a waste of system resources. As a result, the system throughput is relatively low.

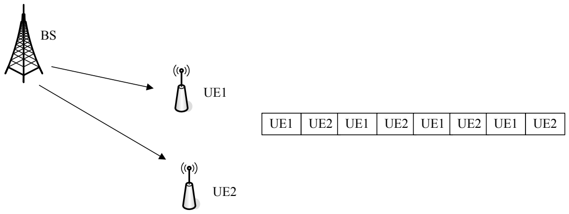

Fig. 1: RR algorithm resource allocation

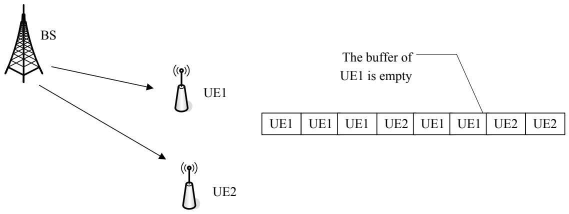

Fig. 2: Max C/I algorithm resource allocation

The left part of Figure 1 depicted the distance from the base station to UE1 and UE2, the right part expresses the result of the physical channel resources allocation in accordance to the RR algorithm. Although the distance is different from the base station to UE1 and UE2, the RR algorithm assigns the same time of using channels to UE1 and UE2 that results in resource wasting.

B. Max C/I Scheduling Algorithm

The Max C/I scheduling algorithm [7] is entirely based on the quality of the channel to perform scheduling, without taking into account of the requested amount of the user's data and the queue information of the other users. It always make the user occupy the best channel to transmit data. When the condition of the channel has decreased, then BS selects the following best channel. Therefore, by using this algorithm, the system throughput is the largest. However, in wireless communication, the user's location is different, the intensity of receiving signal is not the same. So in this case, the node near the base station will always receive services, while the users at the edge have little opportunity to get service due to the relatively low C/I, so this scheduling algorithm is unfair.

Figure 2 shows the result of the resource allocation in the system under maximum C/I scheduling algorithm. It can be observed that only when the buffer data of UE1 have transmitted completely under the channel of better conditions, then the system begans to schedule UE2.

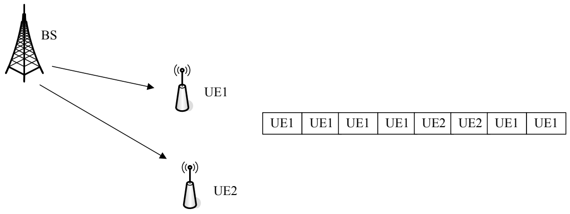

Fig. 3: PF algorithm resource allocation

C. Proportional Fairness(PF) Scheduling Algorithm

The PF algorithm [8] is a compromise algorithm, it considers the channel quality and the throughput over a period of time. Figure 3 shows the result of the resource allocation in the system under PF scheduling algorithm. Although the UE1's channel conditions are better than the UE2's, but after a period of time, the average throughput of UE2 drops, as a result the priority increases, so the UE2 can still be scheduled. The main advantage of the PF algorithm is considering channel conditions and the fairness of service, it can make some compromise between system throughput and fairness, so it is a generic method.

D. Insights

In the above section, we introduce some related algorithms, but there are some disadvantages [9]. First of all, the essence of the above algorithms are fixed priority algorithms, it means that each packet's priority is given, resource is allocated according to the pre-defined proportion of weight, the allocation of resource does not change compared to other algorithms which have dynamic priority. Therefore such algorithm results in a declining system throughput. Secondly, these algorithms [10] only consider the requirements of Bit Error Rate (BER) and the minimum transmission rate. However, in the coexistence of multiple services network, the resource allocation algorithm takes into account of the characteristic of delay, the packet should be sent subject to the delay time below a desired threshold. Besides the delay time, Packet Lost Rate (PLR) should also be considered. Researching on resource scheduling algorithm which can meet different users with different QoS is of great significance [11]. How to allocate resource to meet the need of different users which have different bandwidth requirements, different delay protection and different QoS level is a critical issue. In order to complete the task, the resource allocation algorithm considers the different resource requirements of different users, rather than a fair share of resources for the users absolutely. Therefore in this paper, we propose a scheme which is described in next section to adhere to the above-mentioned desired properties. However, it is worth noting that the wireless resource allocation scheme can be only appropriate for control purposes, but not be used for protection purposes in the smart grid.

