SELF-INTERFERENCE CANCELLATION TOWARDS REAL-TIME SPECTRUM SENSING IN VEHICULAR DYNAMIC SPECTRUM ACCESS SYSTEMS

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ABSTRACT

We propose a new spectrum sensing scheme tailored for vehicular environments that aims to detect primary users (PUs) while secondary user (SU) transmission is active in the same band. In general, it is not easy to detect weak primary signals when a much stronger SU is active. In order to solve this near-far problem, we use a spectrum sensor with a dedicated antenna and a two stage secondary signal cancellation (i.e. elimination of self-interference) technique. For the first stage cancellation in the analog domain we use a secondary signal canceller with additional antenna that mitigates the secondary interference at the sensing antenna by transmitting the SU signal replica. Hence, the SU self-interference is first attenuated by antenna separation, and then cancelled with an inverted phase replica. In contrast to handheld mobile terminals, such physical antenna separation can be made possible on the roof of a vehicle. For the second stage cancellation in the digital domain, we use a signal canceller based on the minimum mean square error (MMSE) method. We evaluate performance of the analog domain canceller experimentally, and performance of the digital domain canceller by computer simulations, to confirm that their joint operation is able to achieve better PU signal detection.

1. INTRODUCTION

As the demand for high quality wireless communication increases, the availability of frequency bands which can be used decreases. In particular, spectrum scarcity makes deployment of new communication systems difficult. From the viewpoint of effective use of frequency resources, the cognitive radio (CR) technology attracts attention [1]. Cognitive radio makes possible reuse of the white space (frequency spectrum holes) which is otherwise not fully exploited in time and space by licensed users.

In order to utilize the white space, the secondary user (SU) must take care not to affect the licensed primary users (PUs). One of the methods to achieve that is spectrum sensing. Sensing is the technique of recognizing the existence of a PU's communication by monitoring the surrounding communication environment [2]. The secondary network nodes perform sensing before starting communication. The SU communication is allowed only when it is decided that a PU is not communicating. SU communication is periodically interrupted and spectrum availability is reassessed through repeated sensing. These quiet periods (QP) are necessary because the SU transmissions create self-interference to the sensing system. In particular, a secondary transmitter collocated with the sensor, even when equipped with a separate antenna, suffers from the near-far problem. The near-far problem is emphasized by the requirement to detect PU transmissions at a very low level, typically below the noise floor [3],[4].

In this conventional sensing approach, there is a possibility that a PU may start communication while the secondary users are in the communication phase. In that case, SU communication will create interference to the PU receivers. Through careful design of the SU communication system, namely, through proper selection of QP for sensing and data communication period (DP) for SU transmissions, the interference caused in this case can be made sufficiently small not to harm the PUs. Still, when a PU transmission occurs during DP, it might be affected by interference. Furthermore, periodic disruption of SU communication reduces channel utilization. There exists a clear trade-off. If the QP is lengthened and/or the DP is shortened, the PU detection probability increases and/or possibility of interference to the PU during communication time decreases. But, consequently, the SU throughput will decrease. The authors of [5] and [6] presented an optimization of the sensing time and the data transmission time for a fixed cycle period, and obtained maximum throughput under the constraint of desired PU detection probability.

A different technique, which allows for simultaneous SU communication and PU detection, is presented in [7]. In this system, SUs communicate using Orthogonal Frequency

Division Multiplex (OFDM). The subcarriers which coincide with the band used by the PU's are nullified and not used for SU communication. Since sensing is performed on the frequencies not used by the SUs, this technique can detect a PU simultaneously with secondary communication. Obviously, this scheme requires prior knowledge about the PU signal. If the information about the PU's signal structure is not available to the SUs, the PU cannot be detected. Furthermore, in the case of PU detection, secondary communication does not stop immediately, but rather after exchange of notification messages between the SU nodes.

