Orthogonal Signaling-based Sensing Data Reporting for Cooperative Spectrum Sensing in Cognitive Radio

Jae Hoon Ko*, Soonmok Kwon* ***Regular Members***, Cheeha Kim* ***Lifelong Member***

ABSTRACT

Cognitive radio (CR) features opportunistic access to spectrum when licensed users (LU) are not operating. To avoid interference to LU, cognitive users (CU) need to perform spectrum sensing. Because of local shadowing, fading, or limited sensing capability, it is suggested that multiple CUs cooperate to detect LU. In cooperative spectrum sensing, CUs should exchange their sensing data with minimum bandwidth and delay.

In this paper, we introduce a novel method to efficiently report sensing data to the central node in an infrastructured OFDM-based CR network. All CUs simultaneously report their sensing data over unique and orthogonal signals on locally available subcarriers. By detecting the signals, the central node can determine subcarrier availability for each CU. Implementation challenges are identified and then their solutions are suggested. The proposed method is evaluated through simulation on a realistic channel model. The results show that the proposed method is feasible and efficient.

Key Words : cognitive radio, spectrum sensing, sensing reporting, orthogonal codes, OFDM

Ⅰ. Introduction

Advances in wireless communications have caused spectrum shortage because the traditional regulation statically allocates spectrum to license holders or services within a specific region for a relatively long time period[1]. On the contrary, recent studies revealed that the utilization of the assigned spectrum is highly sporadic and variable, ranging from 15% to 85% depending on the time and place[2]. Exploiting this situation, cognitive radio (CR) was introduced in[3] to overcome spectrum shortage. In CR, cognitive users (CU) opportunistically access spectrum when licensed users (LU) are not operating. By the prospect of high spectrum utilization, CR has become one of the most active research topics in wireless communications.

An important requirement of CR is that CUs should not cause excessive interference to LUs. To fulfill this, CUs must determine the presence of LUs through spectrum sensing[1]. There are two types of spectrum sensing: local and cooperative spectrum sensing. Local spectrum sensing is a process that a CU detects LU activity by itself, mostly by means of signal processing. Representative algorithms are energy detection, matched filtering, and cyclostationarity-based sensing[4]. In practice, however, local spectrum sensing alone is not sufficient because local fading and shadowing could hinder LU detection. Moreover, the hidden LU problem, which occurs when an LU is located outside a CU's sensing range, cannot be solved by local spectrum sensing. To overcome these limitations, cooperative spectrum sensing collects sensing results from CUs to determine available spectrum. Because CUs likely experience independent channel impairments and observe different LU activities, cooperative spectrum sensing may increase the chance of LU detection and decrease sensing time[4].

Cooperative spectrum sensing may require significant bandwidth for sensing data reporting if the number of participating CUs is large. Moreover,

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if it takes too much time to report sensing data, detection performance can degrade since the collected data could have already become obsolete at the time of use, especially when the temporal variation of LU activity is high. To reduce the bandwidth for reporting, several methods suggest that only informative and reliable sensing data are reported[5,6]. Although these algorithms reduce the reporting time and claim to increase LU detection accuracy, it is difficult to choose which CU is to report. In addition, if a CU is subject to different LUs or independent channel impairment, suppressing its reporting could lead to detection failure. Weiss et al. proposes that multiple CUs simultaneously transmit jam signals so that the central controller can determine universally available subcarriers in an infrastructured OFDM-based CR network (CRN)[7]. Although this method considerably reduces reporting time, it is not clear how to coordinate transmission timing among multiple CUs. And CUs transmit on the subcarrier where LU activity is detected, potentially inducing interference to LUs. Another limitation is that only OR-rule[4] can be applied because the transmitters of jamming signals are not distinguishable.

