A Comparison of Control-channel Schemes in OSA Networks using a Configurable Testbed

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Abstract—**In this paper, the control channel for secondary users in opportunistic spectrum access networks is considered. Given a licensed bandwidth for primary users, we compare the performance of three control-channel schemes: dedicated, underlay, and overlay. The key performance metric for comparison is the primary data rate, i.e., how it is affected by interference from secondary control messaging. The comparison is conducted via a configurable testbed implementation of a primary and a secondary network, each composed from two USRP radios connected through an RF channel emulator. The *MATLAB/Simulink* software toolbox is used to develop the baseband models for the radio transceivers. Trade-offs between the three schemes, as well as insight on the practical implementation of NC-OFDM in opportunistic spectrum access systems, are provided.**

Keywords—**cognitive radio, opportunistic spectrum access, common control channel, USRP, MATLAB/Simulink**

I. Introduction

The popularity of smartphones and other data-intensive mobile devices has spurred an exponential increase in wireless data transmission in the past seven years. Such an increase has led to a shortage of available radio spectrum [1,2], otherwise known as the spectrum crunch. This shortage is a key driver for investigating the use of opportunistic spectrum access in 5G and related technologies [3].

Opportunistic spectrum access (OSA) is a promising technology to improve spectrum utilization efficiency. Typically, a hierarchical structure is adopted in OSA in which primary users (PUs) have priority access to a licensed spectrum while secondary users (SUs) may access the unoccupied portions of the band so long as they do not interfere with the former. This new access paradigm has spawned many research issues [1,2] such as spectrum sensing to identify utilization on the primary network, spectrum sharing to implement secondary access schemes, and spectrum handover to support seamless data communication between SUs.

Besides neighbor discovery, an essential function of the control channel (CC) is to exchange information on the spectrum occupancy of the primary network. While the control channel of the PUs is provisioned within the licensed spectrum, SUs must first establish a control channel to initiate communications. As such, the secondary CC has also been identified as one of the challenging issues in OSA networks [4]. Even though a number of studies have investigated CC schemes, as summarized in [4], to our knowledge an assessment of their performance based on practical implementation has not yet been conducted. To this end, we perform a comparison between the three main schemes referred to in the literature as dedicated, underlay, and overlay. Our intention is to document the effect of secondary control messaging on the data rate of the primary users. We do so through the *configurable* testbed of an OSA system consisting of a primary and a secondary network of software-defined radios connected through an RF channel emulator. The *MATLAB/Simulink* software toolbox is used to develop the baseband model for the radio transceivers.

The remainder of this paper is organized as follows: Section II presents related work and Section III describes the opportunistic spectrum access system model and assumptions. Section IV describes our experimental setup in detail followed by experimental results in Section V and then conclusions.

II. Related Work

A basic design criterion for a secondary control-channel scheme is to minimize interference on primary users. By this criterion, the dedicated control channel (DCC) offers optimal performance because it operates in a band exclusively assigned to secondary users. While reliable exchange of control messaging between SUs is expected, the extra licensing cost can be a limiting factor; an alternative perspective is that the dedicated channel reduces the licensed spectrum of the primary. The authors in [5] consider a dedicated CC in the implementation of their residual idle time-based channel access scheme. In other work [6], the dedicated CC is established in an unlicensed band, forcing the SUs to contend for access, introducing delay and interference from other intraband radios. Similarly in [7], a comprehensive OSA implementation framework, with a host of functionalities such as spectrum sensing, common CC, spectrum coordination, and packet transmission, is proposed; in it, the ISM band is used as a dedicated CC. While most dedicated schemes transmit a narrowband waveform, the authors in [8] propose an Orthogonal Frequency-Division Multiplexing (OFDM)-based channel which is established on the guard bands of the primary systems. This can be viewed as a special case of the dedicated scheme in which the secondary CC is not directly occupied by PUs, but still does not require additional spectrum allocation.

The benefit of the underlay control channel (UCC) is that it requires no spectrum provisioning. This is because it operates in the same band as the primary. The SU transmits control messages through spread spectrum techniques such as ultrawideband [9]. As it uses very low transmit power over a wideband, the transmission of the PU should not be affected. A similar approach is proposed in [10], where a Filtered MultiToned Spread Spectrum (FMT-SS) technique suppresses the subcarriers occupied by the PUs. Besides potential interference, a downside of the underlay scheme is short transmission range; in addition, the high processing gain inherent to spread spectrum limits the data rate.

