A Dynamic Spectrum Access Scheme for Unlicensed Systems Coexisting with Primary OFDMA Systems

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***Abstract*—In this paper, we consider Mobile WiMAX and LTE as the future technologies for primary OFDMA systems and study Dynamic Spectrum Access (DSA) for unlicensed systems coexisting with primary OFDMA systems. We propose an effective DSA scheme that allows an unlicensed system to statistically and opportunistically access the whole spectrum bandwidth during the last consecutive symbols of each primary OFDMA subframe. There is a tradeoff in gaining high normalized throughput by enlarging the access duration in each subframe and keeping low interference caused to the primary system by shorten the access period. Then, we model that tradeoff by deriving the optimization problem that maximizes the normalized throughput of the unlicensed system while guaranteeing the harmful interference constraints set by the primary system. We develop and conduct our simulations in our simulator modified from the powerful WiMAX simulator developed by the WiMAX Forum in Ns-2.**

I. Introduction

The licensed frequency bands have gradually become a scare resource due to the growing demand and usage of wireless systems as well as the fixed allocation policy. However, the utilization of such spectrum bands is low. The FCC's Spectrum Policy Task Force reports in [1] that at any given time and location, only 15% - 85% of the spectrum is utilized. Thus, DSA technique [2] is envisioned as an emerging technology to improve the spectrum utilization. The DSA technology allows a secondary (unlicensed) system to utilize a licensed spectrum when it is not occupied by its owned primary (licensed) system. Such utilization however must guarantee not causing degradation in service to the primary system by protecting the primary system from interference.

There has been recent research on dynamic spectrum access and allocation schemes to enhance the efficiency of spectrum utilization. Weiss et.al in [3] discuss spectrum pooling approach to overlay a unlicensed system on an existing licensed system without sacrificing the primary transmission quality or requiring any changes to the licensed system. In [4], Gerihofer et.al consider the coexistence of Bluetooth and WLAN in terms of reusing sparsely occupied frequency bands in the time domain by exploiting idle periods between bursty transmissions. Willkomm et.al in [5] characterize the behavior of primary users in the cellular spectrum in order to understand if and when spectrum is available, which can be used to enable DSA in cellular bands. In [6], Bernardo et.al propose dynamic spectrum assignment algorithms for multicell OFDMA systems that allow licensed spectrum holders to release spectrum bands for other secondary markets to lease.

In the present paper, on the other hand, by observing the capacity usage and the statistics of spectrum occupancy of a primary OFDMA system as partly reported in our previous work in [7], we argue that a secondary system can statistically and opportunistically exploit the statistics of the available primary spectrum resource in order to improve the spectrum utilization in a coexisting network of both primary and secondary systems. In particular, we propose an efficient DSA scheme, namely DSA-α scheme, that allows a secondary system to access the whole spectrum bandwidth during the last consecutive symbols of each primary OFDMA subframe. This access duration in the time domain is modeled as the access ratio $\bar{\alpha}$ on the maximum OFDM symbols of an OFDMA subframe. We show that the longer the access duration or the higher $\bar{\alpha}$, the higher normalized throughput could be gained by the DSA-α secondary system. However, by accessing the primary spectrum in each subframe, the secondary system will cause interference to the primary system, which is monotonically increasing with the increasing of $\bar{\alpha}$. Hence, in this paper we model that tradeoff by proposing an optimization problem that maximizes the normalized throughput gained by the DSA-α secondary system while guaranteeing the harmful interference constraints set by the primary system.

The rest of this paper is organized as follows. Section II presents the primary OFDMA system model and our modified Ns2-WiMAX simulator basing on the WiMAX Forum simulator. Next, Section III describes our proposed DSA-α scheme and its optimization problem. The simulation results are then presented in Section IV. Finally, conclusion and future work are drawn in Section V.

II. System Model and the Ns2-WiMAX Simulator

A. System Overview

Fig. 1 shows the system model of our proposed dynamic spectrum access scheme, namely DSA-α scheme, where the secondary system operates coexisting with the primary system on the primary spectrum by statistically and opportunistically accessing the available statistics of the primary spectrum resource. In this paper, we consider the primary OFDMA system as a mobile WiMAX primary system.

