

# DECENTRALIZED TRANSMISSION STRATEGY FOR DELAY-SENSITIVE APPLICATIONS OVER SPECTRUM AGILE NETWORK

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## ABSTRACT

With the growing demand of radio resources, maximizing spectrum efficiency becomes increasingly important. Traditional static spectrum allocation lacks the mechanisms for sharing the spectral resources between different allocated bands. Hence, spectrum agility which allows the radio devices to dynamically use the idle spectral band is attracting more and more attention.

In this paper, we show how spectrum agility can be used to satisfy delay sensitive applications over wireless networks. We show that the performance of networks using spectrum agility presents significant improvements over existing network. By utilizing a decentralized, non-cooperative channel searching and switching strategy, different users with various throughput requirements can share the available channel resources in an efficient way to satisfy their own packet loss and delay constraints.

## 1. INTRODUCTION

Current spectrum policy divides the spectrum into a number of allocated bands. Radio devices are only allowed to operate in their designated spectrum bands. Actually, recent measurements by the US Federal Communications Commission (FCC) have shown that even in major urban areas, only 30% of the allocated spectrum is being utilized at any one time. An extreme case is that, when some users suffer from poor performance in an over-crowded band, there might be other idle bands available. However, current regulation prohibits such users from switching to the idle bands which obviously results in an inefficient utilization of precious spectrum resources.

As radio spectrum becomes increasingly scarce, new proposals are now surfacing to utilize opportunistic spectrally agile radios (OSAR) over allocated but often unused frequency spectrum. For example, the FCC has issued a Notice of Public Rulemaking and Order regarding cognitive radio technologies [1]. The Defense Advanced Research Projects Agency (DARPA) has also launched the neXt Generation (XG) Communications program to develop new technologies which allow users to share the spectrum through

adaptive mechanism [2]. In both programs, the concept of spectral agility allows radio devices to dynamically use the idle or sparsely-used spectral bands and hence to increase the overall spectrum efficiency.

In a spectrum agile network (OSAR), different users can be divided into two classes which are, respectively, primary users who have the exclusive access to their designated spectral bands and secondary spectral agile users who are allowed to switch to another channel when no primary user is active on that channel. In this paper, we mainly focus on networks containing only secondary users since the presence of primary users can be viewed as variation of total available spectral bands at any time.

While conceptually simple, the realization of OSAR is highly challenging. Several problems must be solved: sensing over a wide frequency band; identifying and characterizing available spectrum opportunities; coordinating among devices the use of identified opportunities; exploiting the identified transmission opportunities etc.

In this paper, we address the problem of how to coordinate transmission opportunities for delay-sensitive applications over OSAR. Similar problem of dynamic channel allocation has also been studied in cellular network which is more focused on reducing the failure rate when a newly active mobile terminal can not be assigned to a channel, or to minimize the Carrier-to-Interference ratio (CIR). Lots of centralized/distributed, fixed/dynamic/hybrid algorithms have been summarized and compared in [3]. However, these channel allocation mechanisms deal with the geographic reuse of the same channel based on co-channel reuse constraint or/and hand-off dropping probability constraint. In these algorithm, only channel allocation for the newly active user is considered, while in spectrum agile system, channel allocation is done for all the active users based on all the available transmission opportunities.

Other research on channel allocation has also been done for a decentralized peer-to-peer wireless network, such as sensor network, with the objective of minimizing the entire energy consumption [4] [5] [6]. However, in this paper, the objective of our channel allocation mechanism is different and can be summarized as:

- Maximum number of satisfied users whose QoS (e.g. delay, packet loss etc.) can be fulfilled.
- Fast reaction of the secondary users to dynamic changes in the OSAR network (arrival of new primary users, secondary users...)

By designing a coordination or channel assignment mechanism, we want to reach a balanced position among these requirements. We consider a system which is divided into  $N$  channels.  $M$  users transmit their delay-sensitive data in this system with various traffic rates. We adopt a simple MAC layer model with random access mechanism which assumes that each user can randomly put one of its packets into any time slot without considering the packet collision.

For satisfying the QoS requirements (delay and packet loss constraints) of the users, we propose a solution which uses the concept of spectrum agility. Our solution employs a decentralized strategy, in which various active users in different spectrum bands are competing to access the channel resources. Each user tries to best meet its QoS (throughput, delay) constraints by sensing and switching channel in a distributed and sequential manner. The advantages of this distributed transmission strategies are the ease of deployment and reduced overhead.

The rest of this paper is organized as follows. In Section 2, we present a general overview of our system. Section 3 describes in details our optimization problem and solution. Simulation results are shown and discussed in Section 4. Finally, Section 5 concludes the paper.

## 2. SYSTEM MODEL

We consider a system of  $N$  channels (spectrum bands). There are totally  $M$  users transmitting their packets in this system. Initially, each user is assigned to its designated channel. In conventional system, all the users will stay on their channels even though they can experience better performance in some other less-crowded channels. However, with the concept of spectrum agility, users are enabled and encouraged to switch to other channels to optimize their own performance.