In this paper, we propose a method to efficiently report sensing data to the central controller in an infrastructured OFDM-based CRN. In the proposed method, a CU transmits a unique and orthogonal codes on locally available subcarriers. Transmission timing is adjusted based on the feedback from the central controller so that the signals sent by all of the CUs arrive at the central controller simultaneously. Unlike previously suggested methods, the proposed method reports every available subcarrier, which in turn help to determine the subcarrier to be used. Also, by detecting orthogonal codes on each subcarrier, the central controller determines per-CU subcarrier availability. Thus, it is possible to apply various fusion rules, not just OR-rule. The contribution of this paper is as follows. First, a sensing data reporting method is introduced for an infrastructured OFDM-based CRN, which provides per-CU spectrum availability within a short time period. Second, implementation challenges and their solutions are discussed. Finally, the feasibility of the proposed method is thoroughly evaluated on a realistic channel model.

The rest of the paper is organized as follows. In Section II, the architecture and environments of target CRN are described. Section III gives the detail of the proposed method. In Section IV, discussion on implementation challenges are presented. Section V describes performance evaluation. Lastly, Section VI concludes the paper.

Ⅱ. SYSTEM MODEL

In this paper, the central controller is called cognitive access point (CAP). All non-CAP CUs are called cognitive stations (CSTA). We assume a network that consists of one CAP and a number of CSTAs. All CSTAs are within 1-hop of the CAP. The network is presumed to be stationary. OFDM is used for modulation because it is easy to avoid interfering an LU by leaving certain subcarriers unmodulated[7]. Many previous works in the literature[8][9] also assume OFDM-based CRNs. Both the CAP and CSTAs are responsible for local spectrum sensing. No assumption is made on which algorithm is used nor when it is executed. To reduce overhead, CSTAs report only whether a subcarrier is occupied by LU or not. We make no assumption on the location, transmission range, nor the activity pattern of LU.

Ⅲ. Orthogonal Signaling-based Sensing Data Reporting

In the proposed method, every CSTA has a bit sequence called availability notification (AN). AN is unique to a CSTA so that it can be used to identify a CSTA. Management of AN will be discussed in Section IV-1.

Fig. 1 shows the message exchange sequence of the proposed method. The CAP initiates sensing data reporting by transmitting a Query message. Upon receiving the Query message, a CSTA transmits its AN on the locally available subcarriers, while sending null symbols on the others (magnified image

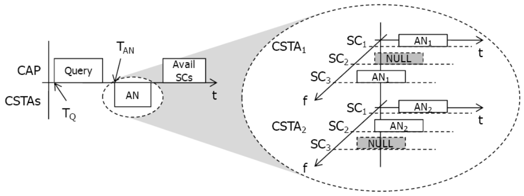

Fig. 1. Message exchange sequence of the proposed method.
그림 1. 제시한 방법의 메시지 전송 순서

of Fig. 1). The resultant time domain signal is called reporting signal. CSTAs adjust transmission timings so that their reporting signals arrive at the CAP simultaneously. Consequently, the CAP receives the combined signal of all of the transmitted reporting signals. From the combined signal, the CAP checks the presence of individual ANs on each subcarrier, determining which subcarrier is available to which CSTA. By applying a sensing data fusion method on the detection results, the CAP derives and announces the set of subcarriers to be used for subsequent data communications. Note that the proposed method does not assume a specific data fusion method.

Detecting an AN from the combined signal is the most important step of the proposed method. To do this, the CAP analyzes the received signal at a symbol level because demodulation removes information about the constituent ANs. In addition, ANs are selected such that they have high auto-correlation and low cross-correlation. High auto-correlation helps to detect an AN in the presence of noise, and low cross-correlation makes it easy to distinguish an AN from other ANs. It is known that the orthogonal codes and the pseudonoise codes employed in CDMA systems have these properties[10]. Among the two types of codes, we choose the orthogonal codes because they have lower (zero) cross-correlation when combined with the perfect alignment. Specifically, we use Walsh codes as ANs[10]. Walsh codes have a length of 2^n for any positive integer n. The number of 2^n-bit Walsh codes is also 2^n, meaning that the maximum number of supportable CSTAs is determined by the length of the employed codes.