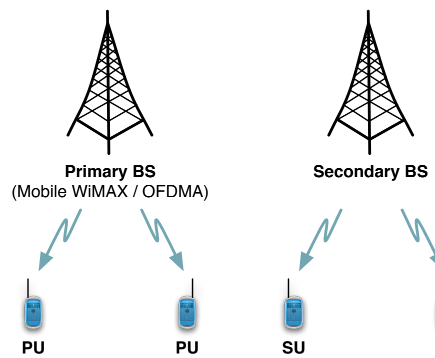

Fig. 1. The coexistent of primary and secondary systems

B. The Ns2-WiMAX Simulator of Primary OFDMA Systems

To simulate primary OFDMA and mobile WiMAX systems, we use the network simulator ns-2.1.5 [8] with an implementation of the IEEE 802.16e-2005 [9] amendment by the WiMAX Forum [10]. In the simulator, all the general WiMAX standard parameters are configured as in [11]. The channel bandwidth is 10 MHz. The downlink (DL) and uplink (UL) permutation types are PUSC and the DL/UL ratio is 2/1 in the TDD scheme used by the simulator. The modulation scheme 64-QAM, $3/4$ rate is currently configured as the same for every primary user. The OFDMA channel model is a COST-HATA-231 bulk path loss component combining with a Clarke-Gans implementation of the Rayleigh Fading model [12].

In this simulator, the primary base station allocates spectrum resource to its serviced primary users by a complex scheduler that maintains important information such as the QoS for each flow, DL queue status for each flow, UL bandwidth grant and the channel state information for each mobile station. The current release of the simulator supports scheduling configuration as either vertical striping or horizontal striping.

In this paper, vertical striping is configured for the scheduler so that the whole spectrum bandwidth can be allocated to the primary users in the time domain. This technique is considered more reasonable for a secondary system to access the available primary spectrum without knowing the complex details of how the primary OFDMA system logically indexes the subcarriers into the subchannels in each OFDMA subframe. To characterize and model the statistics of the spectrum distribution in each OFDMA frame of the primary system, we implement our add-on functionalities in the simulator to capture the needed statistics information of the whole system.

III. Our New Dynamic Spectrum Access Scheme

A. Simulation Statistics of the Primary ODMA System

We simulate the underlying primary system in our modified Ns2-WiMAX simulator in order to characterize the primary spectrum occupancy over the data traffic simulation. Mathematically, the statistics model of each OFDMA resource block i, which is defined as the whole consecutive subchannels at the symbol i in an OFDMA subframe, at time τ can be modeled as a probability density function $\mathbf{pdf}(i, \tau)$.

Fig. 2 shows a statistics example of the cumulative occupancy distribution in the OFDMA DL-subframe during 20 seconds simulation. The simulation is conducted for 1 primary base station and 20 primary users with CBR over UDP traffic. This statistics of the primary spectrum occupancy in the time

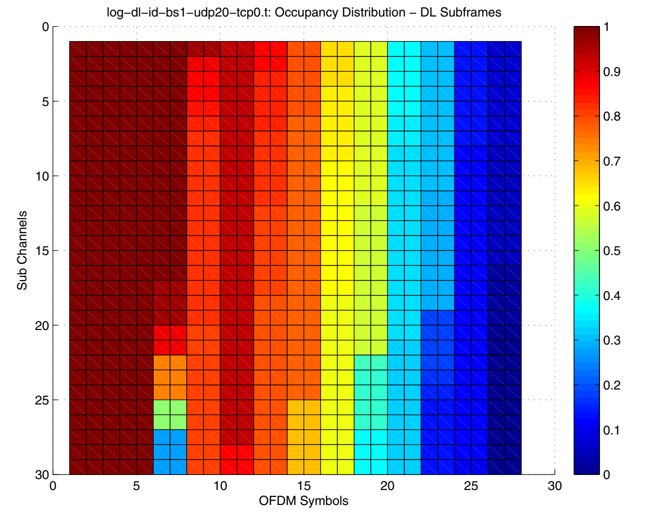

Fig. 2. Occupancy distribution in the DL-subframe

domain indicates that the majority of the primary spectrum resource in the DL-subframe from the symbol 16, for example, to the end of the subframe is not fully exploited. Hence, there is a great potential for secondary systems to operate on the primary spectrum by exploiting this statistics model.