We also divide each channel into time slots which are the smallest time unit of data transmission. Each user transmits its data in the smallest unit of packet and the transmission of each packet requires one time slot. We assume that all the channels have the same channel capacity:  $R$  packets per unit time, while different users have different traffic rates:  $r_i$   $i = 1, 2, \dots, M$ , packets per unit time.

For simplicity, we make the assumption that each user transmits its packets in a random and non-collaborative manner which means each user randomly picks a slot to transmit one of its packets, not considering whether other users are using this slot or not. Hence, for any user, each time

slot has the same probability of getting a packet. We assume that the number of users is greater than the number of channels ( $M > N$ ), therefore different users have to share the same channel which results in packet collision (or packet loss). Packet loss may also be caused by noise corruption in our system. We consider a simple Additive White Gaussian Noise (AWGN) channel and assume that different channels have different Signal to Noise Ratio (SNR)  $\Upsilon_i$   $i = 1, 2, \dots, N$ .  $\Upsilon_i$  is a constant value for every user transmitting in the  $i^{th}$  channel. Denote  $C(i)$   $i = 1, 2, \dots, M$  as the channel number that  $i^{th}$  user is currently using. Hence, the packet loss rate for the  $i^{th}$  user can be expressed as:

$$P_i = 1 - (1 - P_e(\Upsilon_{C(i)})) \prod_{\substack{k:k \neq i \\ C(k)=C(i)}} (1 - \frac{r_k}{R})$$

where  $P_e$  is the packet error rate due to the noise corruption.

Moreover, we assume that each user is subject to the following two requirements: maximum delay and maximum packet loss rate (PLR) constraints. Ensuring these two constraints is very important for real time applications, such as, video conferencing, real time multimedia streaming, etc. For improving the PLR, we consider a very common strategy called ARQ or retransmission. Each packet will be retransmitted until it is correctly received or the maximum number of allowed retransmission is reached. The retransmission limit of the  $i^{th}$  user is denoted as  $q_i$ ,  $i = 1, 2, \dots, M$ . Hence, the effective PLR  $\rho_i$  of the  $i^{th}$  user can be expressed as,

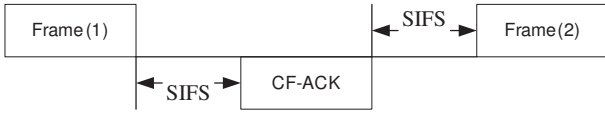
$$\rho_i = P_i^{q_i+1}$$

For analyzing the average transmission delay experienced by each users, we use the model as described in [7]. Considering the transmission of a packet with a payload of  $L$  bits, the average transmission duration for a good cycle,  $T_g$ , where neither the data packet nor the acknowledge packet (CF-ACK) is in error, can be obtained from the timing interval given in Fig. 1. Similarly, the worst transmission duration for a bad cycle,  $T_b$ , in a cycle where the CF-ACK packet is in error can be computed from the timing interval given in Fig. 2. Hence, the average transmission duration  $D_{avg}^i$  of one packet for the  $i^{th}$  user with the retransmission limit of  $q_i$ , can be obtained as follows:

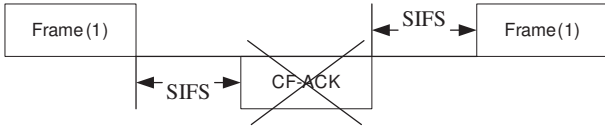
$$D_{avg}^i = (q_i + 1)P_i^{q_i+1}T_b + \sum_{k=0}^{q_i} P_i^k (1 - P_i)(k \cdot T_b + T_g)$$

and the average transmission delay  $D_i$  for the  $i^{th}$  user,  $i = 1, 2, \dots, M$ , can be expressed as:

$$D_i = r_i \cdot D_{avg}^i$$



**Fig. 1.** Successful frame transmission and associated timing.



**Fig. 2.** Retransmission due to CF-ACK transmission error and associated timing.

It should be noted that although retransmission can dramatically reduce the PLR, it will also increase the delay. Hence, for those delay-sensitive applications, there is a strict restriction on the maximum number of retransmission. Combining ARQ with channel sharing mechanism using spectrum agility idea is a more effective solution to satisfy delay and PLR constraints simultaneously.

In this spectrum agile system, we assume that after sensing over the whole spectrum, each user has perfect knowledge of all the information that is useful for decision making, such as SNR level in each channel, traffic volume over each channel etc. Then, the problem we want to address is that, based on all these available information, how do we determine the channel assignment (which users can transmit over which channels) to optimize performance for these delay and PLR sensitive applications over OSAR.