The overlay control channel (OCC) is attractive because it requires no spectrum provisioning nor is its transmission power limited by interference on the primary. Rather, the sensing features of the system are invoked to opportunistically establish a CC in a subband unoccupied by the primary network. Consequently, overlay schemes are limited by the spectrum usage of the PUs. They are also limited by the sensing performance (i.e., probabilities of misdetection and false alarm) of the SUs: based on their different locations, channel conditions, and other factors, the SUs may yield inconsistent results. So, in order to find consensus on a common channel, rendezvous algorithms such as adaptive frequency hopping in [11] and quorum-based in [12] must be employed.

III. Opportunistic Spectrum Access Model

In this section, we present a system model for opportunistic spectrum access. In particular, we present our implementation of dedicated, underlay, and overlay control-channel schemes.

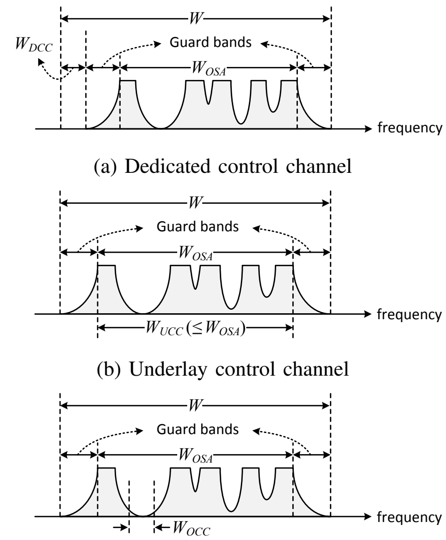
A. Secondary control-channel schemes

Consider first the dedicated scheme illustrated in Fig. 1a. Let W denote the licensed bandwidth of the PU. The bandwidth is partitioned into a dedicated control channel[1], W_{DCC}, an opportunistic spectrum access data channel, W_{OSA}, and guard bands to mitigate interchannel and out-of-band interference. In this example, the spectrum occupancy of the primary is characterized by five non-contiguous subbands.

Next consider the underlay scheme illustrated in Fig. 1b. In contrast with Fig. 1a, note the absence of a separate subband for the control channel. This means there is a wider bandwidth apportioned for the data channel. However, since the UCC, with bandwidth $W_{UCC} \leq W_{OSA}$, transmits in the same band, mutual interference may occur. In order to mitigate such interference, the underlay scheme uses Direct Sequence Spread Spectrum (DSSS) to spread the low-rate control information across the data channel such that it can be transmitted at minimal power spectral density. An important observation in this paper is that when the licensed band of the primary is narrow, interference on the primary is difficult to avoid.

The overlay scheme is illustrated in Fig. 1c. In this scheme, control information is transmitted on a portion of the band unoccupied by the PUs. As such, sensing results are required to determine the OCC. Because the channel has a fixed bandwidth, $W_{OCC} < W_{OSA}$, the SUs, which sense the spectrum independently, may decide on different center frequencies for the channel. The purpose of the rendezvous algorithms cited previously is so the SUs meet on a common channel. In this paper, we propose a more simplistic rendezvous algorithm which is shown to be effective nevertheless: the SU selects the center of the largest idle band as the center frequency of the OCC. This, of course, is conditioned upon the available contiguous bandwidth being wider than W_{OCC}; the scheme fails otherwise. In contrast to the dedicated and underlay schemes, the overlay scheme is affected by fluctuations in the spectrum occupancy of the primary over time. Therefore, the OCC must be adaptive, implying an inherently more complex filter design.

[1]Here the control channel is placed in the leftmost portion of the licensed band, but could be equally placed anywhere within W.



(a) Dedicated control channel

(b) Underlay control channel

(c) Overlay control channel

Fig. 1. Bandwidth partition for control-channel schemes

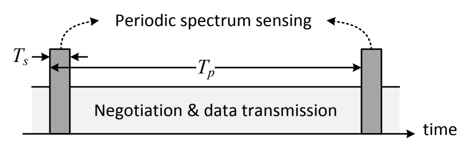


Fig. 2. Periodic sensing structure for secondary user operation.