B. DSA-α: A New Dynamic Spectrum Access Scheme

From the statistics of the primary spectrum distribution, we observe that the spectrum occupancy in each primary subframe is distributed decreasingly from the first OFDMA symbol to the last symbol. Hence, statistically, a secondary system should access the primary spectrum during the last consecutive symbols of each subframe. Fig. 3 illustrates our DSA-α scheme, which allows a secondary system to access a whole consecutive resource blocks during the last symbols of the primary OFDMA subframe. We model this access period as the access ratio $\bar{\alpha}$ on the maximum OFMD symbols of the subframe. Let N_{sym} and $n_{\bar{\alpha}}$ denote the maximum OFDM symbols in the OFDMA subframe and the access period (number of symbols), respectively, hence $\bar{\alpha} = \frac{n_{\bar{\alpha}}}{N_{sym}}$.

In our scheme, it is assumed that either the DSA-α secondary system is scheduled precisely or it implements perfect spectrum sensing so that it can access each subframe accurately at the access point shown in Fig. 3. Detailed discussion on such scheduling and sensing mechanisms is considered as

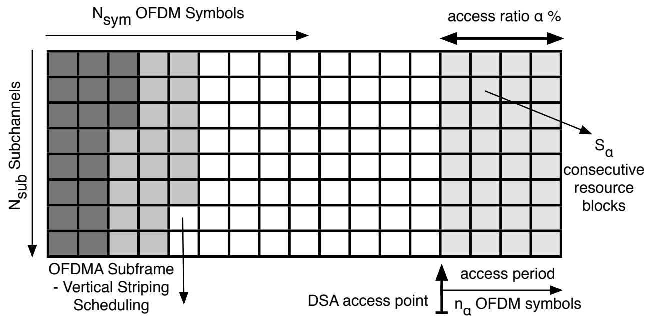

Fig. 3. Illustration of our DSA-α scheme in an OFDMA subframe

the future work. In the next subsections, we present the optimization problem that maximizes the normalized throughput gained by the DSA-α scheme while guaranteeing the harmful interference constraints set by the primary system.

1) Expected Normalized Throughput of the DSA-α Scheme: From the statistics model of the primary spectrum usage, we can derive the cumulative probability distribution for the occupancy of the $S_{\bar{\alpha}}$ consecutive OFDMA resource blocks of the duration ratio $\bar{\alpha}$, which can be exploited by our proposed DSA-α scheme, in the time domain $\tau \in [0, T]$ as:

$$\mathbf{cdf}_f(\alpha \leq \bar{\alpha}, \tau) = \frac{1}{\bar{\alpha} N_{sym}} \sum_{i \in S_{\bar{\alpha}}} \mathbf{pdf}(i, \tau) \tag{1}$$

Hence, we can easily formulate the expected access probability ($\mathbf{p}_{dsa}(\bar{\alpha})$) that the secondary system can opportunistically exploit the available primary spectrum by our DSA-α scheme in the time domain as follows:

$$\begin{aligned} \mathbf{p}_{dsa}(\bar{\alpha}) &= \frac{1}{T} \int_0^T \left(1 - \mathbf{cdf}_f(\alpha \leq \bar{\alpha}, \tau)\right) d\tau \\ &= \frac{1}{T} \int_0^T \left(1 - \frac{1}{\bar{\alpha} N_{sym}} \sum_{i \in S_{\bar{\alpha}}} \mathbf{pdf}(i, \tau)\right) d\tau \end{aligned} \tag{2}$$