Our interest in cognitive radio in the vehicular environment is motivated by scarcity of the spectrum dedicated to vehicular applications. In [8] we argue that, although it involves significant implementation difficulties due to mobility of the nodes, utilization of the white space can be seen as a method to accommodate increasing number of vehicular wireless applications. As the proof of concept we already prototyped and implemented an ad-hoc vehicular cognitive network in the TV white space [9].

The system proposed in this paper aims to enable SUs in a cognitive vehicular network to execute PU detection while communicating, without need to schedule and synchronize quiet periods for sensing. To that goal we investigate use of interference cancellation techniques to mitigate self-interference created to the sensing subsystem by the collocated SU transmitter. The concept of self-interference cancellation was previously used, for instance, in [10] and [11] to enable full duplex wireless communication.

For cognitive vehicular networks, due to high mobility of the nodes which constantly change their location, the white space availability changes frequently. Therefore, a possibility that a PU will appear during secondary communication is larger in comparison to the cognitive networks with static nodes. This makes highly reliable sensing even more important.

In comparison to the existing sensing methods, the proposed system protects a PU with reduced delay. The delay in "conventional" sensing implementations occurs because, as previously mentioned, sensing is performed only periodically, during the quiet intervals when all secondary nodes cease transmission.

The proposed sensing method is in particular applicable to time division multiple access (TDMA) based systems, although systems with other medium access approaches can benefit from it as well. Implementation of the proposed sensing method and its evaluation through field tests is beyond the scope of this paper and remains as future work.

In Section 2 we present the two-stage interference cancellation system and its application to sensing. In Section 3 we provide performance evaluation results. Section 4 concludes the paper.

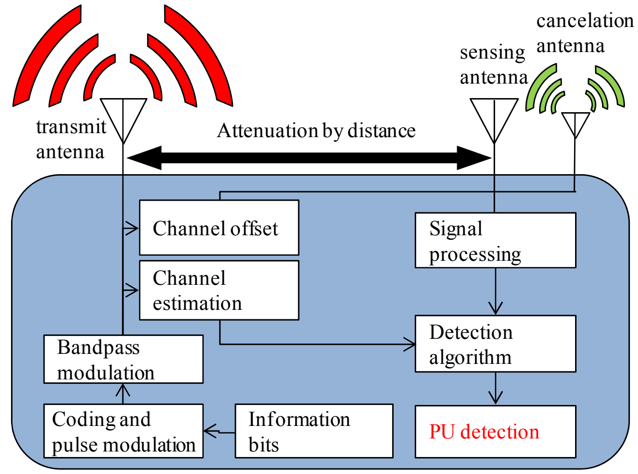


Fig 1 Block diagram of the secondary user transmission device

2. OVERVIEW OF THE PROPOSED SYSTEM

In order to solve the self-interference problem, and enable concurrent sensing and SU transmissions, we propose the method shown in Fig. 1 to attenuate self-interference signal at the sensor. The method employs two stages of interference cancellation. In the first stage cancellation is performed in the analog domain, and the second stage uses cancellation in the digital domain.

Self-interference cancellation in the analog domain is needed to attenuate the SU signal sufficiently to enable cancellation in the digital domain. First, due to the relatively high power and proximity of the SU transmitting antenna to the sensor, the SU signal can exceed the sensor's dynamic range and saturate its front end. Second, the sensor's resolution (number of bits used for analog-to-digital conversion) might not be sufficient to accurately represent a very weak PU signal when it is superimposed onto a strong SU signal.

2.1. Interference Cancellation in the Analog Domain

It is difficult to cancel the self-interference at the sensor entirely. Some attenuation of the self-interference signal is obtained by separating the SU transmit antenna and the SU sensing antenna. Fortunately, the proposed system assumes deployment on a vehicle, and therefore, it is even possible to increase channel loss between these antennas by positioning them at a Non-Line-of-Sight (NLOS) configuration with respect to each other. Additional interference suppression is then obtained using cancellation techniques.