The input and output of AN detection process is illustrated in Fig. 2. For clarity, the diagram omits many details such as RF frontend and channel effects. AN detection is done by comparing the cross-correlation between an AN and the symbols received from each subcarrier. The details are as follows. Say that AN_i belongs to CSTA i and is represented as an array of L symbols $u_i[k]$, $1 \le k \le L$. The signal received from subcarrier j is then denoted as $u_i[k] = \sum_{l \in A_j} u_l[k]$, where A_j is the set of CSTAs that transmitted their ANs on subcarrier j. The cross-correlation between AN_i and r_j is:

$$
\begin{aligned}
\Gamma_{i,j} &= \sum_{k=1}^{L} u_i^*[k] r_j[k] \\
&= \sum_{k=1}^{L} u_i^*[k] \left(\sum_{l \in A_j} u_l[k] \right) \\
&= \begin{cases} \sum_{k=1}^{L} u_i^*[k] u_i[k] & i \in A_j \\ 0 & i \notin A_j \end{cases}
\end{aligned}
$$

since $\sum_{k=1}^{L} u_i^*[k] u_m^*[k]$ is zero if $i \neq m$. "*" represents the complex conjugate, which can be omitted because AN symbol values are all real in this paper[1]. Finally, the CAP determines that AN_i has been transmitted on subcarrier j if $\Gamma_{i,j}$ is greater than a threshold.

Fig. 3 shows an example of AN signal combination and AN detection on a subcarrier, using 4-bit orthogonal codes.

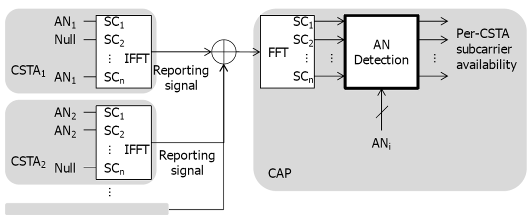

Fig. 2. Model of AN signals combination and detection at the CAP.
그림 2. CAP에서의 AN 시그널의 결합 및 감지 모델

1) We use BPSK modulation for ANs.

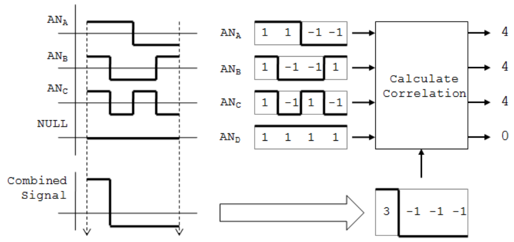

Fig. 3. Example of AN signal combination and detection
그림 3. AN signal의 결합 및 감지 예

Ⅳ. Implementation Issues

The proposed method poses several implementation challenges, which could significantly reduce efficiency as well as effectiveness of the proposed method. The challenges include management of AN, frequency offset compensation and signal transmission timing adjustment, reducing jitter in signal processing, and received signal power equalization.

4.1 Management of ANs

A CAP must keep track of which ANs are currently in use for AN detection. To do so, the CAP can explicitly assign an AN to a CSTA and retrieve it when the CSTA stops operation. It is reasonable that the assignment takes place in the association phase2). Similarly, AN retrieval can be done in the disassociation phase. However, it is possible that a CSTA is turned off or moves away from the network without notifying the CAP. Thus, the CAP should retrieve an AN on any indications that its owner has stopped operation. For example, if a CSTA does not send its reporting signal (equivalently, if a CSTA does not send its AN on any subcarriers) for a long time, the CAP may conclude that the CSTA has left the network and then retrieve its AN.

4.2 Frequency Offset Compensation and Signal Transmission Timing Adjustment

Frequency offset is the difference in the center frequency between a transmitter and a receiver. The main cause is local oscillator errors that cause up/down conversion to/from the center frequency to be asymmetric3). In an OFDM-based system such as the target CRN, frequency offset degenerates orthogonality between subcarriers. Consequently, the proposed method could suffer from reduced AN detection accuracy.