In our model, the spectrum utilization gain that a secondary system could achieve from exploiting the primary spectrum statistics (2) through our DSA-α scheme can be evaluated as the normalized throughput $\mathbb{T}_{dsa}(\bar{\alpha})$. This normalized throughput implicates the expectation from the secondary system that the longer the access period in each primary subframe (by increasing the ratio $\bar{\alpha}$), the higher spectrum utilization. Furthermore, the higher the chance to access the spectrum (by increasing the statistics $\mathbf{p}_{dsa}(\bar{\alpha})$), the higher spectrum utilization. Thus, we can formulate $\mathbb{T}_{dsa}(\bar{\alpha})$ as follows:

$$\begin{aligned} \mathbb{T}_{dsa}(\bar{\alpha}) &= n_{\bar{\alpha}} . \mathbf{p}_{dsa}(\bar{\alpha}) \\ &= \frac{\bar{\alpha} N_{sym}}{T} \int_0^T \left(1 - \frac{1}{\bar{\alpha} N_{sym}} \sum_{i \in S_{\bar{\alpha}}} \mathbf{pdf}(i, \tau)\right) d\tau \end{aligned} \tag{3}$$

2) Expected Interference caused by the DSA-α Scheme: However, by opportunistically and statistically accessing the primary spectrum, the secondary system will cause interference to the primary system, since the DSA-α scheme allows the secondary users (SUs) to access $S_{\bar{\alpha}}$ consecutive OFDMA resource blocks in every primary OFDMA subframe. In each single subframe, at the point in time τ, the co-channel interference power level at the i-th resource block of the whole subchannels and 1 OFDMA symbol caused by a SU k to a primary user (PU) j can be calculated following [13] as:

$$I_{CCI}^{k,j}(i, \tau) = \mathbf{pdf}(i, \tau) \left[|h_{k,j}|^2 . P_{loss}^{k,j} . P_{TX}^{k} \right] \tag{4}$$

where P_{TX}^{k} is the transmission power of the k-th SU, $P_{loss}^{k,j}$ is the path loss power from the k-th SU to the j-th PU, and $|h_{k,j}|$ is the channel gain.

Denote K_{SU} as the number of the SUs accessing $\bar{\alpha}$ portion of each OFDMA subframe. Thus, the expected interference introduced by the DSA-α secondary system to the j-th PU in a subframe at time τ can be derived as:

$$E[I_{dsa}^{j}(\bar{\alpha}, \tau)] = \sum_{k=1}^{K_{SU}} \sum_{i \in S_{\bar{\alpha}}} I_{CCI}^{k,j}(i, \tau) \tag{5}$$

Given a harmful interference threshold $\bar{I}$ for each PU in each subframe, the following constraint can be set by the primary system to avoid harmful interference at any time:

$$E[I_{dsa}(\bar{\alpha}, \tau)] \triangleq \max\{E[I_{dsa}^{j}(\bar{\alpha}, \tau)]\} \leq \bar{I}, \quad \forall \tau \in [0, T] \tag{6}$$

In addition, the harmful interference probability p_h that the interference produced by the DSA-α secondary system exceeds $\bar{I}$ (violating (6)) at time τ can also be modeled as:

$$p_h(E[I_{dsa}(\bar{\alpha}, \tau)] > \bar{I}) = \begin{cases} 1, & \text{if: } E[I_{dsa}(\bar{\alpha}, \tau)] > \bar{I} \\ 0, & \text{otherwise} \end{cases} \tag{7}$$

Then, the expected probability that the secondary system may harmfully interfere the primary system during the whole simulation time T can be estimated as following:

$$\mathbf{p_h}(E[I_{dsa}(\bar{\alpha})] > \bar{I}) = \frac{1}{T} \int_0^T p_h(E[I_{dsa}(\bar{\alpha}, \tau)] > \bar{I}) d\tau \tag{8}$$