B. Secondary sensing

Spectrum sensing by the secondary users is necessary to determine the utilization of the primary spectrum. Specifically, during a period of duration T_p, the SUs sense the spectrum W_{OSA} for a time duration T_s, as shown in Fig. 2. Once the idle channels are identified, the SUs exchange sensing results to confirm both have an identical set of data channels. A 3-way handshake is used for this step, a procedure generally accepted in ad-hoc networks. The SU transmitter sends a control message with its own sensing result through a Request-To- Send (RTS). Upon receiving the message, the SU receiver responds with the data channels judged as commonly available through a Clear-To-Send (CTS). If the exchange of sensing results is successful, data transmission will take place over the selected data channels. Control messages are transmitted only once per sensing period and no retransmission is allowed.

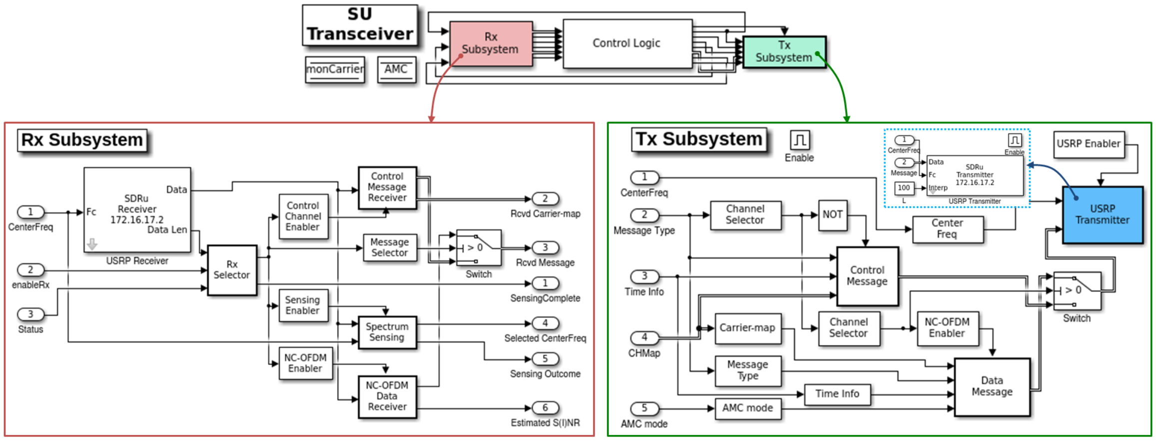


Fig. 3. The block diagram of the baseband model for the SU transceiver.

C. Primary and secondary data transmission

Both the primary and secondary users employ noncontiguous OFDM (NC-OFDM) modulation for data transmission. It is as a variant of OFDM which supports the synthesis of noncontiguous subcarriers per user. This allows the PUs and SUs to operate over the same bandwidth but with different carrier maps. Consistent with OFDM, the guard bands are implemented by nulling subcarriers on both sides of total bandwidth; the remaining subcarriers in W_{OSA} are designated for data and pilot signals. As such, in reference to Fig. 1, the total bandwidth for data in the dedicated scheme is $W - W_{DCC}$ and W in the underlay and overlay schemes. As a means to shield primary and secondary data transmissions from each other, additional guard bands are placed between alternating PU and SU subbands. The width of each guard band is one subcarrier.

IV. Configurable Testbed Implementation

This section describes the testbed, we configured to evaluate the control-channel schemes presented in Section III. The opportunistic access system is partitioned into a primary network and a secondary network, each with two software-defined radios. The radios are the *Ettus* USRP N210s with SBX daughter cards[2]. They are fully connected in a mesh topology through an *Elektrobit* Propsim F8 RF channel emulator. This enables testing direct communication between the two radios in a network while guaging mutual interference between the networks. An AWGN channel with fixed path loss of 20.8 dB is applied to all links. The two rack-mounted host servers have 12 core CPUs and 64 GB memory and run *CentOS* Linux 2.6.32.