On the other hand, the proposed method requires that the reporting signals transmitted by all of the CSTAs arrive at the CAP simultaneously (Section III). Otherwise, orthogonality among ANs deteriorates, which in turn reduces AN detection accuracy. Therefore, a CSTA must adjust the delay between the reception of a Query message and the transmission of its reporting signal (T_Q and T_{AN} in Fig. 1, respectively) considering the propagation distance to the CAP.

One solution to the above challenges is feedback-based synchronization. A CSTA transmits a repetition of a predefined pilot symbol in the association phase. By comparing the received symbol and the pilot symbol, the CAP can estimate the frequency offset as well as the transmission timing offset. This information is then fed back, and the CSTA adjusts its transmission parameters accordingly[11].

4.3 Reducing Jitter in Signal Processing

The proposed method calls for accurate and timely signal processing for simultaneous arrival of reporting signals at the CAP. Specifically, timestamping of T_Q needs to be very accurate because it acts as a reference for scheduling reporting signal transmission. The reporting signal transmission must also occur punctually at T_{AN}. However, it is reported that commercial network interface cards show high jitter in signal processing delay[12,13].

To reduce such jitter, the required signal processing must be done close to the HW. As for accurate reception timestamping, it is suggested that the radio HW records the time at which the first sample of a sample block was generated by the

2) Many point-to-multipoint networks have an association phase for authorization and parameter negotiation. Examples are IEEE 802.11, 802.16, and 802.22.

3) We ignore Doppler shift because the target network is stationary.

analog-to-digital converter (ADC), using the radio clock[14]. With the known sampling rate and the position of the Query message in the sample block, it is possible to extract T_Q with high accuracy. Punctual transmission at T_{AN} can also be implemented by using the radio clock. The sample block of the reporting signal is tagged with the transmission time T_{AN}. The radio HW waits until the radio clock is equal to T_{AN}, and then begins transmission[14].

G. Nychis et al. evaluated the above method by implementing a simple echo protocol, where a node transmits a reply with a given delay after receiving a request[14]. The delay varied in the range from 1 µsec to 100 msec. The experiment results showed that the perfect time spacing was observed by a third node whose measurement resolution is 125 nsec.

4.4 Equalizing Received Signal Power

Received reporting signals may have different strengths if they are transmitted by CSTAs with different distances to the CAP. In addition, the signal strength varies over time because channel status changes continuously. Although in theory the orthogonality between ANs are preserved regardless of their strengths, this does not hold in practice because of imperfect channel status. Consequently, it becomes difficult to detect an AN if its reporting signal is far weaker than others. This calls for a mechanism to equalize the received reporting signal strength observed at the CAP.

Power control mechanisms are categorized into open-loop and closed-loop power control. In an open-loop power control mechanism, the reverse link path loss is estimated based on the forward link signal strength, assuming that the two links are closely correlated. Although the assumption may not hold if multipath fading occurs, this mechanism provides fast and cheap way to compensate large scale variations such as shadowing[15]. A more sophisticated mechanism is closed-loop power control where the CAP gives CSTAs feedback based on the received signal power[10]. This mechanism generally performs better than open-loop power control because the reverse link path loss is not estimated but measured. We can think of mixing the two power control mechanisms for the proposed method. A possible approach is to perform closed-loop power control at the association phase, and then use open-loop power control to fight signal power fluctuation.

Ⅴ. Performance Evaluation

In this section we assess the performance of the proposed method. First, AN detection accuracy is investigated via simulation on a realistic channel model. Next, the performance of cooperative spectrum sensing is evaluated by applying an aggregation rule to the AN detection results.

