DECENTRALIZED TRANSMISSION STRATEGIES FOR DELAY-SENSITIVE APPLICATIONS OVER SPECTRUM AGILE NETWORKS

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ABSTRACT

With the growing demand of radio resources, maximizing spectrum efficiency becomes increasingly important. Traditional static spectrum allocation lacks effective mechanisms for sharing spectral resources. Through adaptive resource allocation, spectrum agility allows the radio devices to dynamically use the idle spectral band and is becoming increasingly attractive because it can provide a large number of resources for delay sensitive and high-bandwidth applications such as multimedia transmission.

In this paper, we show how spectrum agility may be used to satisfy delay sensitive applications over wireless networks. Simulation results demonstrate that the performance of networks using spectrum agility presents significant improvements over existing networks. 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

Existing wireless networks are based on dynamically varying resources with only limited support for the Quality of Service (QoS) required by the delay-sensitive, bandwidth-intense and loss-tolerant multimedia applications. This variability of resources does not significantly impact delay insensitive applications (e.g. file transfers), but has considerable consequences for multimedia applications and often leads to unsatisfactory user experience.

The dominant concepts and techniques in wireline multimedia communications are not well suited for dynamic wireless environments. Too often, the research focus has been to modify existing algorithms and protocols to the rapidly varying resources of wireless networks. However, existing solutions do not provide adequate support for multimedia applications in crowded wireless networks, either when the interference is high or when the stations are mobile. To fulfill the necessary QoS requirements under such conditions, wireless stations need to harvest additional resources as well as optimally adapt their transmission strategies to the available resources.

Spectral agility provides a new direction for wireless multimedia services. Current policy divides the spectrum into a number of fixed bands and radio devices are only allowed to operate in their designated spectrum bands. 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. 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. In fact, the FCC has issued a Notice of Public Rulemarking and Order regarding cognitive radio technologies [1]. The Defense Advanced Research Project Agency (DARPA) has also launched the neXt Generation (XG) program to develop new technologies for spectrum sharing 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 this paper, we propose a new OSAR paradigm that allows competing wireless stations to dynamically exchange spectral resources and adapt their cross-layer optimized transmission strategies, to improve the quality of delay-sensitive multimedia applications. In particular, we will focus on OSAR networks [8][9] in which wireless stations can utilize various wireless channels, thereby dynamically gathering additional resources to satisfy multimedia delay and bandwidth requirements.

In OSAR networks, users can be divided into two classes: the primary users who have exclusive access to their designated spectral bands and the secondary spectral agile users that can access idle spectral bands when no primary users are active on them. For simplicity, we mainly focus on networks containing only secondary users since the presence of the primary users can be viewed as a variation of the available idle spectral bands.

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While conceptually simple, the realization of OSAR is highly challenging. Several problems must be solved: sensing opportunity over a wide frequency band; characterizing available spectrum opportunities; coordinating multiple access of the identified opportunities; and exploiting the identified transmission opportunities for users.

Our focus here is to coordinate transmission opportunities for delay-sensitive applications over OSAR. The similar problem of dynamic channel allocation has also been studied in cellular network which focuses on reducing the failure rate, or minimizing the Carrier-to-Interference Ratio (CIR). Various centralized or 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 constraints and hand-off dropping probability constraints. In these algorithms, only channel allocation for the newly active users is considered. On the other hand, channel allocation has also been studied for decentralized peer-to-peer wireless networks (e.g. sensor networks), with the objective of minimizing the entire energy consumption [4] [5] [6].

In this paper, since various users are simultaneously competing for resources to support different QoS (e.g. delay, packet loss etc) requirements, the objectives of our channel allocation mechanism can be summarized as:

- Maximize the number of satisfied users whose basic QoS can be fulfilled;
- Enable fast reaction of the secondary users to dynamic changes in the OSAR network (arrival of new primary users, secondary users, etc).