The baseband transceiver models necessary to construct the opportunistic access system were developed in *MATLAB* R2013b/*Simulink*8.2. Communication on the data channel for both primary and secondary users is based on an NC-OFDM waveform. The dedicated and overlay CCs, on the other hand, employ a narrowband waveform while DSSS is used for the underlay CC. The SUs also require spectrum sensing capabilities. As an example, Fig. 3 illustrates the block diagram of the baseband model for the SU transceiver designed in Simulink. The control waveform and NC-OFDM data waveforms are generated and transmitted in the TX Subsystem; the RX Subsystem provides either control message or data retrieval, depending on the respective operating channel, as well as spectrum-sensing capabilities. TX/RX Subsystems are driven by a main controller. In every transceiver model, the frame (packet) detection and synchronization is achieved through a delay and correlation algorithm [13]. The correlation peak threshold for frame detection is determined heuristically such that the probability of false alarm is less than 0.1. The baseband signals are upconverted to a center frequency of 722 MHz. The remainder of this section provides specifics of the transceiver models as well as their parameter setting for the experiments.

A. NC-OFDM transceiver for PU/SU data channels

The *IEEE* 802.11a OFDM PHY model provided by *MATLAB/Simulink* served as the basis to develop the NC-OFDM baseband transceiver for the PU/SU data channels. In the original OFDM model, a symbol is composed from 64 subcarriers and a 16-sample cyclic prefix: 12 of the subcarriers are nulled as guard bands and the DC offset; the remaining 52 active subcarriers form the opportunistic spectrum access channel, W_{OSA}; 48 are data subcarriers and 4 pilot subcarriers uniformly interleaved in between. The licensed bandwidth of the primary users, W, is set as 1 MHz or 15.625 kHz per subcarrier. An OFDM frame is formed by 25 symbols, each symbol $80\mu s$ in duration. The first two symbols are training sequences for frame synchronization and detection. The corresponding maximum achievable bit rate is 2.7 Mbps with 64-QAM and coding rate 3/4.

While the NC-OFDM system has the same symbol and frame structures as the OFDM system, it enables dynamic allocation of the 52 subcarriers through selective deactivation.

[2]The identification of any commercial product or trade name does not imply endorsement or recommendation by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

This means that it transmits on only a subset of subcarriers as defined per the carrier map of either the primary or the secondary network. The carrier map is a binary vector of size 52 representing the status of each subcarrier as either active or inactive. When transmitting, the inactive subcarriers are simply nulled before the NC-OFDM symbol generation (i.e., before the IFFT); when receiving, the inactive subcarriers known a priori through the carrier map are suppressed by the FFT-based subcarrier-nulling filter. In our experiments, we vary the number of subcarriers and their positions in the NC-OFDM symbol per the carrier map. As such, static allocation of pilot subcarriers as in the OFDM system is not desired. Rather, the pilots are uniformly distributed amongst the active subcarriers, maintaining the ratio of 1 pilot subcarrier per every 12 data carriers, or fraction thereof.

B. BPSK transceiver for SU dedicated/overlay control channel

The narrowband transceiver model for the SU dedicated and overlay control schemes uses BPSK modulation with coding rate 1/2. It was developed from the QPSK transmitter and receiver models provided by *MATLAB/Simulink*. The sampling rate of the narrowband signal is set as 50 kHz and the roll-off factor of the root-raised cosine (RRC) filter as 0.35. Accordingly, $W_{DCC} = W_{OCC} = 67.5$ kHz, intending that the SU will require at least 5 unoccupied contiguous subcarriers to implement either the dedicated or overlay schemes.

C. DSSS transceiver for SU underlay control channel

The underlay scheme uses DSSS modulation to spread the 50 kHz narrowband control signal over the opportunistic spectrum access bandwidth, W_{OSA}. Our DSSS transceiver applies a short code scheme (i.e., each information bit will be modulated using full PN sequence) with 63 PN chips. The information bit is modulated using BPSK. The actual bandwidth of the underlay channel, W_{UCC}, is about 803 kHz with a roll-off factor of 0.35 for the RRC filter.

D. Spectrum sensing for SU

A 64-point FFT-based energy detection scheme is used to sense the W=1 MHz spectrum. The sampling frequency is hence selected as 1 MHz at complex baseband. In reference to Fig. 2, the sensing duration T_s is set to 20 ms, which corresponds to 250 NC-OFDM symbols in our experiment, an amount sufficient to determine the spectrum correctly [14]. The sensing period, T_p, is set to be 3s.