The signal which cancels the self-interference signal is generated in the vicinity of the receiving antenna. In the ideal case, at the sensing antenna this cancellation signal is equal in strength to the transmitted signal, but its phase is

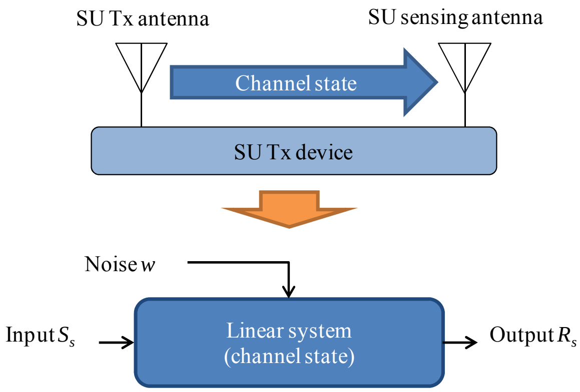


Fig 2 Estimation of the channel between the SU Tx and the sensor in the digital domain

reversed. Since the cancellation antenna can be positioned much closer to the sensing antenna the equal power inverse phase signal can be generated with lower transmit power. It is very important to notice that, because of this low power, the cancellation signal creates very little interference to the SU signal except in the very proximity of the sensing antenna. In this way, the self-interference cancellation system does not deteriorate SUs' communication ability. Thus, analog cancellation results in increased primary signal versus self-interference ratio (PSR) only in the proximity of the sensing antenna.

2.2. Interference Cancellation in the Digital Domain

The second stage of self-interference cancellation provides fine SU signal rejection at the sensor because it includes sophisticated digital domain signal processing. To obtain additional interference rejection on the signal which is already enhanced in the analog domain, estimation of the channel between the SU transmit antenna and the sensor antenna is performed in accordance to Fig. 2. Although it is trivial to replicate the SU transmission at the analog canceller with inverted phase, the SU signal is still affected by the path loss between the SU transceiver and the sensor. The channel state comprises not only of the usual complex channel gain coefficient, but also of the quantity introduced by the analog cancellation attenuation. Provided that the channel state is accurately estimated, the self-interference signal can be reproduced and cancelled. In the ideal case, the remaining signal contains only the additive white Gaussian noise (AWGN) and the PU signal, if present.

In accordance with Fig. 2, the self-interference channel is modeled as a linear system with the transmitted signal as the input, and the signal received at the sensing antenna as the output. The modeled signal contains: 1) sensor thermal noise w; 2) remaining secondary signal after analog cancellation; and possibly 3) the desired PU signal. The linear system estimates the complex channel gain coefficient h. The employed minimum mean square error (MMSE) estimation method identifies this coefficient through accumulated information on N past inputs and outputs:

$$
\begin{aligned}
R_{s,t} &= z_t^T \theta_t + w_t \\
z_t^T &= \left[-R_{s,t-1}, \cdots, -R_{s,t-n}, S_{s,t-1}, \cdots, S_{s,t-n}\right] \\
\theta_t &= \left[a_1, \cdots, a_n, b_1, \cdots, b_n\right]
\end{aligned}
\qquad (1)
$$

If the number of considered samples N increases, the estimation error will decrease. Larger N results in a more accurate estimate of the coefficient h, but the computational complexity will increase too. In order to reduce computational complexity, the modified recursive form of MMSE is used. That is, identification of the channel gain is performed as the Recursive Least Squares (RLS) algorithm. Thereby, a presumed channel coefficient is updated iteratively:

$$
\begin{aligned}
R_{s,N+1} &= z_N^T \hat{\theta}_N = h'_{s,N+1} s_{s,N+1} \\
\hat{\theta}_N &= \hat{\theta}_{N-1} + L_N \varepsilon_N \\
\varepsilon_N &= R_{s,N} - z_N^T \hat{\theta}_{N-1} \\
L_N &= \frac{P_{N-1} z_N}{\rho_N + z_N^T P_{N-1} z_N} \\
P_N &= \frac{1}{\rho_N}\left[P_{N-1} - \frac{P_{N-1} z_N z_N^T P_{N-1}}{\rho_N + z_N^T P_{N-1} z_N}\right]
\end{aligned}
\qquad (2)
$$

with ε denoting the difference between the results of consecutive iterations. Index N also denotes the present time.