To achieve both objectives, we propose a channel assignment mechanism for spectrum agility. Employing a decentralized strategy, various active users in different spectrum bands compete to access the available channel resources. Each user needs to determine an optimal strategy to exchange its resources (spectral band) that will maximize its benefits (e.g. QoS) over time. The resource exchanges are likely to benefit both the welfare of the user and the overall system. The resource exchange strategies need to be dynamically derived by the users distributively. The advantages of distributed 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 with N idle channels (spectrum bands) and M (secondary) users. With spectrum agility, users can switch to other channels to optimize their own performance. For multimedia applications, packet loss and delay are two important factors affecting the QoS. Hence, analysis of packet loss and delay based on different channel conditions, number of users, traffic characteristics as well as MAC protocol is required for predicting/evaluating user QoS under different channel assignment.

We model each channel as a IEEE 802.11a network adopting the Distributed Coordination Function (DCF) as its MAC protocol. The analysis of packet loss and delay for DCF can be found in [7]. The packet loss rate can be expressed as

$$\rho = 1 - (1 - P_e)(1 - P_c)$$

where P_e is the probability of packet transmission failure due to channel interference, such as noise, multi-path interference, etc and P_c is the probability of packet loss due to packet collision. P_c and the delay depend on the number of users, their traffic rates and characteristics, their deployed cross-layer strategies (e.g. retransmission limits), etc. In [7], the packet loss and delay are analytically determined solely under the saturation condition, which assumes that each user transmits at the highest possible data rate. However, for our analysis, different wireless nodes may transmit at different rates, a case previously not considered in the statistical analysis [7]. Consequently, in this paper, we adopt a simplified approach for determining the packet loss rates and delays experienced by the various wireless stations that explicitly considers their traffic rates and various retransmission limits.

We divide each channel into time slots, representing the smallest time unit of data transmission. We assume that all the channels have the same channel capacity: R packets per unit time while different users have different traffic rates: $r_i, \;\; i = 1, 2..., M$, packets per unit time with $r_i \leq R$.

The packet transmission of each user is assumed to be random and non-collaborative, i.e. each user randomly picks a time slot to transmit one of its packets, not considering whether other users are using this slot or not. Thus, for any user, each time slot has the same probability of getting a packet. The number of users is assumed to be greater than the number of channels ($M > N$), therefore different users have to share the same channel which potentially can result in packet collision (and loss). In addition, packet loss can also be caused by noise corruption. We consider a simple Additive White Gaussian Noise (AWGN) channel with the assumption that different channels have different Signal to Noise Ratio (SNR) $\Upsilon_i, \;\; i = 1, 2..., N$. Υ_i is a constant value for all users transmitting in the i^{th} channel. Denote $C(i), \;\; i = 1, 2..., M$ as the channel number that the i^{th} user is currently using. Then, 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 $P_e(\Upsilon_{C(i)})$ is the packet error rate due to the noise and the last product term represents the collision probability experienced in channel $C(i)$ being used by the user i.

Furthermore, to provide the necessary QoS for a particular multimedia user, the following two requirements need to be satisfied: the delay should not exceed a maximum delay D_{max}, and the packet loss rate (PLR) should be minimized. To reduce the PLR, we consider a very common strategy called Automatic Repeat Request (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 $q_i,\ i = 1, 2..., M$. Hence, the effective PLR ρ_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 [8]. Considering the transmission of a packet with a payload of L bits, the average transmission duration for a good cycle is denoted as T_g while the worst transmission duration for a bad cycle is denoted as T_b. Therefore, the average transmission duration D^i_{avg} of one packet for the i^{th} $i = 1, 2, ..., M$ user with the retransmission limit of q_i, can be obtained as follows:

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

and the average transmission delay D_i for the i^{th} user can be expressed as:

$$D_i = r_i \cdot D^i_{avg}$$

It should be noted that although retransmission can dramatically reduce the PLR, it will also increase the delay. Hence, for delay-sensitive applications, such as multimedia streaming, there is a strict restriction on the maximum number of retransmission. To improve the performance of delay-sensitive applications, the cross-layer retransmission limits [9] can be further combined with spectrum agility.