5.1 Simulation Details

Fig. 4 shows a schematic diagram of the simulation procedure. In the simulation all signals are represented as sequences of complex numbers (symbols) as though analog signals are sampled at a certain rate. First, a CSTA modulates its AN using BPSK, and generates a reporting signal by applying inverse fast fourier transform (Fig. 2). To avoid inter-symbol interference, a guard interval is inserted to the reporting signal. Imperfect power equalization is simulated by multiplying each symbol of the reporting signal with a coefficient, which is drawn from a Log-normal distribution[16]. The signal is then fed to the channel, where it is contaminated by one-way Rayleigh fading. The signals from all of the CSTAs are combined, and additive white gaussian noise (AWGN) is applied. The CAP receives the resultant signal, applies fast fourier transform and removes the guard interval, and then

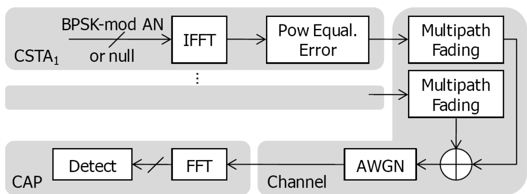

Fig. 4. Schematic diagram of simulation procedure to evaluate AN detection accuracy.
그림 4. AN 감지 정확성을 평가하기 위한 시뮬레이션의 도식

performs AN detection (Section III).

Simulation parameters are summarized in Table I. Power equalization error is represented by the mean and standard deviation of the difference between the desired and the received power level. We set 0 and 1.5 dB to the mean and standard deviation, respectively[16]. Threshold is set to the 75% of the ideal auto-correlation value. For example, if 32-bit Walsh codes are used as ANs, and signal power is equalized so that the amplitude of received symbol is 1, the ideal auto-correlation value is 32 · 0.75 = 24. The LU active ratio means the probability that a subcarrier is occupied by a LU.

Table 1. Simulation parameters for AN detection accuracy test
표 1. AN 감지 정확성 테스트를 위한 시뮬레이션 파라메터

Parameter	Value
Total number of STAs	32
Total number of subcarriers	128
Power equalization error	Log-N(0, 1.5) dB[16]
Max. Doppler freq.	10 Hz
AN	Walsh codes
Detection threshold	70% of ideal auto-correlation

5.2 AN Detection Accuracy

We first study how the detection accuracy changes as signal-to-noise ratio (SNR) varies. SNR varies in the range from 0 to 20 dB. We measure three metrics: false alarm, miss detection, correct detection ratio. False alarm is an event that the CAP fails to detect an AN. Miss detection is the opposite event, where the CAP falsely detects an AN that has not been transmitted. Correct detection means that the detection results are same as those that actually transmitted. The LU active ratio is fixed to 50%. The simulation results show that the detection accuracy improves as SNR grows, but improvement when SNR > 12 dB is marginal (Fig. 5). Performance improvement due to SNR increase is expected because the transmitted ANs are less contaminated by noise. Given that the SNR of a typical office environment is around 15 dB[17], the proposed method shows fairly robust performance.

Next, we investigate the effect of the length of ANs and LU active ratio on detection accuracy. We tested 32, 64, and 128-bit Walsh codes for ANs, while fixing the number of CSTAs to 32. LU active ratio changes from 0.1 to 0.9. SNR is fixed to 10 dB. Fig. 6 illustrates the simulation results. It is obvious that longer codes improves detection accuracy. The reason is that longer codes are less amenable to noise. Also, as LU active ratio grows, detection accuracy increases. This is because of inter-AN interference, which means that an AN hinders detection of other AN. Using longer codes alleviates this problem. However, decision on using longer AN should be made carefully because it also increases reporting signal transmission time.

Finally, we study the degree of performance degradation caused by timing error. As noted in

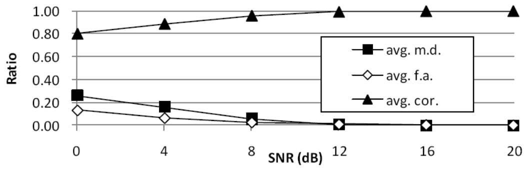

Fig. 5. Trend of detection accuracy as SNR varies
그림 5. SNR값에 따른 감지 정확성의 변화

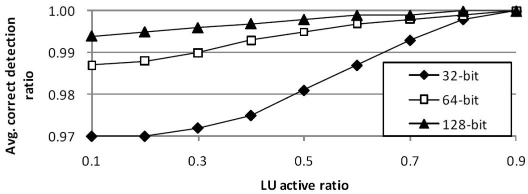

Fig. 6. Trend of correctly detected AN ratio as LU active ratio changes
그림 6. LU의 활성화 비율에 따른 정상 감지된 AN의 비율의 변화