### 3. PROBLEM STATEMENT AND SOLUTION

To address this dynamic channel allocation problem, two possible solutions can be identified: one is based on a centralized transmission strategy and the other based on a decentralized transmission strategy. In the centralized strategy, every user (wireless terminal) should inform a central coordinator about its QoS requirements, experienced channel condition etc. Subsequently, this coordinator will fairly allocate the available channels among the different users. However, this strategy would incur additional transmission overhead and there would be additional system costs associated with the operation and maintenance of a dedicated OSAR control infrastructure.

In this paper, we propose a simpler and more flexible solution based on decentralized transmission strategies, in which various active users are engaged in a non-collaborative transmission. A common control (sub-)channel is allocated where information between the various transmitter/receiver pairs can be exchanged, thereby enabling the various trans-

mitters to communicate to the receivers the channel(s) on which they transmit as well as other information necessary for transmission (e.g. desired or experienced QoS etc.). The advantages of this distributed transmission strategies are the ease of deployment and reduced overhead. However, providing optimal transmission for various applications under this transmission scenario is very challenging since multiple users with different application requirements and channel conditions are simultaneously competing over the available OSAR resources that are continuously changing.

In a distributed transmission, the incremental goal of the  $i^{th}$  user,  $i = 1, 2, \dots, M$ , can be expressed as:

$$\begin{aligned} \min_{\epsilon, q} \quad & \rho_i(\epsilon, q) = P_i^{q+1} \\ \text{s.t.} \quad & D_i(\epsilon, q) < D_i^{max} \end{aligned}$$

where  $D_i^{max}$  is the maximum delay constraint for the  $i^{th}$  user. This minimization is done for all the possible choice of channel  $\epsilon = 1, 2, \dots, M$  and for all the possible retransmission limit  $q$ .

Game theoretic formulation [8] [9] can help in ensuring good channel allocation performance in spectral agile networks.

#### 3.1. Introduction to Game theory

From a game theoretic perspective, every user in this spectral agile network can be modelled as a rational decision-maker. The following elements constitute a model of rational choice: a set  $A$  of actions from which the decision-maker (in our case each wireless terminal) makes a choice; a set of possible consequences  $C$  of these actions (e.g. increasing delay, packet loss etc.); a consequence function  $g: A \rightarrow C$  that associates a consequence with each action; and a preference relation (a complete transitive reflexive binary relation)  $\geq$  on the set  $C$ . The  $i^{th}$  decision-maker's preference,  $i = 1, \dots, M$ , is specified by a utility function  $U_i$ . The utility  $U_i$  defines the preference relation  $\geq$  by the condition,  $S_x \geq S_y$  if and only if  $U_i(S_x) \geq U_i(S_y)$  (where  $S_x$  and  $S_y$  are two possible strategies for the  $i^{th}$  player). A strategy for a decision-maker is defined as an action with its corresponding consequence. Let  $S_i$  be a strategy chosen by the wireless terminal  $i$ ,  $i = 1, \dots, M$ . Let  $S_{-i}$  denote the strategies adopted by wireless stations other than the wireless station  $i$ . Thus,  $S_{-i} = (S_1, \dots, S_{i-1}, S_{i+1}, \dots, S_M)$ . A strategy  $S^* = (S_1^*, \dots, S_i^*, \dots, S_M^*)$  is a Nash Equilibrium if and only if, for  $i = 1, \dots, M$ , and for all possible strategies  $S_i, U_i(S_i^*, S_{-i}^*) \geq U_i(S_i, S_{-i}^*)$ .

#### 3.2. Application of Game theory to streaming Multimedia over OSAR

We regard all the users in our spectral agile OSAR system as players engaging in a decentralized transmission compe-

tion game. Each player chooses a strategy that will influence the performance of the other players, as well as himself. In our setting, a player strategy is the selection of a channel and the choice of a retransmission limit.

For the  $i^{th}$  user, the utility  $U_i$  depends on the QoS of his application (e.g. the delay and packet loss required for a particular application). Hence, each player in the network will derive the following utility  $U_i$   $i = 1, 2, \dots, M$ , by selecting a channel and adopting a retransmission strategy:

$$U_i(\epsilon, q_i) = 1 - \rho_i = 1 - P_i^{q_i+1}$$

*given*  $D_i(\epsilon, q_i) < D_i^{max}$

where  $D_i(\epsilon, q_i)$  is the delay that the  $i^{th}$  user experiences on channel  $\epsilon$  if his retransmission limit is set to  $q_i$ . Note that the user's utility does not only depend on his strategy but also on all the other players' strategies.

Hence, the rules of this game can be summarized as, each user tries to maximize its utility function by switching to the best (least-crowded) channel and retransmitting within its delay constraint. All the users do this channel switching in a sequential way which means, at any time, only one user is allowed to switch.

This process leads to Nash equilibrium when no user wants to switch channel or change its retransmission strategy which indicates that any change in operating point near the equilibrium will decrease the utility of the user. Each user operates at an optimal operating point based on its requirements and on the OSAR network characteristics.