V. Experimental Results

In this section, we compared the dedicated, underlay, and overlay schemes. The key metric for comparison is the data rate of the primary network, i.e., how the rate is affected by control messaging. In subsection A, we examine our implementation of NC-OFDM to identify what factors affect its performance and in subsection B, we validate the functionality of our OSA system as a whole. The experimental results related to the CC schemes are discussed in subsection C.

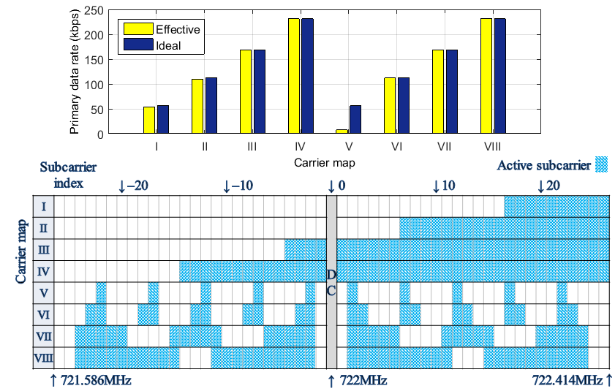


Fig. 4. Primary data rate of our NC-OFDM for different carrier-maps.

A. Performance of the implemented NC-OFDM

We first consider the primary data channel in isolation; we then consider the primary and secondary data channels in concurrent operation. In our controlled experiments, both the primary and secondary radios transmit at a constant power spectral density (PSD) of -80.5 dBm/Hz. Because the PSD is constant, the actual transmission power varies in proportion to the number of active subcarriers. In conjunction with the path loss, the PSD delivers a signal-to-noise ratio (SNR) of about 10 dB to the receivers (estimated noise PSD is about -111.6 dBm/Hz). This SNR values permits a subcarrier modulation of QPSK with coding rate 1/2.

For validation purposes, we test the effective rate of NC-OFDM in our implementation when all subcarriers are active against the ideal OFDM rate. For example, the ideal rate for OFDM using QPSK 1/2 on a 1 MHz bandwidth is 600 kbps. In our implementation of NC-OFDM, we report an effective rate of 599.92 kbps. This confirms that the frame synchronization and detection works well when all subcarriers are active[3].

When some are inactive, however, a drop in performance in some circumstances is witnessed. Fig. 4 displays the effective and ideal primary data rates for eight example carrier maps labeled I-VIII. The ideal rates increase in proportion to the number of active subcarriers. Observe that the effective rates track the ideal rates very well, except for carrier map V. The latter relates to the autocorrelation properties of the training sequence used in NC-OFDM, as discussed in [14]. Poor autocorrelation properties translate into misdetected frames and in turn a drop in the data rate. The autocorrelation properties improve i) when more subcarriers are active and ii) when the active subcarriers are contiguous. In fact, while carrier maps I and V have the same number of active subcarriers, the performance for V is much worse because its active subcarriers are sparsely distributed. Since our NC-OFDM implementation uses the long training sequence defined in *IEEE* 802.11 standard, a drop in the data rate in some cases cannot be avoided.

Fig. 5 shows the data rates of the primary and secondary NC-OFDM systems on adjacent data channels for two carrier

[3]The suite of modulation and coding schemes in the IEEE 802.11a PHY were all tested with comparable results.

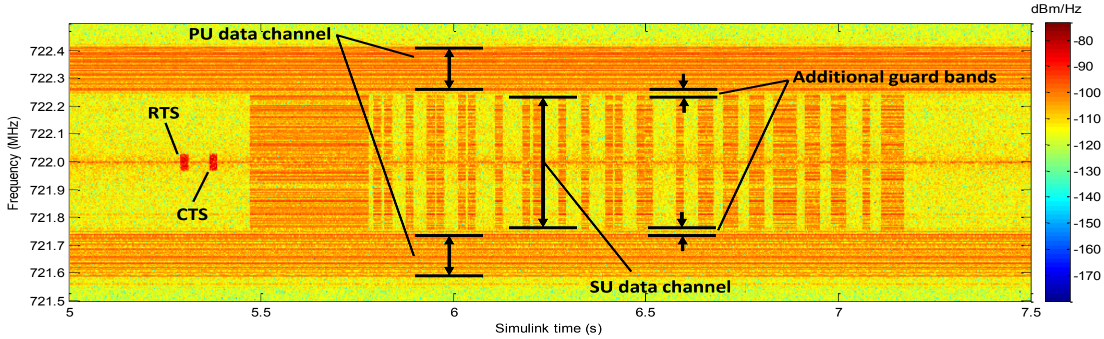


Fig. 6. Sample spectrogram view for OSA implementation using overlay CC.