Thus, the primary system can also avoid harmful interference by setting up a limit for harmful interference occurrence by introducing a harmful probability threshold $\bar{\mathbf{p}}_{\mathbf{h}}$, which requires the DSA-α system to guarantee the following condition:

$$\mathbf{p_h}(E[I_{dsa}(\bar{\alpha})] > \bar{I}) \leq \bar{\mathbf{p}}_{\mathbf{h}} \tag{9}$$

It can be seen from the proposed interference models that the higher the access ratio $\bar{\alpha}$, the higher the expected interference (5), which means the higher the chance it may become harmful interference to the primary system by violating either the constraint (6) or (9). Thus, obviously, there is a tradeoff in gaining the normalized throughput (3) as high as possible by increasing $\bar{\alpha}$, while guaranteeing the harmful interference constraints (6) and/or (9) by reducing $\bar{\alpha}$.

3) Maximization of the Normalized Throughput by the DSA-α Scheme: One of the main objectives in dynamic spectrum access is to allow a secondary system to gain as much spectrum resource utilization as possible, while keeping the interference to the primary system as low as possible. Hence, in our scheme, we maximize the normalized throughput (3) while guaranteeing the harmful interference constraints (6) and/or (9) set by the primary system. We formulate such maximization of spectrum utilization as the following optimization problem in our DSA-α scheme:

$$\bar{\alpha}^* = \arg\max_{\bar{\alpha}} \quad \mathbb{T}_{dsa}(\bar{\alpha}) \tag{10}$$

$$= \arg\max_{\bar{\alpha}} \quad \frac{\bar{\alpha}N_{sym}}{T}\int_0^T \left(1 - \frac{1}{\bar{\alpha}N_{sym}}\sum_{i\in S_{\bar{\alpha}}} \mathbf{pdf}(i,\tau)\right) d\tau$$

subject to:

$$c_1 : E[I_{dsa}(\bar{\alpha},\tau)] \leq \bar{I}, \quad \forall\tau \in [0,T], \quad \text{and/or} \tag{10a}$$

$$c_2 : \mathbf{p_h}(E[I_{dsa}(\bar{\alpha})] > \bar{I}) \leq \bar{\mathbf{p}} \tag{10b}$$

The physical meaning of the optimization (10) is twofold. First of all, it provides a comprehensive mathematical tool for a secondary system to gain the optimal normalized throughput by deploying our DSA-α scheme, while avoiding harmful interference to the primary system. Second of all, it provides a powerful economical tool for the primary system who wants to lease any $\bar{\alpha}$ portion of its licensed spectrum in each OFDMA subframe by adjusting the interference threshold $\bar{I}$ (*hard-interference-constraint*) and/or the probability threshold $\bar{\mathbf{p}}$ (*soft-interference-constraint*). The hard-interference-constraint (10)a restricts the DSA-α secondary system not causing harmful interference at any time, while the soft-interference-constraint (10)b eases that restriction by accepting harmful interference to be occurred sometimes under the limitation of the probability threshold $\bar{\mathbf{p}}$. Obviously, by increasing those interference thresholds, the primary system could statistically lease more of its available licensed spectrum resource.

IV. Performance Evaluation

This section validates the performance of our proposed DSA-α scheme via simulations conducted in our modified WiMAX simulator in the network simulator Ns-2.1.5. In all simulations, the primary system data traffic is generated as the downlink (DL) traffic in the period of $T = 20$ seconds. For the CBR traffic over UDP, the packet size is 1500 bytes and the rate is 1 Mbps.

First of all, the expected access probability (2) to access the primary OFDMA DL-subframe is evaluated as shown in Fig. 4. The primary system consists of 1 primary base station providing data service in different scenarios to 5, 10, 15, 20, 25, and 30 CBR/UDP primary users (PUs). These results reflex well the statistics of the occupancy distribution of the primary spectrum. The expected access probability or the opportunity for the DSA-α secondary system decreases when this system wants to exploit higher portion of the primary spectrum. However, it is also observed that sometimes this expected access probability increases when the access ratio $\bar{\alpha}$ increases, for example in the cases of 25 and 30 primary users and $\bar{\alpha} \in (65, 75)\%$. This is due to the vertical scheduling algorithm implemented in the simulator that sometimes allocates the data bursts from the next symbol before finishing allocating all the subchannels from the previous symbol in the primary DL-subframe (see symbols 6 to 10 in Fig. 2). It is also seen that the heavier the primary traffic, the less opportunity for the DSA-α secondary system.