The solution of this distributed game may not be optimal. In fact, Nash equilibria are not necessarily the global optima. Moreover, by utilizing different channel sensing and switching protocol, the spectral agile system can reach different (sub)optimal point (Nash equilibrium). Indeed, Nash equilibrium is reached in a sequential manner by each user making a decision one after another. Hence, in order to control the order of this sequential decision making process, a protocol can prioritize the users based on different criteria, such as traffic rate, packet loss, etc, and then give some users the priority to make a decision before the others. In Section 4.1, we will assess the performance of different protocols.

## 4. SIMULATION RESULTS

We test our strategy in a system with 10 channels and 20 users. All the channels have the same channel capacity  $R = 5Mbps$  while each user's normalized traffic  $\frac{r_i}{R}$  is uniformly distributed over  $[0.02 \ 0.2]$ . Each channel is an AWGN channel with SNR uniformly distributed over  $[8 \ 12]dB$ . For calculating the packet error rate due to noise corruption, we assume that each user adopts BPSK modulation and each

packet contains 4000 bits. Concerning the transmission delays,  $T_b$  and  $T_g$  are equal and assigned value  $0.884ms$  (SIFS is set to  $10\mu s$  and the size of an acknowledgement packet is set to 320 bits).

We set the PLR constraint to be 5% and the delay constraint to  $250ms$ . 1000 monte carlo simulations are averaged to generate all the results.

### 4.1. Convergence to Nash Equilibrium

In our distributed and non-collaborative channel switching strategy, each user is not sophisticated enough to anticipate the rational decisions of the other users. Hence, Nash Equilibrium can only be reached in a successive manner until no user makes a movement.

In a practical wireless network, channel characteristics always undergo rapid changes and each user's traffic also varies quickly over time. All these changes require the system to reach new Nash Equilibrium. Moreover, channel scanning and switching cost extra expense, such as power consumption, transmission delay etc. Hence, fast convergence rate is critical for our strategy to respond promptly to channel and traffic changes, as well as to reduce extra cost.

We test the convergence properties of 4 different protocols from an initial random channel assignment:

- Round robin - Each user makes his decision sequentially.
- Ordered Round Robin - The higher-traffic users make their decisions before the lower-traffic users.
- Higher Packet Loss Priority - At any time, the user who experiences the highest packet loss rate makes a decision.
- Random - At any time, each user has the same probability to make a decision.

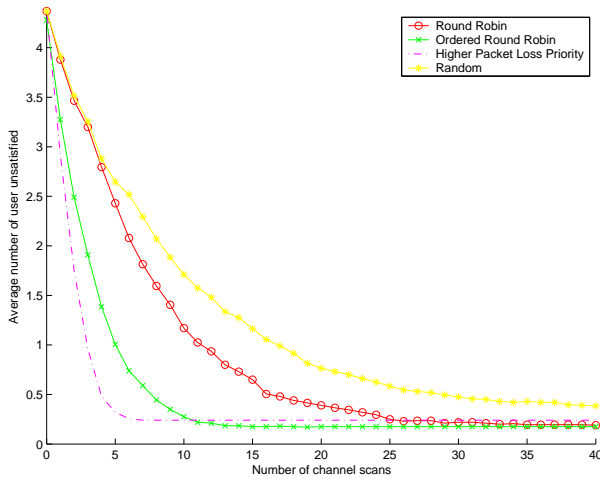
Note that, all the users of the OSAR network need to be synchronized to respect such protocols. A control channel can handle such a synchronization among the secondary users.

Fig. 3 and Fig. 4 show the average number of users whose packet loss and delay constraints can not be satisfied simultaneously after a certain number of channel sensing (Fig. 3) and switching (Fig. 4) respectively. As shown in these figures, all the protocols lead to Nash equilibria. Indeed, after a certain number of iterations, none of the users can increase its utility by switching to another channel. Note that with the chosen simulation parameters, even at Nash equilibrium, certain users still have a small probability of not satisfying their delay or(and) packet loss constraint.

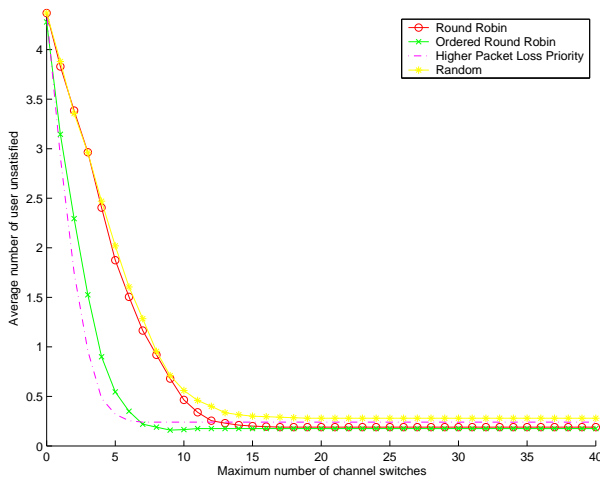
Moreover, these four protocols reach different Nash equilibria with different convergence rates. The Higher Packet

Loss Priority protocol which gives the priority to the user who experiences the highest packet loss rate converges faster to Nash equilibrium than the other protocols and hence reduces the number of unsatisfied users more quickly. However, at the equilibrium, the Ordered Round Robin protocol satisfies on average more users than the other 3 protocols.