In OSAR systems, each station senses a relatively narrow frequency band, and characterizes available opportunities for only a limited number of channels. We consider a case where the various stations exchange this information among themselves so that each user has knowledge about the channel characteristics and contention levels in all available channels.

3. PROBLEM STATEMENT AND SOLUTION

The main problem addressed in this paper is to determine the optimal channel assignment to maximize the number of users with satisfied QoS requirement. For dynamic channel allocation problem, two possible transmission strategies can be identified: one centralized and one decentralized. In the centralized strategy, each user should inform a central coordinator about its QoS requirements, current channel condition and loss. Subsequently, this coordinator will fairly allocate the available channels among the different users. However, this strategy would incur significant transmission overhead, as well as extra system cost associated with the operation and maintenance of a dedicated OSAR control infrastructure.

We propose a simpler and more flexible decentralized transmission strategy, 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 transmitters 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.

Game theoretic formulation [10] [11] can help in ensuring good channel allocation performance in spectral agile networks.

3.1. Introduction to game theory

Every wireless station i (i=1,...,M) in the OSAR network can be modeled as a rational decision-maker that deploys an utility function U_i and operates under a resource constraint RC_i. The utility U_i defines the preferential relationship between two possible strategies: $S_x \geq S_y$ if and only if $U_i(S_x) \geq U_i(S_y)$, while satisfying the resource constraint RC_i. Let S_i be a strategy chosen by the station i, i=1,...,M and S_{-i} denote the strategies adopted by wireless stations other than the station i, i.e., $S_{-i} = (S_1, ..., S_{i-1}, S_{i+1}, ..., S_M)$. A collection of strategies $S^* = (S_1^*, ..., S_i^*, ..., S_M^*)$ is a Nash Equilibrium if and only if, for $i = 1, ..., M$, 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 multimedia streaming over OSAR

We regard all the users in our spectral agile OSAR system as players engaging in a decentralized transmission competition game. User i employs a strategy S_i that determines how to change the retransmission limit q_i, whether to switch channels and which channel $C(i)$ to switch to based on whether the constraints $D_i(S_i) < D^i_{max}$ and $P_i^{q_i+1} < PLR^i_{max}$ are satisfied. $D_i(S_i)$ is the delay that the i^{th} station experiences, D^i_{max} is the maximum tolerable delay and PLR^i_{max} is the maximum tolerable PLR that can be determined based on the perceived quality degradation by the user. We define a utility function U_i as:

$$U_i(S_i) = \begin{cases} 1 - \rho_i = 1 - P_i^{q_i+1} & D_i(S_i) < D^i_{max} \\ 0 & otherwise \end{cases}$$

As a decentralized transmission strategy, we propose a simple game rule such that each user tries to maximize its utility function by switching to the best (least-crowded) channel and retransmitting within its delay constraint. Only one station is allowed to switch channels at each time instant and all stations deploy the same strategy for channel switching and cross-layer transmission. The system regulates the time instant and the order in which peers can play the game (select a channel).

The game between the wireless users converges to Nash equilibrium when no user wants to switch channel or change retransmission strategies (any change in operating point near the equilibrium will decrease the utility of the station). The solution of this distributed game may not be optimal as Nash equilibria are not necessarily global optima. By utilizing different channel sensing and switching protocol, the spectrum agile system can reach different Nash equilibria.

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.

Based on our distributed channel switching strategy, another important factor is the switching order which may lead to different convergence rate as well as system performance at the equilibrium. By prioritization, the system can regulate the time instant and the order in which uses can play the game (select a channel). We consider the performance of four different channel switching orders from an initial random channel assignment.

- Round robin - each user makes his decision sequentially.
- Ordered Round Robin - users with higher-traffic make their decisions before users with lower-traffic.
- Higher Packet Loss Priority - user experiencing the highest packet loss rate makes the decision.
- Random - 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. In Section 4.1, we will assess the performance of these different protocols by simulation.

