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## On Average Waiting Time in Shared Dynamic Spectrum Allocation

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**Abstract:** Dynamic spectrum allocation is a promising approach toward optimum utilization of rarely used frequency bands. However, to dynamically share the spectrum as a Commons, there are challenges to overcome, such as tendency of greed in holding the spectrum. In particular, under heavy traffic load, a system may hold the spectrum more than its requirement to avoid delay in accessing the spectrum again. This kind of behavior can cause traffic blocking for all other systems participating in the sharing pool and will be more critical for time sensitive applications. Consequently, the awareness of the Average Waiting Time (AWT) and the factors controlling the AWT is crucial for a system to manage its time sensitive traffic. In this paper, analytical and simulation studies are performed to investigate the controlling factors for the AWT, which will be helpful for the systems to manage their time sensitive applications. To eliminate the impact of greed, Greed Elimination Model based on distributed coordination function with upper limit on transmission duration, is presented and analyzed.

**Key words:** Dynamic spectrum allocation, spectrum sharing, spectrum as a Commons, average waiting time

### INTRODUCTION

Traffic load in wireless communication networks is subject to time and regional variations, which leads to variations in the utilization of spectrum resources. Therefore, radio spectrum can be underused by one system and may experience a shortage with another (Leaves *et al.*, 2004; Sharif *et al.*, 2005; Sharif and Fan, 2006; Xia *et al.*, 2007). As indicated by the Spectrum Policy Task Force (FCC, 2002) and by other reports such as the measurements conducted from January, 2004-August, 2005 for frequency bands below 3 GHz (Cordeiro *et al.*, 2005; McHenry, 2005), the average spectrum usage is only about 5.2%. Interestingly, it also reveals that heavy spectrum utilization often takes place in unlicensed bands while licensed bands often experience low or medium utilization (e.g., TV or cellular bands, respectively). Therefore, for the dynamic spectrum allocation the spectrum management policies need revision.

Most of the public debates on the spectrum management policies usually break out into two dissimilar approaches, Commons and Quasi-Private Property (Cooper, 2006).

- The Commons spectrum approach is one where all systems have equal rights to access the spectrum, e.g., today's unlicensed bands. Unlicensed spectrum

bands have spurred tremendous innovation, productivity and led to greater spectral efficiency as compared to licensed bands. However, there are some challenges related to implementation of the Commons.

- The spectrum as Quasi-Private Property encourages spectrum sharing between licensed donor and rental systems where the rental systems must not cause any harmful interference to the donor system. However, in a quasi-private property approach, the change in legacy systems is needed that is, the donor systems need additional components which will act as a gatekeeper.

Due to the high spectrum scarcity in unlicensed bands and due to the fact that the significant revolutions in radio spectrum usage have originated in the unlicensed bands, the spectrum as a Commons is the focused spectrum sharing environment.

To realize the potential benefits of spectrum sharing, there are some challenges to overcome. One out of those is the possible tendency of greed in individual systems. In unreliable radio environments such as the unlicensed frequency bands or Commons, contention-based protocols are used for wireless communication due to their irregular and unpredictable interferences. Therefore, to support time-bounded traffic with a certain Quality of Service (QoS) is extremely difficult (Mangold *et al.*, 2004).

It is because in contention based protocols there is no surety regarding availability of free spectrum. In addition to that, there may be a tendency of greed in individual systems to hold the spectrum band more than their requirement to avoid delay of accessing the band again, in particular under heavy traffic load. This may cause a great deal of problems for real time applications of all other systems waiting for transmission. As a result, these individual systems may waste spectrum to improve their own performance at the expense of overall spectral efficiency and performance degradation for other systems. If this kind of behavior happens frequently, which is quite possible under heavy traffic load, then the benefits of dynamic spectrum allocation among multiple radio systems may disappear, or may turn out to be more critical for real time traffic. With the plethora of new real time applications emergence, the tendency of greed becomes more critical. Therefore, the awareness of the AWT and the corresponding controlling factors, is crucial for a system to manage the time sensitive traffic.

To minimize the AWT and the impact of greed Greed Elimination Model is presented and analyzed. In this study, detailed analysis and simulation are performed to investigate the controlling factors for AWT. Furthermore, some possible improvements to minimize the said problem are also presented.

**GREED ELIMINATION MODEL AND ASSUMPTIONS**

Our model is based upon the opportunistic spectrum sharing, as it is one of the most suitable way to share the spectrum, when the spectrum is taken as a Commons. Suppose under opportunistic spectrum sharing scenario,  $k$  represents the average number of systems competing for free subbands at any instant and while waiting for transmission, all the blocked systems are queuing up their data independently. Another basic assumption made is the probability of collision while accessing the subband is considered negligible, as it may happen because the subband assessment is not instantaneous.