Based on the previous observation, one possible solution is to start with the Higher Packet Loss Priority protocol, after several iterations, then switch to the Ordered Round Robin protocol until convergence. By doing so, the system can operate in an optimal way and maximize both the convergence rate and the number of satisfied users at the equilibrium.



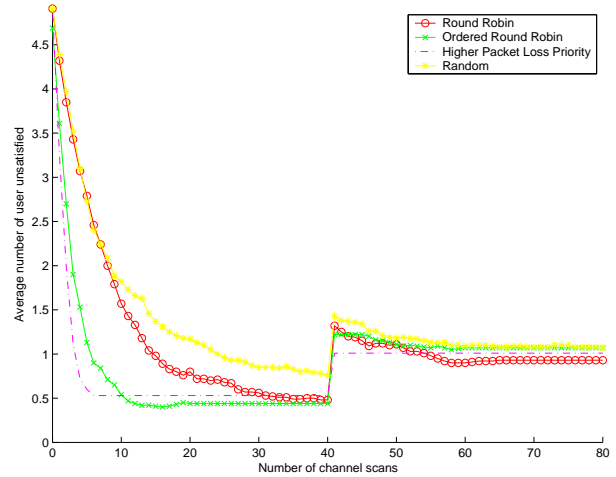
**Fig. 3.** Average number of unsatisfied users after a certain number of channel scans for uniform traffic distribution



**Fig. 4.** Average number of unsatisfied users after a certain number of channel jumps for uniform traffic distribution

Fig. 5 simulates the dynamic changes of the unsatisfied

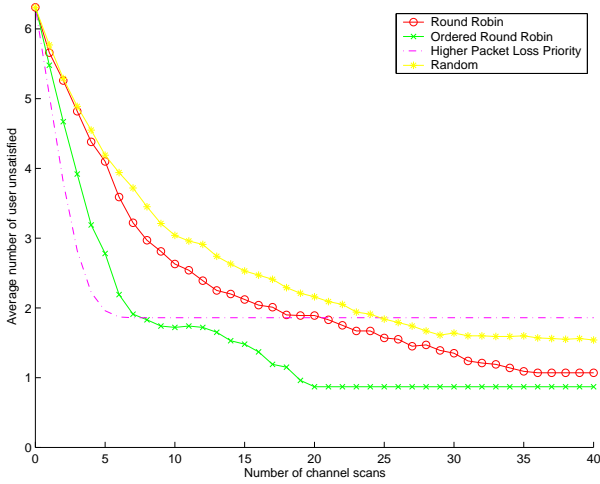
users due to the presence of primary users. In this simulation, after 40 channel scans, a primary user becomes active on one channel. Hence, all the secondary users who transmit their packets on this channel have to stop transmission and switch to other channels immediately. It is shown in Fig. 5 that the number of unsatisfied users increases suddenly after a primary user seizes the channel. However, our distributed channel switching mechanism can adapt to this dynamic changes and converge to the new equilibrium quickly, as well as decrease the average number of unsatisfied users.



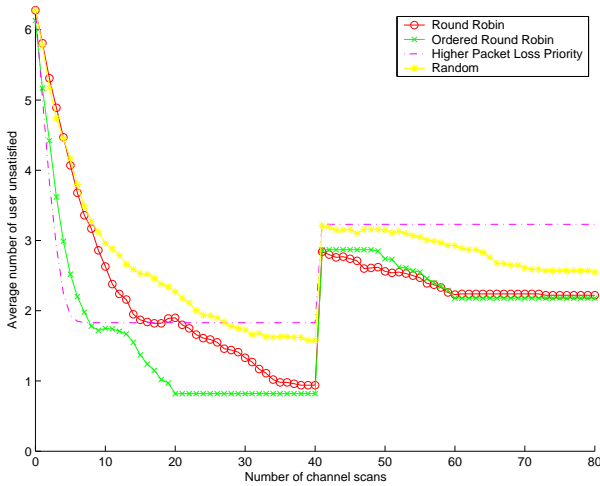
**Fig. 5.** Average number of unsatisfied users after a certain number of channel scans, for a uniform traffic distribution with one channel being occupied by a primary user after 20 scans