III. SYSTEM MODEL

In this paper, we research on the problem of adaptive wireless resource allocation. For real-time business, if the delay of the packets is greater than the delay threshold, then the packet is discarded, while for non-real-time services, as long as the queue does not overflow, the packet will not be discarded. In this paper, we assume that the queue is infinite and don't consider the discarded packet caused by queue overflow and the problem of retransmission. In addition, we assume that the total transmission power of the base station in the sub-channels is average distribution. Because, on the one hand, the loss of throughput of the system is very small through the average distribution of power among sub-channels, on the other hand such distribution greatly reduces the computational complexity of the algorithm.

We propose that the system of the smart grid contains 19 plots, each plot has 3 sectors. We propose each sector has N sub-channels and K packets. It is assumed that base station has perfect and instant channel information for all downlink transmissions via the feedback channel. To describe the optimization problems, we firstly define the work of Base station as follows [12].

1) Detect stage: the base station selects a beam to transmit a signal to measure the user's Signal to Noise Ratio (SNR);
2) Feedback stage: the user feedbacks the Channel State Information (CSI) of the time - frequency channel;
3) The base station collects the feedback information and allocate space, time, frequency resource for the user to transmit data based on certain scheduling criteria.

Then we define some notation as follows. B is the whole bandwidth of the available wireless frequency band, we divide the whole channel into N sub-channels. So the bandwidth of the sub-channel B_0 is $\frac{B}{N}$. The downlink diagram of a multi-user system is depicted as Fig 4. the transmitting power of each sector is denoted by P_T. packets are classified into two collections: A_0, A_1. If the packet k is non real-time services, packet k$\in A_0$, else packet k$\in A_1$. If the k^{th} packet is allocated on the n^{th} sub-channel, the resource allocation indicator $\rho_{k,n}$ =1, else $\rho_{k,n}$=0. S_k denotes the volume of the k^{th} packet. Transmission rate $C_{k,n}$ of the k^{th} packet on n^{th} sub-channel can be expressed as

$$C_{k,n} = B_0 * log_2(1 + P_{k,n} * \gamma_{k,n}) \tag{1}$$

where $P_{k,n} = P_T/N$ is the transmitting power when the k^{th} packet on the n^{th} sub-channel, $\gamma_{k,n}$ denotes the SNR of the k^{th} packet on the n^{th} channel.

Considering the real-time services, packet loss rata is often an important indicator of the QoS measurement. If the waiting time of the data exceeds the waiting time threshold, the packets will be dropped. In a period of time, the percentage of the lost packets denotes by PLR, expressed as η_k. As considering the non real-time services, throughout is an important indicator of QoS. We divide packets into three categories which are denoted as Φ_1, Φ_2, Φ_3 according to the degree of priority. α_{Φ_i} i$\in \{1, 2, 3\}$ denotes the utility parameters of messages from high priority to low. We set $\alpha_{\Phi_1} = 0.6, \alpha_{\Phi_2} = 0.3, \alpha_{\Phi_3} = 0.1$. T_n^{th} denotes the waiting time threshold of delay queue on the

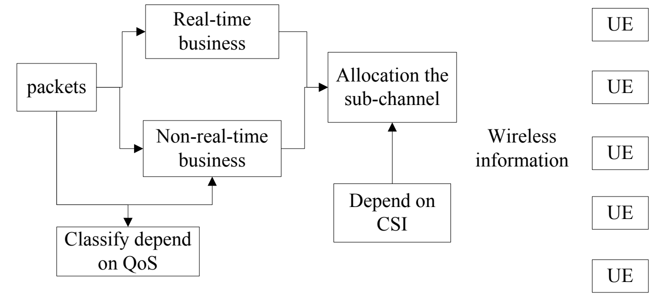

Fig. 4: Downlink diagram of a multi-user system

n^{th} channel. D_k^* denotes maximum delay time that the k^{th} packet can be tolerated. D_k denotes the time of the k^{th} packet delay. Based on the above analysis, the optimization model of maximizing the total capacity of a channel allocation problem can be defined as follows:

$$max \sum_{k=1}^{K} \alpha_{\Phi_i} \sum_{n=1}^{N} \rho_{k,n} C_{k,n} \tag{2}$$

s.t.

$$\eta_k \leq \eta_k^{req} \ , k \in \Phi_i \tag{3}$$

$$\sum_{n=1}^{N} \rho_{k,n} = 1, k \in \{1, 2, \ldots, K\} \tag{4}$$

$$D_k \leq T_n^{th} \tag{5}$$

Formula (3) indicates the PLR of packets k$\in \Phi_i$ can not surpass the threshold η_k^{req}. Formula (4) indicates each packet can transmit on one sub-channel every time. Formula (5) indicates the waiting time of k^{th} packet delay in the queue should be less than the waiting time threshold on the n^{th} channel.