For minimizing the AWT and the impact of greed, our model put an upper limit on the transmission duration in conjunction with the Distributed Coordination Function (DCF). That is, any system can transmit its queued data uninterruptedly, no longer than the  $Q$  duration of time. As the DCF is based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) and binary exponential backoff, therefore, brief introduction for the same can be viewed as follows. Before each transmission, a system

have to monitor the subband for  $M$  units of time. If during this interval, the power on the subband never exceeds a predefined deference threshold, then the system has the permission to transmit. If the power exceeds the deference threshold the system defers a random amount of time, called the deference interval  $D_L$  and repeats the monitoring procedure after that.

$$D_L \sim U(M, L),$$

where,  $L \in \{l_{min}, \dots, l_{max}\}$

The range  $[M, L]$  from which the uniformly distributed deference interval is chosen is doubled each time a system detects subband busy. The lower limit is fixed at some suitable value  $M$ , while the upper limit is initially  $l_{min}$  and step by step reaches at  $l_{max}$  after some unsuccessful tries. After approaching  $l_{max}$  the range for deference interval is kept constant indefinitely.

**PERFORMANCE ANALYSIS**

Consider at any time  $t$ , the  $j$ th system wins the contention after some unsuccessful tries. At time  $t+Q$  system  $j$  stops transmission and draws a deference delay from a uniform distribution  $D_L \sim U(M, l_{min})$ . The time intervals from the instant the subband becomes clear (i.e.,  $t+Q$ ) until the blocked systems are scheduled to monitor the subband are random variables, denoted by  $R_i$ , where,  $R_i \neq R_j$ , as shown in Fig. 1.

According to the Fig. 1, who will win the contention for transmission in the next cycle, depends upon the remaining deference time  $R_i$ , the lesser the better. As any random variable  $R_i$  represents the residual life for sensing the carrier again, therefore, the Residual Life Theorem (Kleinrock, 1976) can be applied for the distribution of  $R_i$ , as given below,

$$f_{R_i}(r) = \frac{1 - F_{D_L}(r)}{E[D_L]} \tag{1}$$

where:

$F_{D_L}(r)$  is the cumulative distribution function of deference interval  $D_L$  and  $E[D_L]$  is the mean of  $D_L$ .

Deference process after approaching at maximum limit  $l_{max}$  becomes a renewal process. Under heavy traffic load, it is quite reasonable to assume that the renewal process starts during the first transmission period and that it will be in steady state at the end of the first busy period. Therefore, Eq. 2 can be used for all blocked systems.

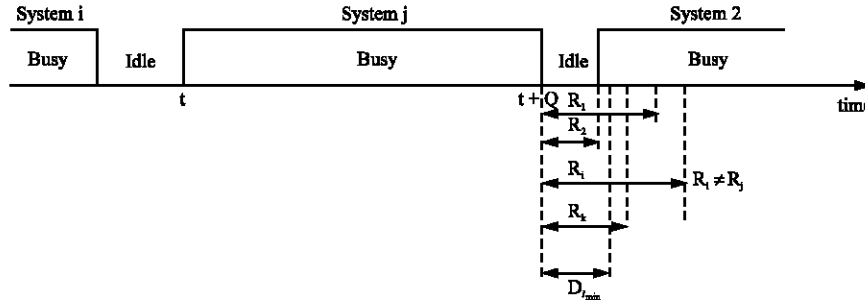


Fig. 1: Residual life and competition for next transmission cycle

$$f_{R_i}(r) = \begin{cases} \frac{1 - F_{D_{l_{max}}}(r)}{E[D_{l_{max}}]}, & 0 \leq r \leq l_{max}, i \neq j. \\ 0, & \text{otherwise} \end{cases} \quad (2)$$

The distribution function of deference delay for the currently transmitting system j can be written as,

$$f_{D_{l_{min}}}(x) = \begin{cases} \frac{1}{l_{min} - M}, & M \leq x \leq l_{min} \\ 0, & \text{otherwise} \end{cases} \quad (3)$$

The probability of any blocked system to win the contention for transmission in the next cycle can be obtained by using joint probability function for two variables. Figure 1 shows that any system i with minimum  $R_i$  out of all blocked systems will compete with the currently transmitting system j for transmission in the next cycle.