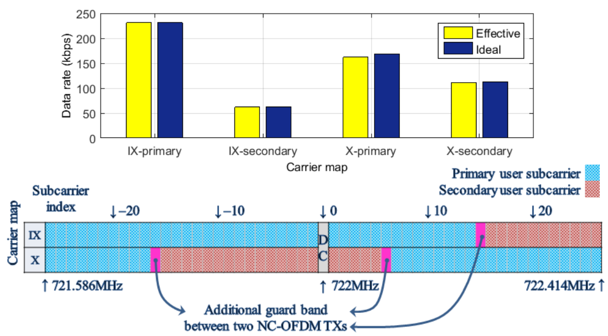


Fig. 5. Data rates when two NC-OFDM transmits together.

maps labeled IX and X. The channels are separated by a single-subcarrier guard band per the design in Section III-C. Note that the effective rates fall within 96% of the ideal rates. This confirms that the systems interfere minimally with each other.

B. Performance of the implemented OSA system

In this subsection, we demonstrate the operation of our OSA system for the overlay control channel as an example. In this set-up, the secondary USRPs operate normally as transceivers and one primary USRP transmits only; the other primary USRP, rather, is repurposed to sense the licensed spectrum 721.5-722.5 MHz from which the spectrogram in Fig. 6 is generated. The PU transmits continuously on the noncontiguous data channels 721.58-721.74 MHz and 722.26-722.42 MHz. Based on the sensing results, the SUs find a common control channel at 722 MHz, which is the center of the idle subcarriers detected. The two small bars, whose widths are 67.5 kHz, in the spectrogram correspond to the narrowband RTS and CTS secondary control messages. Upon successful completion of the 3-way handshake described in Section III-B, the secondary users exchange information on the data channel 721.76-722.24 MHz.

C. Performance comparison of control-channel schemes

In our controlled experiments, we consider the carrier maps in Fig. 4 for the primary network. The maps are grouped into Set A (I-IV) and Set B (V-VIII). In Set A, the active subcarriers are contiguous and, as such, only require one guard band between the primary and secondary data channels. This is optimal because all but one of the data subcarriers may be utilized. In Set B, on the other hand, the active subcarriers are uniformly distributed throughout. In contrast to the primary and secondary data channels, the PSD of the secondary control channel in the experiments were not held constant, but varied as reported in parentheses in Fig. 7. The minimum PSD for each secondary CC scheme was determined such that the probability of successful transmission on the AWGN channel (in the absence of primary interference) exceeded 0.95.

Figs. 7 and 8 show the experimental results for Set A. In Fig. 7, the normalized data rate of the primary versus the number of active subcarriers (10-40) in each of the four carrier maps (I-IV, respectively) is reported. The normalized rate is defined as the measured rate divided by the effective NC-OFDM rate described in Section V-A, not the ideal rate. This means that any reduction in the normalized rate from the value of 1 reflects interference of the secondary CC on the primary, not the shortcomings of NC-OFDM. The dedicated and overlay schemes inflict less interference than the underlay for all PSDs. In fact, the normalized primary data rates for the overlay and dedicated are almost identical for each carrier map. Even if the underlay scheme has a lower PSD compared to the other two, the control message transmission in the same bandwidth leads to more interference on the PUs. The main effect is misdetection due to low signal-to-interference-ratio (SINR). The effect is exacerbated when the number of active subcarriers is small because shorter training sequences are less robust to interference. For better performance of the underlay scheme, a licensed spectrum greater than 1 MHz for the primary network will be necessary; then the secondary UCC can be spread wider, reducing its PSD. Although not included in the Fig. 7, we also varied the secondary CC PSD from -73.6 to -79.2 dBm/Hz for the overlay scheme. No change in the normalized primary data rate was observed. In short, if the bandwidth of the OCC exceeds the required 67.5 kHz, or at least 5 contiguous subcarriers, it behaves like a DCC. Recall from Section III-A, however, that the absolute data rate for the overlay scheme is actually higher than the dedicated scheme because its W_{OSA} is wider. Hence for Set A, the overlay scheme delivers the best results.