IV. THE RESOURCE ALLOCATION SCHEME

Formula (2) expresses a problem of assembly optimization. There is no effective way to obtain the optimal solution for this problem currently. In this paper, we put up a sub-optimal algorithm, the steps of the algorithm are described as follows:

A. Information Classification

At time t, there are several packets which need to be allocate resource. According to the degree of business requirements, these packets can be divided into three packets which are denoted as Φ_1, Φ_2, Φ_3. The steps of classifying packets as follows:

1) Initialization: Let $\Phi_1 = \Phi_2 = \Phi_3 = \phi$. We define the set of available sub-channels as $\Omega = \{1, 2, \ldots N\}$, where N is the sequence number of available sub-channels, n$\in$ Ω, and we define the set of available packets $\Phi = \{1, 2, \ldots K\}$, where K is the total number of available packets, k$\in$ Φ. Let $\rho_{k,n}$=0.
2) For k$\in$ Φ: If $D_k^* \leq 3ms$, $\Phi_1 = \Phi_1 + \{k\}$. If $3ms < D_k^* \leq 100ms$, $\Phi_2 = \Phi_2 + \{k\}$. If $D_k^* > 100ms$, $\Phi_3 = \Phi_3 + \{k\}$.

Algorithm 1 The process of AWRA algorithm

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Require: $R_k$:the RLT of $k^{th}$ packet.
  $\Phi$: The set of packets.
  $\Omega$: The set of all sub-channels.
  $\Gamma$: The set of available sub-channels.
  $\gamma_{k,n}$: The SNR of the $k^{th}$ packet on the $n^{th}$ channel.
  $D_k$: the time of the $k^{th}$ packet experienced delay.
  $T_n^{th}$: the waiting time threshold of delay queue on $n^{th}$ channel.
Ensure: $\Omega = \{1, 2, 3, .., N\}$
  while $\Omega \neq \{\emptyset\}$ and $\Phi \neq \{\emptyset\}$ and $\Gamma \neq \{\emptyset\}$ do
    $k = min\{R_k\}$
    for all $n^*$ in $\Omega$ do
      $n^* = arg \overset{max}{n \in \Omega} \{\gamma_{n,k^*}\}$
      $\Phi = \Phi \backslash \{k^*\}$
      if $D_k > T_n^{th}$ then
        $\Omega = \Omega \backslash \{n^*\}$
      end if
    end for
    for all $n^*$ in $\Gamma$ do
      $n^* = arg \overset{max}{n \in \Gamma} \{\gamma_{n,k^*}\}$
      $\Phi = \Phi \backslash \{k^*\}$
      if $D_k > T_n^{th}$ then
        $\Gamma = \Gamma \backslash \{n^*\}$
      end if
    end for
  end while
```

B. Sub-channels Allocation

Then we allocate sub-channels for the packet k belong to Φ_1, Φ_2, Φ_3:

1) Considering the source of the packets, because the packets come from different nodes which have different available sub-channels. We define nodes as $N_1, N_2, \ldots$,with regard to the packet i come from node N_i, the available sub-channels are $\Gamma = \{f_1, f_2, \ldots f_{N_i}\}$. Besides, RLT is an important factor should be considered in the process of scheduling. When several packets are transmitted into the same sub-channel, the packet which has the least value of RLT should be transported in advance. $R_k = D_k^* - D_k$, R_k denotes the RLT of the k^{th} packet.
2) According to the priority, we should allocate sub-channels for the packet k$\in$ Φ_1. we should choose the packet which has the least value of RLT in advance, Seek $k^* = min\{R_k\}$. Packet k^* comes from node N_{k^*}, the available sub-channels are $\{f_1, f_2, \ldots f_{N_{k^*}}\}$, then we seek $n^* = arg \overset{max}{n \in \Omega} \{\gamma_{n,k^*}\}$. If $f_{n^*} \in \{f_1, f_2, \ldots f_{N_{k^*}}\}$, we allocate the n^* channel for the k^* packet. Therefore $\rho_{k,n}$=1. Until the packet in the buffer queue have be fully transmitted. After allocation sub-channel for k^*, we set $\Phi_1 = \Phi_1 \backslash \{k^*\}$ and then transmit the following packets, then let $D_k = \sum_{i=1}^{k-1} t_{i,n}$. Where $t_{i,n} = S_i / C_{i,n}$ denotes the transmitting time of the i^{th} packet on the n^{th} sub-channel. If $D_k > T_n^{th}$, we