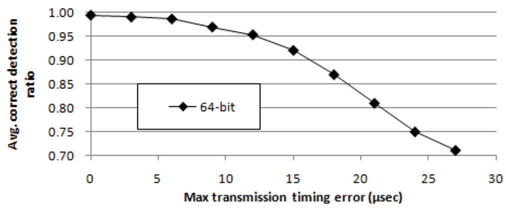

Fig. 7. Trend of correctly detected AN ratio as the transmission timing errors change
그림 7. 전송 시간 에러에 따른 정상 감지된 AN의 비율

Section III, CSTAs must transmit their ANs simultaneously. If there exists a timing error, the detection accuracy would decrease. The LU active ratio is set to 0.5, the length of AN 64 bits. We measure the average correct detection ratio while changing the maximum timing error. The results show that the accuracy degrades as the maximum transmission timing error increases (Fig. 7).

5.3 Cooperative Spectrum Sensing Accuracy

In this subsection, the performance of cooperative spectrum sensing is investigated by applying a fusion rule to the sensing data collected by the proposed method. We use M-out-of-N rule, where the CAP concludes that a subcarrier is available if more than M out of N CSTAs report as such[4]. In the simulation, M varies from 70 % to 100 % of N = 32, where the case of 100 % degenerates into OR-rule. Note that M-out-of-N rule with M > 50% is robust to miss detection than false alarm errors, which is desirable because avoiding interference to LU is the foremost requirement of CR. Regarding an office environment, SNR is set to 15 dB. To alleviate inter-AN interference, 64-bit Walsh codes are assigned to 32 CSTAs. In practice, sensing data from different CSTAs can be similar if they are close together relative to the LU' transmission range. Therefore, we impose correlation among the LU activities observed by CSTAs. Correlation changes in the range from 0 to 0.9, and LU activity is adjusted accordingly so that the ratio of universally available subcarriers becomes approximately 70%. The rest of the simulation settings is same as summarized in Table I.

Fig. 8 is the ratio of subcarriers that are correctly detected. Except the case of M = 1, the ratio of correctly detected subcarriers is greater than 0.97 regardless of correlation. As correlation among sensing data grows, detection accuracy slightly improves. The reason is that correlated sensing data is complementary to each other in that misdetection is likely to be compensated by correct detection of other similar sensing data. Detection accuracy increases as M becomes large, because M acts as a buffer against false alarm errors.

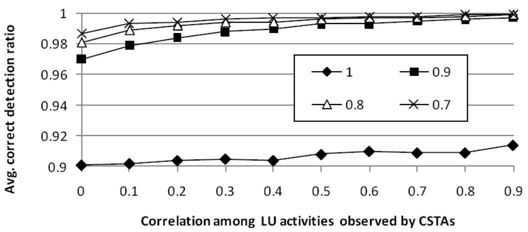

Fig. 8. Detection accuracy of cooperative spectrum sensing.
그림 8. 협동적인 스펙트럼 감지의 정확성

Ⅵ. Conclusion

In this paper, we introduced a method for multiple CSTAs to simultaneously report their sensing data to a CAP in an infrastructured OFDM-based CR network. All CSTAs transmit their unique and orthogonal codes on locally available subcarriers at the same time. From the combination of the signals, the CAP determines that a subcarrier is available at a CSTA if its orthogonal code is detected on the subcarrier. We identified several implementation challenges and then discussed their solutions. The accuracy of sensing data reporting was evaluated via simulation using a realistic channel model. The results showed that the proposed method is feasible and performs well.

References

〔1〕 I.F. Akyildiz, W. Lee, M.C. Vuran, S. Mohanty, "NeXt generation dynamic spectrum access cognitive radio wireless networks: a survey," Elsevier Computer Networks, 50, pp.2127-2159, 2006.