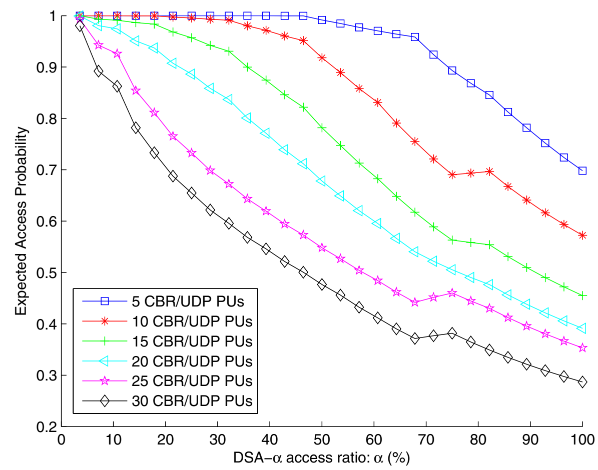

Fig. 4. Expected Access Probability in DL-Subframe: CBR/UDP Traffic

The normalized throughput (3) gained by the DSA-α secondary system in the primary DL-subframe for different simulation scenarios is evaluated and shown in Fig. 5. It is seen that

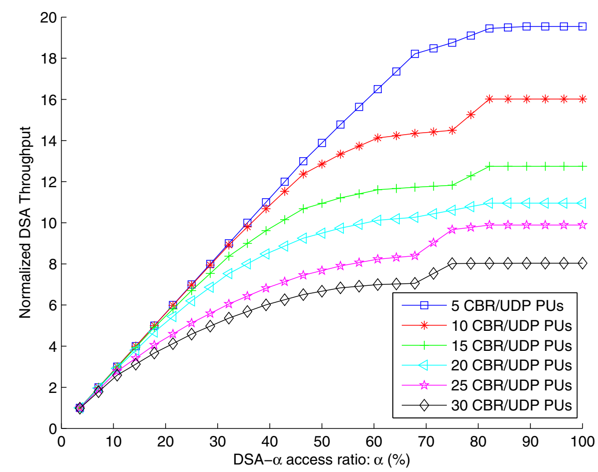

Fig. 5. Normalized Throughput in DL-Subframe: CBR/UDP Traffic

this normalized throughput is monotonically increasing when the secondary system accesses more portion of the spectrum resource in each primary DL-subframe. However, this normalized throughput becomes saturated when the access ratio $\bar{\alpha}$ is higher than 50% of the maximum OFDM symbols in each DL-subframe. This is reasonable since the vertical striping scheduling allocates the spectrum resource to the primary users from the first OFDMA symbol until the last symbol and hence the portion of the spectrum at the last symbols is mostly underutilized. This confirms again our motivation and validates the formulation of our DSA-α scheme.

Fig. 6 illustrates the numerical calculation of the maximum expected interference model proposed in (5) during the simulated data traffic time. The DSA-α network consists of only one SU with the transmission power $P_{TX} = 2$ W [13]. To simplify the numerical calculation, the channel gain and the path loss are set to be 1. These results validate our interference model that the expected interference monotonically increases when $\bar{\alpha}$ inceases. Thus, when the primary system sets $\bar{I}$ for the hard-interference-constraint (10)a, the system can determine