set $\Omega = \Omega \backslash \{n^*\}$ and repeat the above procedure until $\Omega = \phi$ or $\Phi_1 = \phi$.

3) If $\Phi_1 = \phi$ but $\Omega \neq \phi$, then we allocate sub-channels for the packets k$\in \Phi_2$, repeat (2) until $\Omega = \phi$ or $\Phi_2 = \phi$.
4) If $\Phi_2 = \phi$ but $\Omega \neq \phi$, then we allocate sub-channels for the packets k$\in \Phi_3$, repeat (2) until $\Omega = \phi$ or $\Phi_3 = \phi$.
5) If there are some packets which come from certain nodes and can not find available sub-channels, packet k^* come from node N_{k^*}, the available sub-channels are $\{f_1, f_2, \ldots f_{N_k}\}$. Set k^* packet on the n^* channel, $f_{n^*} \notin \{f_1, f_2, \ldots f_{N_{k^*}}\}$, we allocate sub-channels for packet k^*, Seek $k^* = min\{R_k\}$. $n^* = arg \underset{n \in \Gamma}{max}$ $\{\gamma_{n,k^*}\}$, $\Phi_1 = \Phi_1 \backslash \{k^*\}$, If $D_k > T_n^{th}$, set $\Gamma = \Gamma \backslash \{n^*\}$, repeat the above procedure repeat the above procedure until $\Gamma = \phi$ or $\Phi_1 = \phi$.
6) If $\Phi_1 = \phi$ but $\Omega \neq \phi$, then we allocate sub-channels for the packets k$\in \Phi_2$, repeat(5) until $\Gamma = \phi$ or $\Phi_2 = \phi$.
7) If $\Phi_2 = \phi$ but $\Omega \neq \phi$, then we allocate sub-channels for the packets k$\in \Phi_3$, repeat(5) until $\Gamma = \phi$ or $\Phi_3 = \phi$.

V. SIMULATION RESULTS AND PERFORMANCE ANALYSIS

In this section, we verify the performance of the proposed resource allocation algorithm through numerical simulation and comparing with traditional PF algorithm. The parameters of simulation scene shown in Tabel II. In order to reflect the intuitive nature of the simulation performance, we defined that $\eta_k < 0.02$ is satisfied by real-time packets. In order to evaluate the performance of the proposed algorithm,we define four metrics, including the average PLR, the average delay time of packet, average transmitting rate and overall system throughput. We will compare our algorithm with the following PR algorithm in these metrics respectively. The first two evaluation metrics are used for real-time services and we use the messages of VoIP as representatives of real-time services. The third evaluation metric is used for non-real-time services and we use the messages of FTP as representatives of non-real-time services. The results for the various evaluation criterions were given in the following figures.

TABLE II: Simulation parameters

Simulation parameters	Value
Residential structure	19 plots,3 sectors
Channel model	typical urban
Carrier frequency	2GHz
Bandwidth	10MHz
The maximum transmit power on base station	46dbm
The noise index on base station	5dbm
The number of sub-channels	50
Latency threshold	30ms
PLR threshold	0.02