〔2〕 FCC, "ET docket no. 03-222", December 2003. [Online]. Available: http://hraunfoss.fcc.gov/edocs public/attachmatch/FCC-03-222A1.pdf

〔3〕 J. Mitola III, "Cognitive radio: an integrated agent architecture for software defined radio," Ph.D. Thesis, KTH Royal Inst. Technology, Stockholm, Sweden, 2000.

〔4〕 T. Yucek, H. Arslan, "A Survey of Spectrum Sensing Algorithms for Cognitive Radio Applications," IEEE Communications Surveys and Tutorials, 11(1), pp. 116-130, 2009.

〔5〕 C. Sun, W. Zhang, K.B. Letaief, "Cluster-based Cooperative Spectrum Sensing in Cognitive Radio Systems," in Proc. IEEE ICC, Glasgow, Scotland, pp. 2511-2515, Jun. 2007.

〔6〕 E. Peh, Y.-C. Liang, "Optimization for Cooperative Sensing in Cognitive Radio Networks," in Proc. IEEE WCNC, Hong Kong, pp. 27-32, Mar. 2007.

〔7〕 T.A. Weiss, J. Hillenbrand, A. Krohn, F.K. Jondral, "Efficient Signaling of Spectral Resources in Spectrum Pooling Systems," in Proc. SCVT, Eindhoven, Netherlands, Nov. 2003.

〔8〕 S. Feng, H. Zheng, H. Wang, J. Liu, P. Zhang, "Preamble Design for Non-contiguous Spectrum Usage in Cognitive Radio Networks," in Proc. WCNC, Budapest, Hungary, pp. 705-710, Apr. 2009.

〔9〕 M. Krondorf, T.J. Liang, G. Fettweis, "On Synchronization of Opportunistic Radio OFDM Systems," in Proc. IEEE VTC Spring, Marina Bay, Sinigapore, pp. 1686-1690, May. 2008.

〔10〕 S.G. Glisic, Adaptive WCDMA: Theory and Practice, Wiley, 2003.

〔11〕 M. Morelli, "Timing and Frequency Synchronization for the Uplink of an OFDMA System," IEEE Transactions on Communications, 52(2), pp. 296-306, 2004.

〔12〕 V. Shrivastava, N. Ahmed, S. Rayanchu, S. Banerjee, K. Papagiannaki, A. Mishra, "CENTAUR: Realizing the Full Potential of Centralized WLANs through a Hybrid Data Path," in Proc. ACM MOBICOM, Beijing, China, pp. 297-308, Sep. 2009.

〔13〕 G. Bianchi, A. Di Stefano, C. Giaconia, L. Scalia, G. Terrazzino, I. Tinnirello, "Experimental assessment of the backoff behavior of commercial IEEE 802.11b network cards," in Proc. IEEE INFOCOM, Anchorage, AK, USA, pp. 1181-1189, May. 2007.

〔14〕 G. Nychis, T. Hottelier, Z. Yang, S. Seshan, P. Steenkiste, "Enabling MAC Protocol Implementations on Software-Defined Radios," in Proc. USENIX NSDI, Boston, MA, USA, pp. 91-105, Apr. 2009.

〔15〕 A.M. Monk, A. Chockalingam, L.B. Milstein, "Open-loop power control error on a frequency selective CDMA channel," in Proc. IEEE GLOBECOM, San Francisco, CA, USA, pp. 29-33, Nov.-Dec. 1994.

〔16〕 A.J. Viterbi, A.M. Viterbi, and E. Zehavi, "Performance of Powercontrolled Wideband Terrestrial Digital Communications," IEEE Transactions on Communications, 41(4), pp. 559-569, 1993.

〔17〕 M. Garcia, R. Agu¨ero, L. Mun.oz, J.A´ . Irastorza, "Smart Enhancement of TCP Performance Over Lossy WLAN Channels Through the Combined Use of Link Layer Techniques," Wireless Personal Communications, 37(1-2), pp. 91-103, 2006.G3

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