In order to shed light on traffic adaptivity of our dynamic channel switching mechanism, we also test it for a staircase distributed traffic instead of uniformly distributed one. In this simulation, we set two classes of traffic, one is low-rate traffic which requires 5% of the channel capacity, and the other one is high-rate traffic at 20% of the channel capacity. Each user is randomly assigned to one of the two traffic classes. Fig. 6 and Fig. 7 show the average number of unsatisfied users for a staircase traffic model. Compared to the uniformly distributed traffic model, the network contains more users with high traffic. As the high traffic users can not afford so many retransmission dues to their delay constraints, they generally suffer from a smaller probability of satisfying their packet loss constraint than lower-traffic users. This explains why the average number of unsatisfied users is larger in this staircase distributed traffic case. With the increase of the number of high traffic users, the Higher Packet Loss Priority protocol becomes less and less efficient due to the inflexibility of this protocol: as soon as the user which experiences the highest packet loss doesn't want to switch channel, the network reaches his equilibrium. For

this new traffic model, the Ordered Round Robin protocol not only has the fastest convergence rate, but also satisfies the maximum number of users at the equilibrium.



**Fig. 6.** Average number of unsatisfied users after a certain number of channel scans, for staircase traffic distribution



**Fig. 7.** Average number of unsatisfied users after a certain number of channel scans, for staircase traffic distribution with one channel being occupied by a primary user after 40 scans

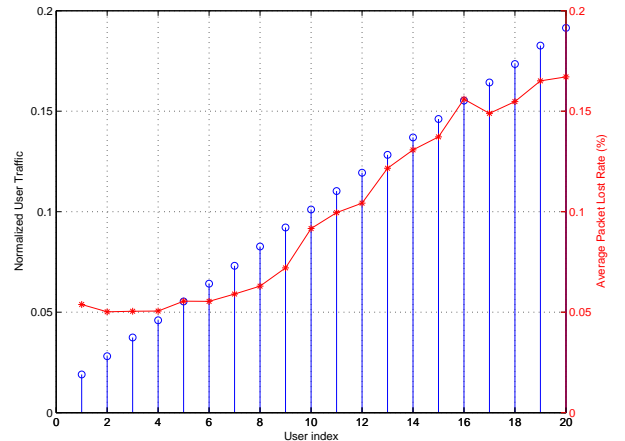
#### 4.2. Performance Gain by Spectrum Agility

In this simulation, we consider the performance gain achieved by the Ordered Round Robin channel sensing and switching mechanism compared with a static channel assignment.

Fig. 8 and Fig. 9 show the average packet loss rate for different users by using two different schemes: (1) only retransmission without sequential channel scanning and switch-

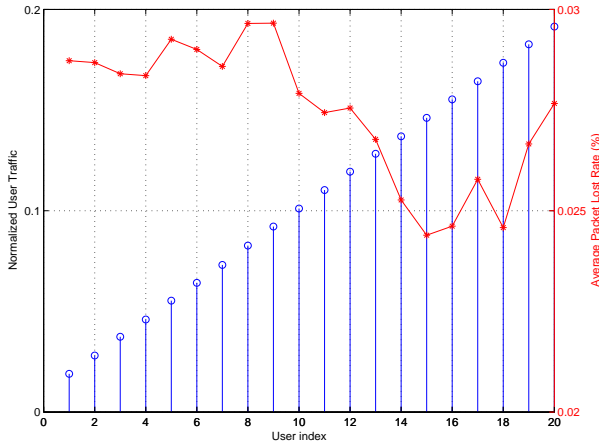
ing and (2) both retransmission and sequential Ordered Round Robin channel scanning and switching. For these two figures, users are shown in the increasing order of their traffic. Since all the users need to satisfy their own delay constraints, they can not make arbitrary number of retransmissions to meet their PLR constraints. That explains why in Fig. 8, even with retransmission, almost all the users can not satisfy their PLR constraints on average. In this case, some of the channels may be over-congested while some other channels might be sparsely-used or even idle. Hence, channel switching is important to guarantee the QoS of each user.

As shown in Fig. 9, by using channel scanning and switching, an (sub)optimal channel assignment can be reached where on average all the users' PLR and delay constraints (as shown in Fig. 10) can be satisfied. Also as shown in Fig. 10, in general, lower-traffic user will have more retransmissions than higher-traffic users which is predictable, since lower-traffic users have a higher probability of experiencing larger PLR because of sharing channel with higher-traffic users, but due to the low traffic rate, they can afford more retransmissions. These two factors of channel switching and retransmission balance each other and reach a fair assignment of radio resources for every user to meet both its PLR and delay constraints.