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 with respect to 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 $0.884ms$.

We set the PLR constraint to 5% and the delay constraint to $250ms$. To generate the results, 1000 Monte Carlo simulations are averaged.

4.1. Convergence to Nash equilibrium

In this section, convergence properties of different switching orders as described in Section 3.2. are accessed by simulation. Fig. 1 and Fig. 2 show the system benefit in terms of the average number of users whose packet loss and delay constraints can not be satisfied simultaneously after a certain number of channel sensing (Fig. 1) and switching (Fig. 2) respectively. From the figure, we can observe the benefits of spectrum agility since the number of unsatisfied users at Nash equilibrium is considerably reduced compared with the starting point (which represents the performance of existing wireless networks where stations cannot migrate to alternate channels). 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, the different deployed resource exchange strategies reach different Nash equilibria with different convergence rates. The Higher Packet Loss Priority strategy converges faster to Nash equilibrium and hence reduces the number of unsatisfied users more quickly. However, at the equilibrium, the Ordered Round Robin strategy satisfies on average more users than the other resource exchange mechanisms.

Fig. 3 simulates the dynamic changes of 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. 3 that

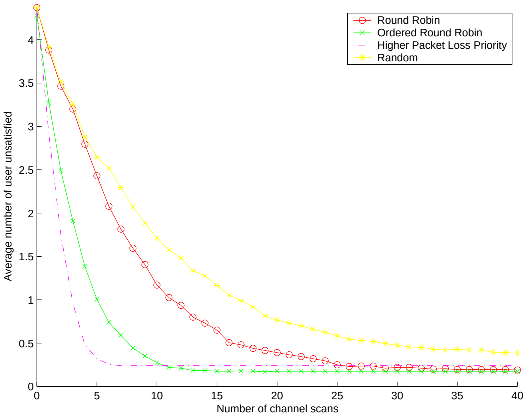

Fig. 1. Average number of unsatisfied users after a certain number of channel scans for uniform traffic distribution

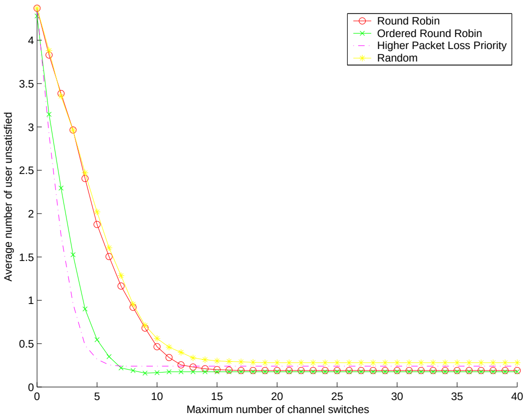

Fig. 2. Average number of unsatisfied users after a certain number of channel jumps for uniform traffic distribution

the number of unsatisfied users increases suddenly after a primary user seizes the channel. Our distributed channel switching mechanism can adapt to this dynamic changes and converge to the new equilibrium quickly. Note that since this change corresponds to perturbing a Nash equilibrium, the system converges rapidly to a new Nash equilibrium.

In order to shed light on the 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. 4 and Fig. 5 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. Since high traffic users cannot afford many retransmissions, they generally suffer from higher packet loss rates 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 efficient due to the inflexibility of this protocol: as soon as the user who experiences the highest packet loss does not want to switch channel, the network reaches its 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. Hence, Ordered Round Robin protocol is more robust than the other protocols.