The replicated SU signal (i.e. estimated signal of a self-interference signal) is made using the estimate h_{N+1}. Since the proposed system performs sensing on the transmitter side, the reference signal for generating a replica signal is already known. Using the replicated signal, the self-interference signal is then subtracted from the superimposed signal (i.e. the sum of PU transmit signal and the SU transmit self-interference signal) received at the sensing antenna. Using this approach in combination with the self-interference cancellation in the analog domain, the weak embedded PU signal is emphasized. The next step in our sensing procedure is to perform PU signal detection on the signal resulting from the SU self-interference cancellation.

2.3. Detection of the PU signal

The test statistics used to detect presence of a PU in the signal which results from the self-interference cancellation

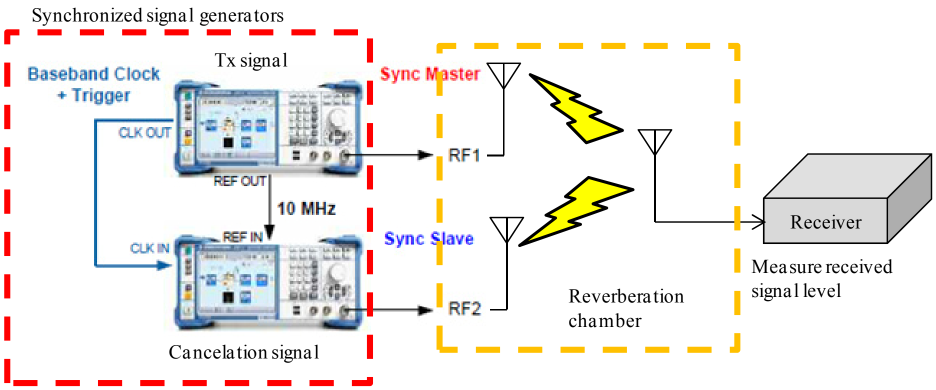


Fig 3 Test setup for analog self-interference cancellation in the reverberation chamber

is simple and robust energy detection. Since PSR is a relative measure of the PU signal power versus total power, it increases after the self-interference cancellation. However, elimination of the strong self-interference signal from the signal received by the sensing antenna results in a weak signal which is a superposition of the PU signal, the AWGN, and a residual cancellation error. Therefore, an appropriate detection threshold must be specified to detect the low level primary signal.

Since the energy detection belongs to the class of blind detection algorithms, the proposed system is sensitive to interference from other secondary nodes. In particular, if simultaneous transmission from one or more secondary nodes occurs while sensing is performed, energy detection can interpret that transmission as a PU transmission. This problem can be mitigated if a matched filter which is matched to the PU signal is used for detection. Furthermore, if the cognitive network is TDMA based, it is guaranteed that under normal operational conditions only a single node transmits at a given time.

3. EVALUATION OF THE PROPOSED SYSTEM

We evaluated the proposed sensing system by means of experiments and computer simulations. As presented in the previous section, the sensing system consists of three components. The analog cancellation is evaluated experimentally. The digital cancellation and PU detection are evaluated through simulations.

3.1. Experimental Evaluation of the Analog Domain Cancellation Procedure

The analog self-interference cancellation is first evaluated in the laboratory environment using the setup presented in Fig. 3. Two synchronized Rohde & Schwarz SMBV100A signal generators are used to create the SU signal and its inverted phase replica. These signals are received by an Ettus Research USRP N210 software defined radio (SDR) which acts as a sensor. The transmission and reception antennas are placed in the Faraday cage which acts as a reverberation chamber (presented in Figs. 4 and 5).