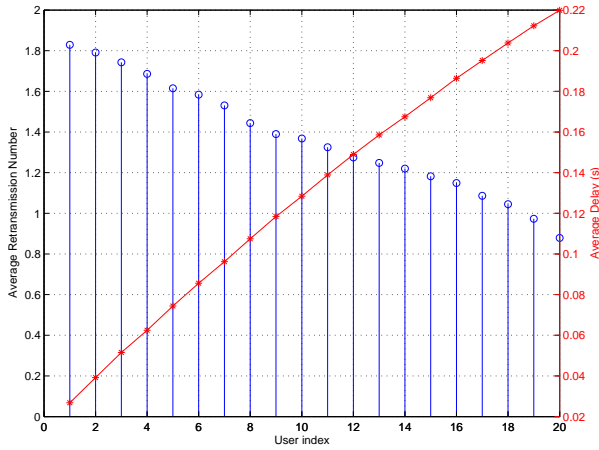


**Fig. 8.** Average packet loss rate without switching under uniform traffic distribution

We also test the performance of our mechanism under the staircase distributed traffic as defined in section 4.1. Performance of average packet loss rate and delay at the equilibrium are shown in Fig. 11 and Fig. 12 respectively. The same conclusion can be drawn from these two figures that all the users' QoS can be satisfied by utilizing this channel switching mechanism combined with retransmission strategy. Moreover, It should also be noted that, in this case, different users within the same class of traffic experience almost the same PLR and delay, which indicates the fairness



**Fig. 9.** Average packet loss rate of ordered round robin channel switching at the equilibrium under uniform traffic distribution

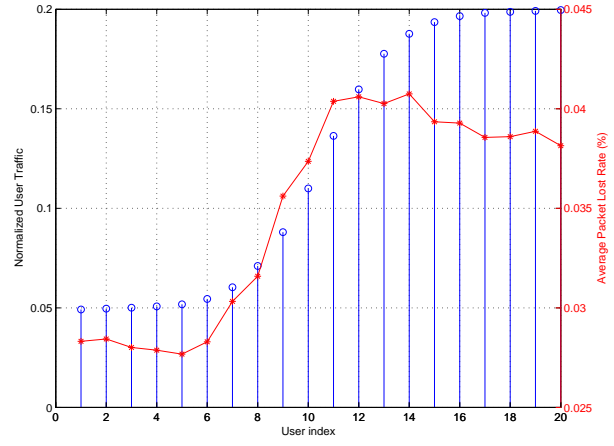


**Fig. 10.** Average delay of ordered round robin channel switching at the equilibrium under uniform traffic distribution

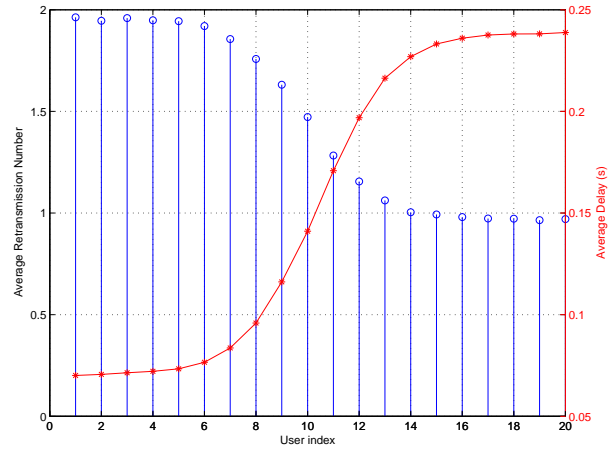
in our channel assignment. Actually, at the equilibrium, all the users with different traffic will be evenly distributed over available channels based on their PLR and delay constraints.

In an actual system, channel sensing and switching may introduce additional cost, such as power consumption, overhead and loss of connection, etc, which we ignore in our current simulation and channel switching mechanism. By considering this affect and trying to reduce the average channel sensing and switching, we may change our mechanism to be totally satisfaction based, which means if the active user can satisfy his QoS constraint on the current channel, he will stay even there might be better channel available.

Fig. 13 and Fig. 14 show the average PLR and delay for this new mechanism under an uniform distributed traffic. Compared to the Fig. 9 and Fig. 10, this mechanism