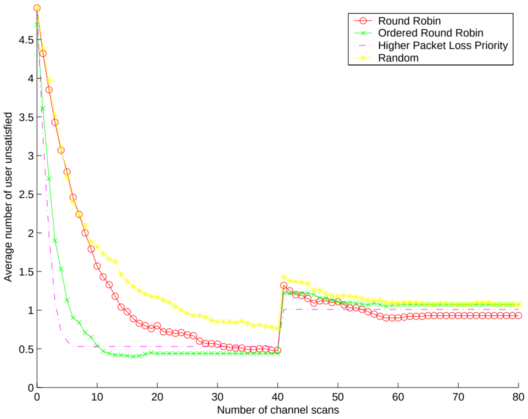

Fig. 3. Average number of unsatisfied users after a certain number of channel scans, for a uniform traffic distribution with one channel being occupied by a primary user after 40 scans

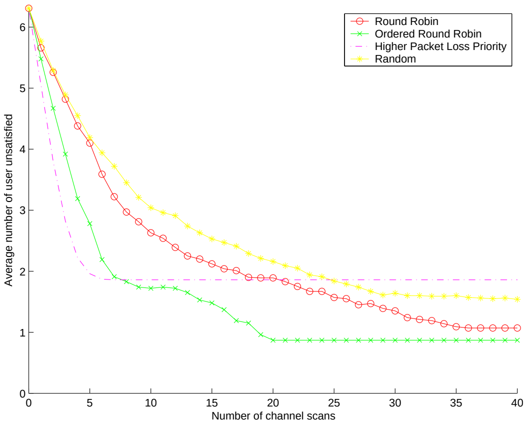

Fig. 4. Average number of unsatisfied users after a certain number of channel scans for staircase traffic distribution

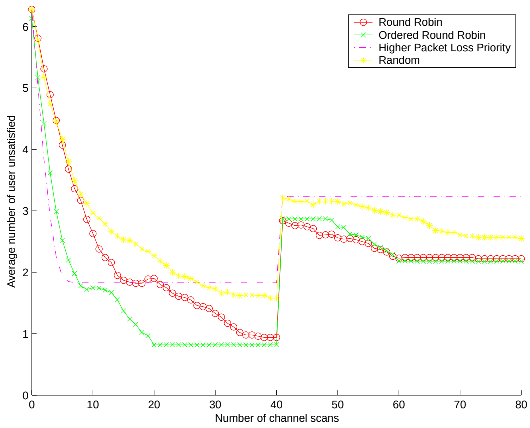

Fig. 5. Average number of unsatisfied users after a certain number of channel scans for staircase traffic distribution with one channel being occupied by a primary user after 40 scans

4.2. Performance gain by spectrum agility

In this simulation, we consider the performance gain achieved by the Ordered Round Robin protocols at the equilibrium compared with a static channel assignment.

Fig. 6 and Fig. 7 show the average packet loss rate for different users by using two different schemes: (1) only retransmissions without channel scanning and switching and (2) both retransmission and sequential Ordered Round Robin channel scanning and switching. In both figures, users are shown in the increasing order of their traffic. Since all the users are constrained by their own delay requirement, they cannot make arbitrary number of retransmissions to meet their PLR constraints. That explains why in Fig. 6, even with retransmission, almost all the users can not satisfy their PLR constraints on average. In general, 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. 7, by incorporating 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. 8) can be satisfied. Fig. 8 also indicates that, predicably, lower-traffic user in general will have more retransmissions than higher-traffic users, 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 spectral resources.

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. 9 and Fig. 10, respectively. The same conclusion can be drawn from these two figures that all the users's QoS can be satisfied by utilizing this channel switching mechanism. Moreover, It should also be noted that, in this case, different users within the same class of traffic experience similar PLR and delay, illustrating the "fairness" of our proposed channel assignment mechanism.

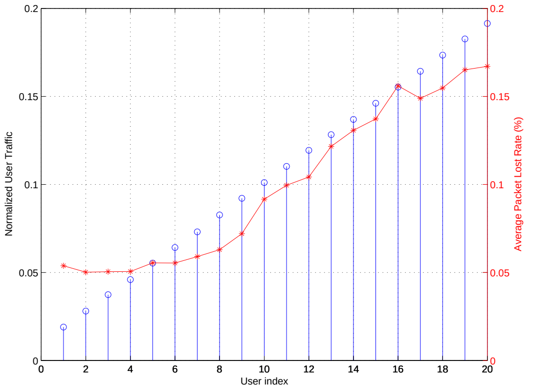

Fig. 6. Average packet loss rate without switching under uniform traffic distribution