$$P[D_{l_{min}} > R_{min}] = \int_{x=0}^{l_{min}} \int_{r=0}^x f_{D_{l_{min}}}(x) f_{R_{min}}(r) dx dr \quad (4)$$

where  $R_{min} = \min(R_1, \dots, R_i, \dots, R_k)$ . For equally probable,  $i \neq j$

independent and identically distributed random variables, we have:

$$F_{R_{min}}(r) = P\left[\min_{\substack{i=1 \\ i \neq j}}^k (R_i) \leq r\right] = 1 - [F(r)]^{k-1} \quad (5)$$

where,  $F(r)$  is the cumulative distribution function of  $R_i$ . Applying this to Eq. 4, we can get:

$$P[D_{l_{min}} > R_{min}] = \int_{x=0}^{l_{min}} f_{D_{l_{min}}}(x) [1 - (F(x))^{k-1}] dx \quad (6)$$

It is quite clear that any of the (k-1) blocked systems can win the contention with equal probability. Thus the probability that a particular blocked system will transmit in the next transmission cycle can be written as:

$$P = \frac{1}{(k-1)} P[D_{l_{min}} > R_{min}] = \quad (7)$$

$$\frac{1}{(k-1)} \int_{x=0}^{l_{min}} f_{D_{l_{min}}}(x) [1 - (F(x))^{k-1}] dx$$

Therefore, the average number of transmission cycles an arbitrary system will wait can be obtained from,

$$Avg N_{wait\_cyc} = \frac{1}{P} = \frac{(k-1)}{\int_{x=0}^{l_{min}} f_{D_{l_{min}}}(x) [1 - (F(x))^{k-1}] dx} \quad (8)$$

In order to find the average waiting time, there is a need to get average cycle period, because all cycles are not the same in length. Each cycle consists of two parts, the transmission time Q and the idle time I, which can be seen in Fig. 2, where Q is a constant, but I depends upon residual life of random variables R. Therefore, the average idle time  $E[I]$  is needed first which can be calculated as given in Eq. 9. The average waiting time for any blocked system can be written as,

$$Avg T_{wait\_msec} = (Avg N_{wait\_cyc})(Q + E[I]) = \frac{(k-1)(Q + E[I])}{\int_{x=0}^{l_{min}} f_{D_{l_{min}}}(x) [1 - (F(x))^{k-1}] dx} \quad (9)$$

$$\text{where, } E[I] = \int_{-\infty}^{+\infty} x dF_I(x).$$

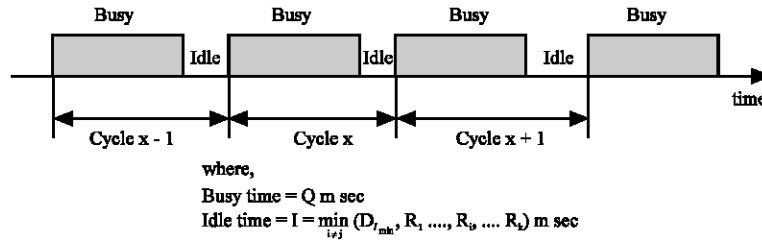


Fig. 2: Length of transmission cycles

RESULTS AND DISCUSSION

In the simulation and analytical studies performed, it is assumed that the free band monitoring time is  $50 \mu\text{sec}$  and the upper limit for the deference interval can reach the maximum  $12 \text{ m sec}$ . Furthermore, in each transmission cycle there are  $10 \text{ m sec}$  for burst transmission, whereas, the burst may consist of a large number of short packets, provided that the inter-packet gap is less than  $20 \mu\text{sec}$ . Keeping in mind the time sensitive applications, the significance of the model considered can be seen in results obtained, i.e., the average waiting time is raising very slowly with the increase in the number of systems. The growing number of systems is actually accommodated with the reduction in the average transmission time which is also apparent from the simulation results. The initial upper limit for deference interval also plays an important role for the average waiting time, a slight increase in the initial limit reduces the average waiting time considerably. The simulation is performed for three different values of initial upper limit for deference interval,  $0.5, 0.75$  and  $1$ , as shown in Fig. 3.

Figure 4 presents the simulation and theoretical results obtained that the analytical results fit well with the simulation results. The difference between the simulation and analytical results is approximately  $4\%$  or less. It is apparent from the simulation results that lowering the upper limit of transmission duration reduces the average waiting time sharply (Fig. 5).