**Fig. 11.** Average packet loss rate at the equilibrium under staircase traffic distribution

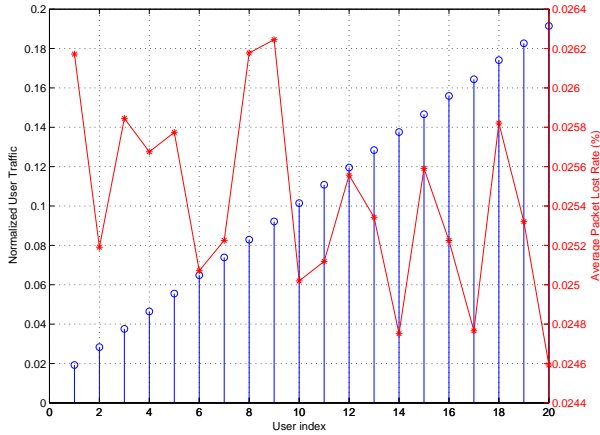


**Fig. 12.** Average delay at the equilibrium under staircase traffic distribution

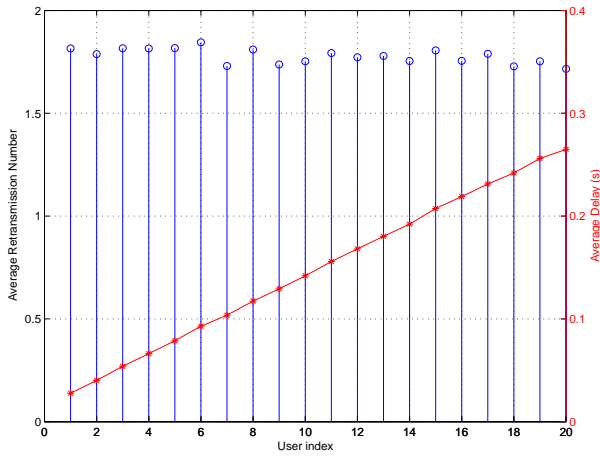
introduces small performance loss, especially in terms of the average number of retransmission. As shown in Fig. 14, almost all the users require the same number of retransmission to satisfy their PLR constraints, while in Fig. 10 and Fig. 12, typically higher-traffic users need less retransmission since they always occupy the best channel. If minimizing the average channel sensing and switching is most important, we can adopt this scheme that is totally depend on satisfaction, otherwise, for more efficient utilizations of spectrum resources, we should enable each user to find a better channel even his current channel can satisfy his QoS.

### 4.3. Traffic Splitting

As we stated in the previous section, due to the delay constraint, each user can not make arbitrary number of retransmissions to satisfy his PLR constraint. This problem is more



**Fig. 13.** Average packet loss rate under uniform traffic distribution for the channel switching mechanism totally depend on satisfaction



**Fig. 14.** Average delay after under uniform traffic distribution for the channel switching mechanism totally depend on satisfaction

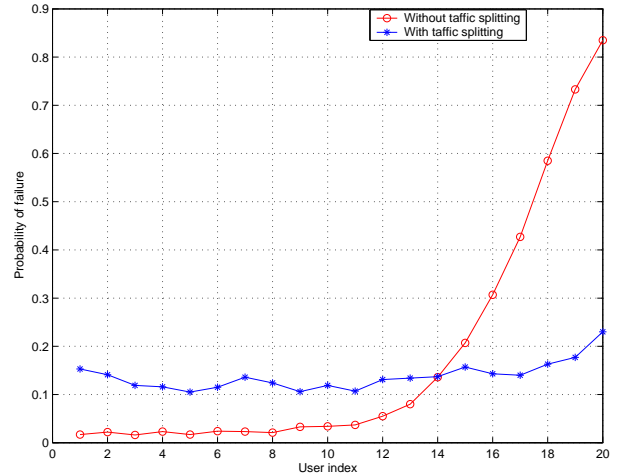
severe for the high-traffic users, since if all the users have the same delay constraints, the largest-traffic user has the smallest chance to retransmit its packets.

This problem is illustrated in the following simulation. We keep the PLR constraint as 5% and impose a more stringent delay constraint  $200ms$ . Solid curve with circle in Fig. 15 shows the average failure rate for different users in an increasing order of their traffic. A failure is defined as, at the equilibrium, both delay and PLR constraints can not be satisfied simultaneously. As shown by the curve, because of the strict delay constraint, the user with the largest traffic has a very high failure rate at about 82%.

One possible solution to this problem is traffic splitting. With the concept of spectrum agility, onboard intelligence may enable a wireless terminal to dynamically use a variety

of MAC, modulation schemes and acquire multiple channels access simultaneously. One example is adaptive modulation: higher modulation scheme can be used to occupy several adjacent frequency band and decrease the transmission rate. This gives the user more opportunities to retransmit its packet within its delay constraint.

In our simulation, we consider a simple case where, at any time, the user that obtains the chance to switch channel can split half of its traffic to the second best channel if his constraints can not be satisfied only with retransmission. Solid curve with asterisk in Fig. 15 shows the average failure rate for this traffic splitting scheme. By comparing these two curve, it is obvious that traffic division can greatly reduce the failure rate for the high-traffic users. However, users with lower traffic will suffer from higher failure rate as shown in this simulation, since the traffic from high-rate users will increase the PLR for the lower-traffic one.



**Fig. 15.** Average Failure Rate without and with traffic splitting in an increasing order of users' traffic

## 5. CONCLUSION

In this paper, we address the problem of ensuring QoS for delay and packet loss rate constrained applications over OSAR network. We investigate a distributed, non-collaborative channel switching mechanism to improve system performance by utilizing spectrum agility concept. Convergence rates of different channel switching protocols with various order have been studied by simulation in this paper. Also, simulation results shows that this mechanism satisfies more users, and hence more efficient utilization of available spectrum resources. We have also shown that our distributed transmission strategies can adapt to dynamic change in the network such as the presence of new primary users.



## 6. REFERENCES

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