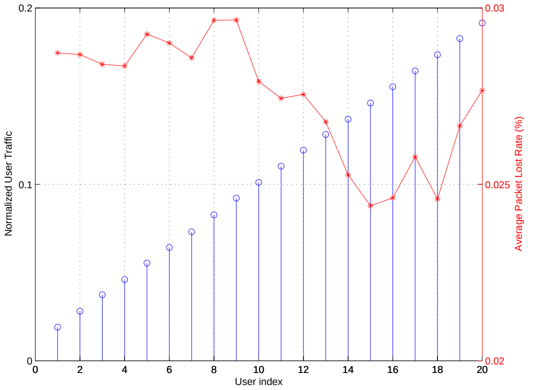

Fig. 7. Average packet loss rate of ordered round robin channel switching at the equilibrium under uniform traffic distribution

In an actual system, channel sensing and switching may lead to additional cost, such as power consumption, overhead and loss of connection. Taking this issue into consideration by reducing the average channel sensing and switching, our new mechanism encourages an active user to remain in a channel as long as his QoS constraints are satisfied, even though better channels are available.

Fig. 11 and Fig. 12 show the average PLR and delay for this new mechanism under an uniform distributed traffic. Compared to the Fig. 7 and Fig. 8, this mechanism introduces small performance loss, especially in terms of the average number of retransmission. As shown in Fig. 12,

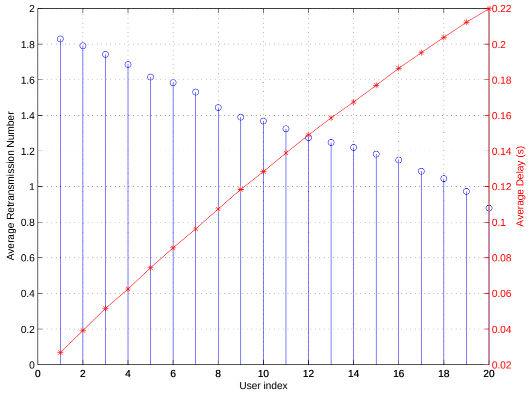

Fig. 8. Average delay of ordered round robin channel switching at the equilibrium under uniform traffic distribution

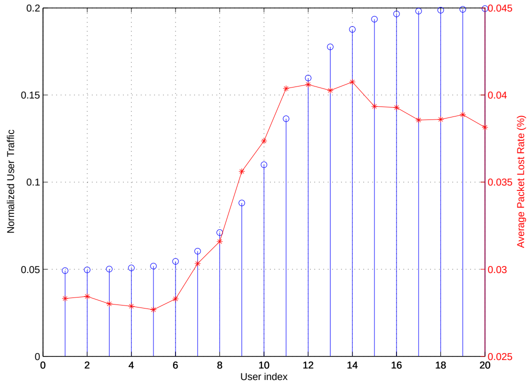

Fig. 9. Average packet loss rate at the equilibrium under staircase traffic distribution

almost all the users require the same number of retransmission to satisfy their PLR constraints, while in Fig. 8 and Fig. 10, typically higher-traffic users need less retransmission since they always occupy the best channel.

4.3. Traffic splitting

As we stated in the previous section, due to the delay constraint, each user can only deploy a limited number of retransmissions to satisfy his PLR constraint. Give similar delay constraints, the stations with a higher traffic will have little chance to retransmit their packets.

This problem is illustrated in the following simulation. We keep the PLR constraint as 5% and impose a more stringent delay constraint $200ms$. The solid curve with circle in Fig. 13 shows the average failure rate for different users in an increasing order of their traffic. For each user, a failure occurs whenever his QoS requirement (both delay and PLR constraints) can not he satisfied at the equilibrium. As shown by the curve, by only adopting retransmission and dynamic distributed channel switching, users with higher traffic still experience very severe failure rate.