Complementary results to the normalized primary data rate in Fig. 7, in terms of the probability of a successful handshake on the secondary control channel, are reported in Fig. 8. The

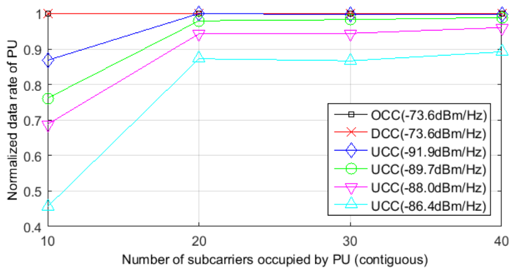


Fig. 7. Normalized data rate of PU under secondary control message transmission when PU subcarriers are compactly concentrated.

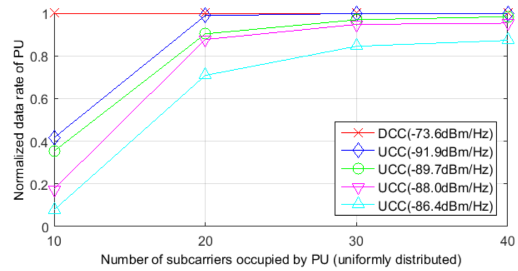


Fig. 9. Normalized data rate of PU under secondary control message transmission when PU subcarriers are uniformly distributed.

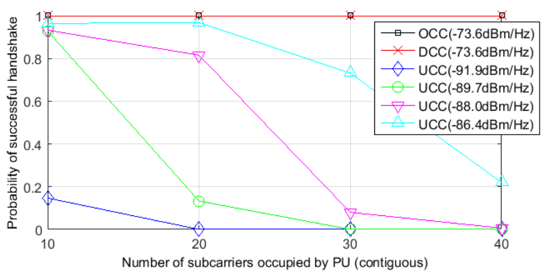


Fig. 8. Probability of successful handshake per control channel schemes when PU subcarriers are compactly concentrated.

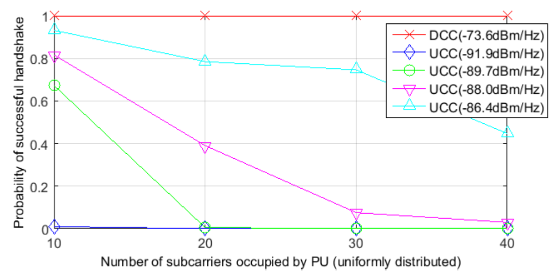


Fig. 10. Probability of successful handshake per control channel schemes when PU subcarriers are uniformly distributed.

figure shows that, as the primary occupies more of the licensed bandwidth, the underlay control channel has to deal with more and more interference. The dedicated and overlay schemes, on the other hand, remain impervious.

In Set B, however, the OCC scheme breaks down because carrier maps V-VIII do not have at least 5 contiguous idle subcarriers. Accordingly, results for the OCC are omitted in Figs. 9 and 10. When compared to Set A, the performance of the underlay scheme for the respective secondary CC PSD in Set B is worse across all carrier maps. This is because training sequences in which the subcarriers are sparsely distributed are less robust to noise.

VI. Conclusion

In this paper, we compared the performance of three secondary control-channel schemes in opportunistic spectrum access networks: dedicated, underlay, and overlay. The comparison was conducted through a testbed implementation of a primary and a secondary network, each composed from two USRP radios connected through an RF channel emulator. The key performance metric was the primary data rate. We found that, when the spectrum occupancy of the primary features an idle band of contiguous subcarriers whose width can accommodate the overlay channel, the overlay scheme outperforms the other two; otherwise it fails. In the former case, the overlay scheme outperforms the dedicated scheme because the primary data channel need not be partitioned into a separate control channel; hence the wider bandwidth translates into a higher data rate. It outperforms the underlay scheme because, despite its lower power spectral density, the secondary underlay control messaging takes place across same band as the primary, so interference reduces the data rate. Hence for superior underlay performance, a wider bandwidth than 1 MHz will be necessary.

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