Figure 5 shows that When the system load in the range of 0.1 to 0.5, the PLR of VOIP is almost zero. When the system load is less than 0.6, the average PLR under the algorithm is less than the maximum value of the services can be tolerated (VoIP services is 0.03). However, when the system load increases, the PLR of services is rising rapidly. This is because most of sub-channels are used to request real-time services transmission, thus some of the other's packets must wait for a very long period of time to occupy sub-channels, the load has been far beyond the system capacity. In addition, it can be observed that the PLR of the proposed algorithm is always lower than the PF algorithm. This is flexible because the algorithm provides a more flexible priority calculation. According to the number of packets and the delay time, the priority is adjusted to meet the requirements of the real-time services.

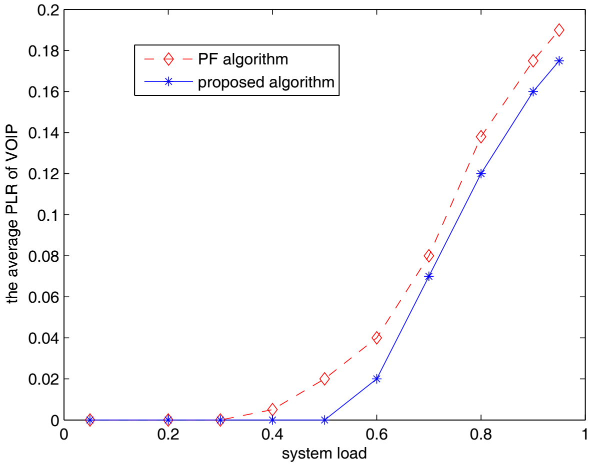

Fig. 5: The average PLR of real-time services

Figure 6 shows that the average delay time of real-time services under the proposed algorithm is lower than the PF algorithm. The reason is similar with the average PLR, because the algorithm gives higher priority to the real-time services.

Actual system generally does not allow the load is too high, so the main consideration of system load range is from 0.2 to 0.7. Therefore, considering the average PLR and average packet delay requirements of the real-time services, this algorithm basically meets the QoS requirements.

Figure 7 shows the average transmission rate of the FTP service performance. FTP services does not request a minimum transmission rate, but the algorithm in the system load is still able to provide higher transmission rates. as the system load increases, the average transmission rate decreases rapidly, however, compared to the PF algorithm, the proposed algorithm is able to provide a better average transmission rate. This is because this algorithm makes a better utilization of the multi-packet diversity.

Figure 8 shows that the proposed algorithm can provide higher system throughput. When the system load is high, the system throughput can reach at 23 Mbps which is very closed to the maximum throughput under ideal conditions. The system throughput of Max C/I algorithm is the highest while the RR algorithm is the lowest.

In summary, when the system load is less than 0.7, the proposed algorithm can basically meet the different QoS

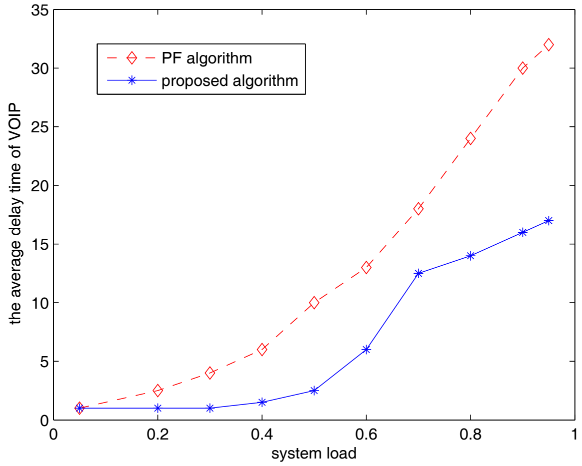

Fig. 6: The average delay time of real-time services

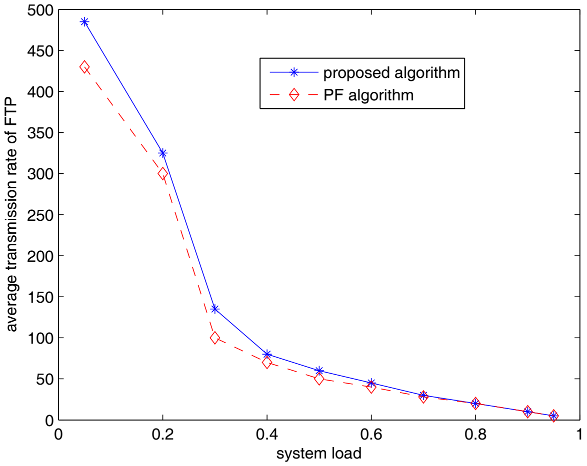

Fig. 7: The average transmitting rate of non-real-time services

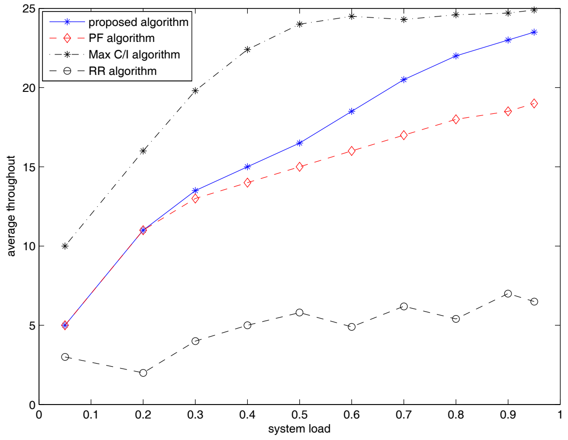

Fig. 8: System throughput

requirements of different services. The proposed algorithm gives the real-time services a higher priority, thereby improves the perception of the real-time services, and makes better use of the non-real-time services which demands less delay requirements, finally improves the spectrum utilization of the system. From the above simulation, the proposed resource allocation algorithm can not only reduce the PLR of packets significantly, but also improve the throughput performance.

VI. CONCLUSION

In this paper, based on the different delay queues and QoS requirements of packets in smart grid, we proposed an AWRA algorithm which classifies the packets into three categories and optimally allocated wireless resource for these packets. The process of resource allocation considers the length of packets delay queue, RLT, the QoS requirements of packets and the channel condition. Simulation results show that the proposed algorithm can reduce the PLR of real-time services, improve the throughout performance and satisfy the packets' QoS requirements of smart grid.

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