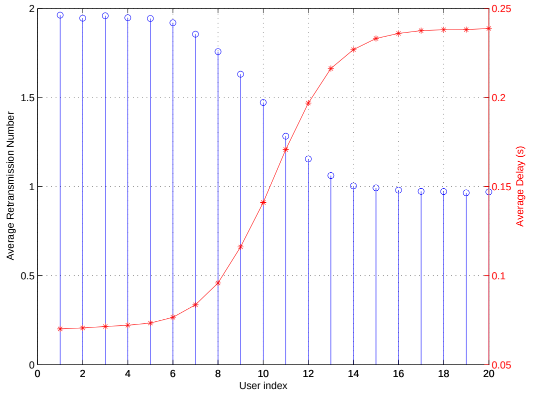

Fig. 10. Average delay at the equilibrium under staircase traffic distribution

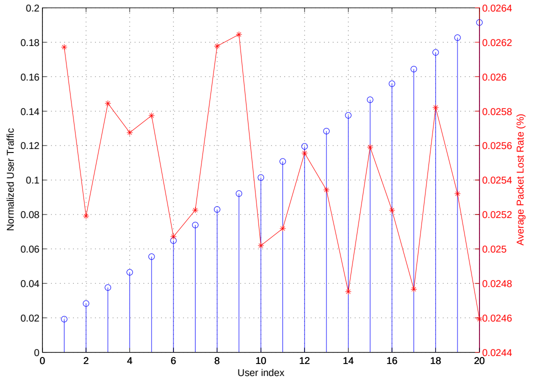

Fig. 11. Average packet loss rate under uniform traffic distribution for the channel switching mechanism totally depend on satisfaction

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, an user that acquires 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. The solid curve with asterisk in Fig. 13 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,

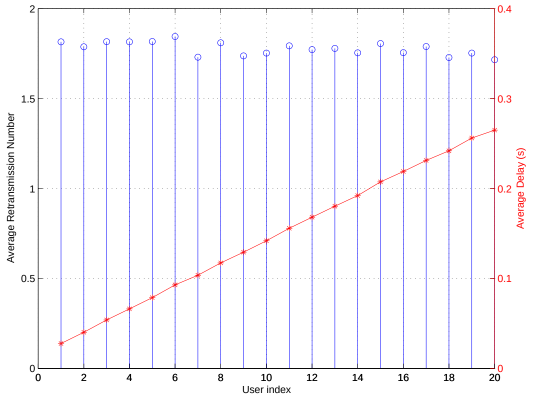

Fig. 12. Average delay after under uniform traffic distribution for the channel switching mechanism totally depend on satisfaction

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.

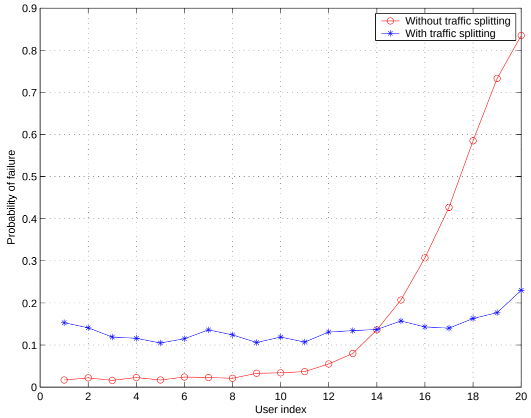

Fig. 13. Average Failure Rate without and with traffic splitting in an increasing order of users' traffic

5. CONCLUSION

In this paper, we investigate the problem of providing QoS for delay sensitive multimedia applications over OSAR networks. We propose a distributed, non-collaborative channel switching mechanism that improves the system performance by utilizing the spectrum agility. Convergence rates of different channel switching protocols have been studied by simulation in this paper. Also, simulation results shows that this mechanism satisfies more users, and hence leads to a more efficient utilization of the available spectrum resources. We have also shown that our distributed transmission strategies can effectively adapt to dynamic changes in the network such as the presence of new primary users.

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