3.1.1. Synchronizing the Vector Signal Generators

Two synchronized vector signal generators are used to emulate operation of the SU transmitter and the analog domain signal canceller. One vector signal generator is used to generate the SU signal. The second generator transmits its inverted phase replica. In order to achieve cancellation of these signals at the sensing antenna careful synchronization between these two generators in the baseband must be achieved. To that goal, they are synchronized in the master-slave configuration with the SU transmitter acting as the source of the synchronization signals. The internal clocks are synchronized using the 10MHz line. The interference canceller is triggered by the SU generator over the dedicated

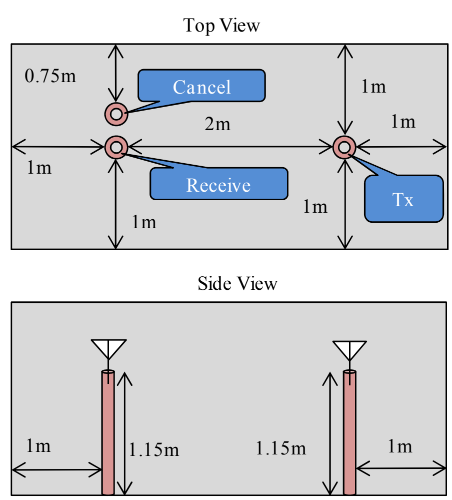


Fig 4 Placement of antennas in the reverberation chamber

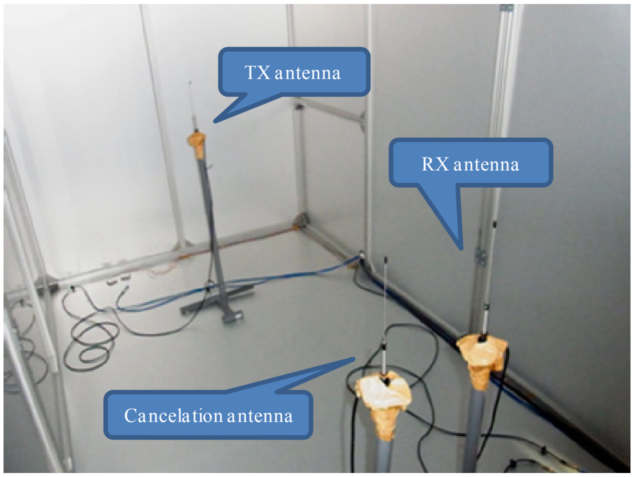


Fig 5 Actual placement of antennas in the reverberation chamber

trigger line. Coaxial cables of equal length are used to feed transmit antennas of the same type.

3.1.2. Reverberation Chamber

The reverberation chamber serves twofold purpose. First, it acts as a Faraday cage, enabling us to perform experiments in the licensed band without obtaining adequate experimental license. Second, unlike the anechoic chamber which suppresses reflection of electromagnetic waves, its metallic walls create rich multipath environment. Although the propagation inside the chamber is Line-of-Sight (LOS) strong reflections result in fading comparable to the Rayleigh fading. This is because the waves reflected from the highly conductive sides travel over a short distance and do not attenuate much in comparison to the LOS component. Furthermore, the angular distribution of reflections is approximately uniform (which is one of conditions for Rayleigh fading to occur) and the polarization of the waves is not randomized by the reflective surfaces [12].

A multipath environment similar to Rayleigh enables us to test the analog cancellation procedure under the relatively unfavorable conditions.

TABLE 1 Experimental Evaluation Parameters

Parameter	Value
Sequence Length	10000 symbols
Data Source	PRBS, PRBS 9
Symbol Rate	100.0ksym/s
Filter type	Gaussian
Filter coefficient	0.30
Number of samples	320000
Sample Rate	3.20 MHz