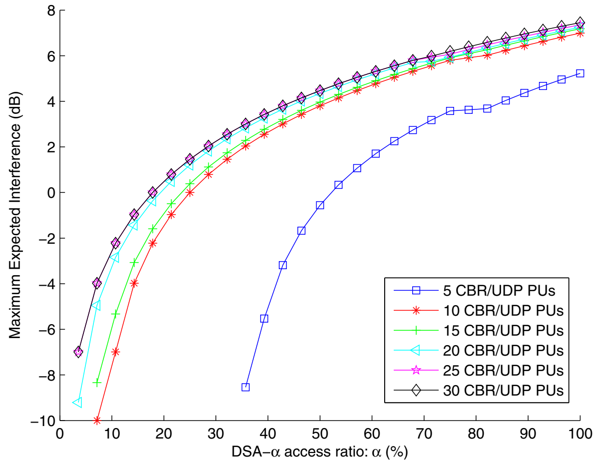

Fig. 6. Maximum Expected Interference in DL-Subframe: CBR/UDP Traffic

the maximum access ratio at which the constraint (10)a is still satisfied and then the optimization (10) can be solved. For the future work, the detailed simulation of both a primary system and a DSA-α secondary system will be implemented to evaluate the actual expected interference and to compare it with the proposed model. In addition, the simulation and evaluation of the soft-interference-constraint (10)b are considered as the future work as well.

We also validate the performance of our DSA-α scheme in scenarios of having primary WiMAX users with FTP traffic over TCP using Best Effort (BE) WiMAX profile with unlimited rate. Fig. 7 illustrates the normalized throughput (3) gained by the DSA-α secondary system. The trend in this graph again reflexes the effectiveness and the performance of our scheme. It is also observed that with FTP/TCP traffic, there is less opportunity for spectrum utilization by the secondary system than in the case of CBR/UDP traffic. This is due to the fact that FTP/TCP PUs have unlimited BE profile, where FTP traffic uses as much capacity as possible.

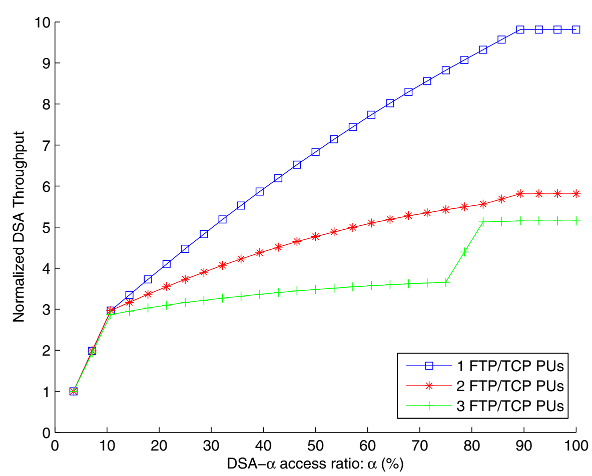

Fig. 7. Normalized Throughput in DL-Subframe: FTP/TCP Traffic

V. Conclusion

In this paper, we have proposed a dynamic spectrum access scheme (DSA-α scheme) that allows a secondary system to statistically and opportunistically access the whole spectrum bandwidth during the last consecutive symbols of each primary OFDMA subframe. To characterize the spectrum occupancy distribution of a primary OFDMA system, we have conducted the simulations in our simulator modified from the WiMAX simulator developed by the WiMAX Forum in Ns-2. Then, we have formulated the normalized throughput gained by the secondary system and its expected interference models to the primary system. We have shown that there is a tradeoff in gaining high normalized throughput by enlarging the access duration in each subframe and keeping the expected interference lower by shorten the access period. Thus, this tradeoff has been modeled by deriving the optimization problem that maximizes the normalized throughput, while guaranteeing the hard-interference-constraint and/or the soft-interference-constraint set by the primary system.

For the future work, we will implement the complete simulation for the coexistence of a DSA-α secondary system and a primary OFDMA system in our simulator to simulate the actual expected interference and compare it with the proposed models. This work expects the realization of a scheduling method for the secondary system to precisely access the primary spectrum. Spectrum sensing can also be implemented to allow the secondary system knowing exactly when to access the primary spectrum. Last but not least, improving the primary system to tolerate higher interference, which allows the DSA-α secondary system accessing higher portion of each subframe symbols, is also raised as the future work.

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