It is shown here that the AWT is a function of upper limit on the transmission duration  $Q$  and the initial upper limit for deference interval  $I_{min}$ . However, the ATT depends a lot upon the average number of systems  $K$ , competing for spectrum bands at any instant of time. As far as the AWT is concerned, it increases very slowly with the increase in the number of systems competing for spectrum band, which is the beauty of the model considered. Furthermore, it is quite clear from the results obtained that reducing the maximum transmission duration decreases the average waiting time for all blocked systems. For example, for  $Q = 10, 5, 1 \text{ m sec}$ , the

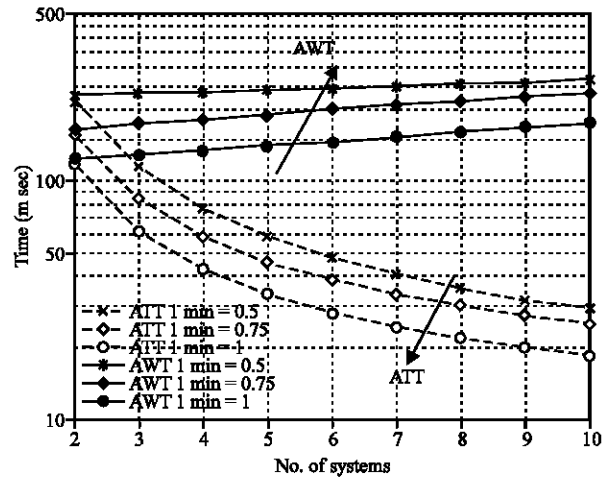


Fig. 3: Simulation results for AWT and ATT as a function of the number of systems competing for spectrum

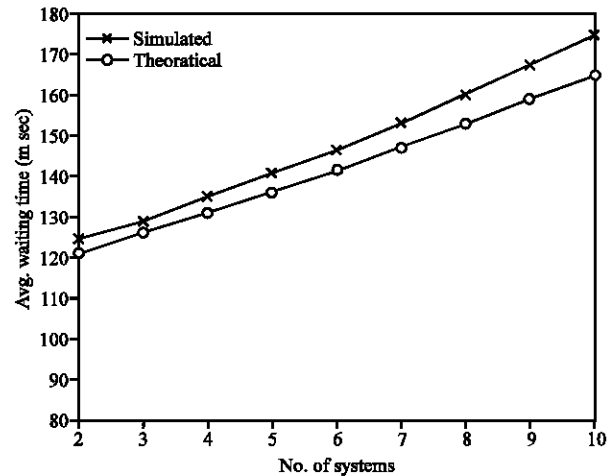


Fig. 4: Simulation and numerical results for AWT as a function of the number of systems competing for spectrum

AWT goes to  $220, 113, 15 \text{ m sec}$ , respectively, for a particular set of parameters. But, reducing the transmission time causes a noticeable wastage of spectrum resources. It is because reducing the

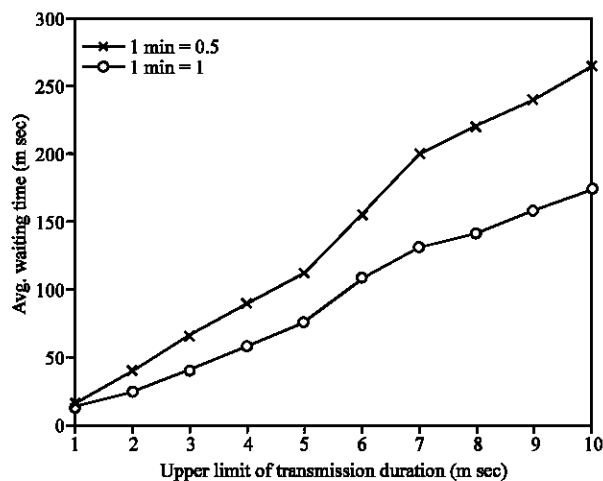


Fig. 5: AWT as a function of upper limit on transmission duration

transmission time increases the number of occurrences for non-negligible probability of the idle time and consequently there is an increase in the overall spectrum wastage. Similarly, the initial upper range  $l_{min}$  for deference interval also plays an important role for the reduction in the average waiting time. However, there is a possibility of slight spectrum wastage in terms of a comparatively longer idle time. Therefore, by knowing the impact of controlling factors as discussed earlier, an optimal solution for the upper limit on the transmission duration and for the initial upper range of deference interval can easily be found through the tradeoff between the acceptable average waiting time for the time sensitive applications and the overall spectrum utilization.

**CONCLUSIONS**

To minimize the average waiting time and the impact of greed in the scenario where the spectrum is taken as a commons, greed elimination model is presented and analyzed. In this study, keeping in mind the importance of the AWT for time sensitive applications, the analytical and simulation studies are performed to investigate the controlling factors for AWT, which is helpful for those systems who do not want to invest a lot for change in legacy systems. The results obtained present the impact of transmission duration, the average number of systems competing for spectrum and the initial upper limit for

deference interval, upon the AWT and the ATT. With some trade off in these parameters, the acceptable AWT for the time sensitive applications can easily be found.

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