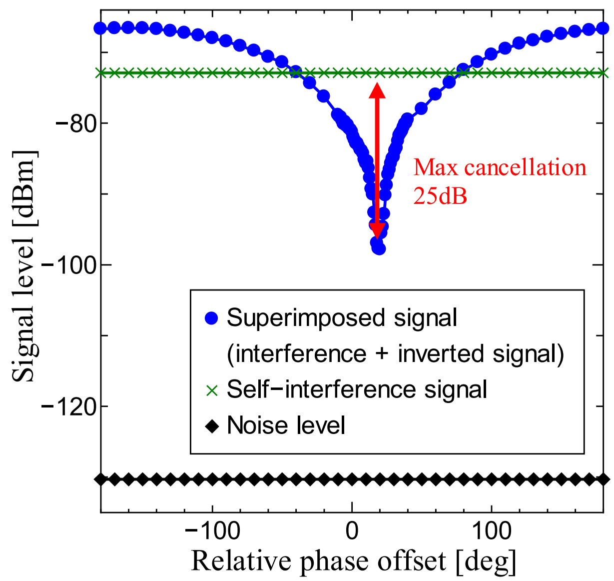


Fig 6 Result of analog domain cancellation

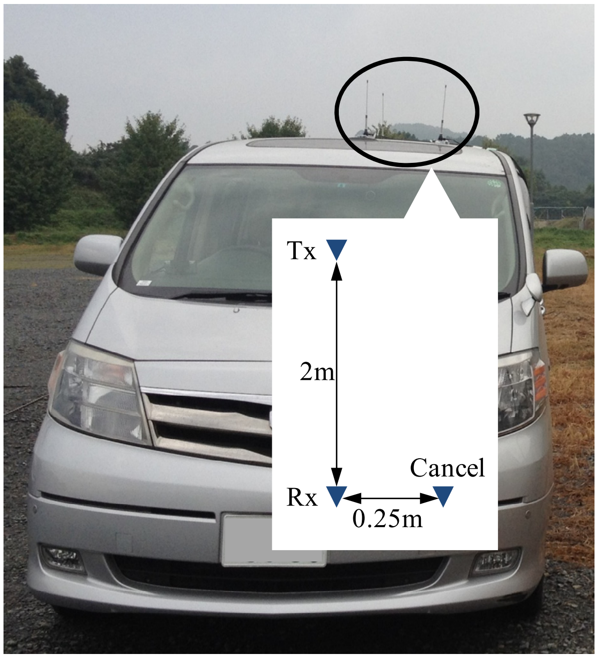
3.1.3. The Experimental Evaluation

The self-interference signal was centered at the carrier frequency F_c = 282.6MHz, with bandwidth W = 100kHz, and transmit power P_S = -30dBm. The modulation is 16QAM. These and other experimental evaluation parameters are summarized in Table 1.

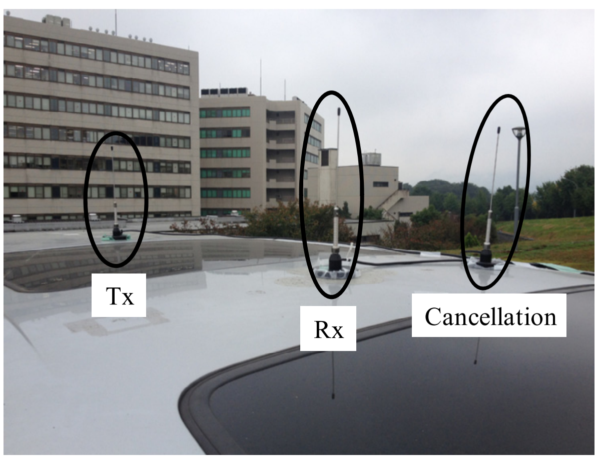
The results of experiments are shown in Fig. 6. When only the self-interference signal was received, its power was -73dBm (represented by the green line in Fig. 6). Since transmitted signal power is -30dBm, we can estimate the propagation loss to be 43dB.

When the cancellation signal was transmitted in addition to the SU signal, a maximum signal attenuation of 25dB had been observed, corresponding to the timing which provides approximately opposite phase of the signals. Of course, the signal becomes stronger when the self-interference signal and a cancellation signal are co-phased. We observed a 5dB increase in comparison to the case with only the self-interference signal being transmitted. In free space a 3dB increase should be observed. Our conjecture is that the multipath environment in the reverberation chamber created additional 2dB increase.

In addition to a fully controllable idealized environment of the reverberation chamber, we tested the analog cancellation in a realistic outdoor environment on a car roof presented in Fig. 7. We were able to perform these experiments after obtaining a license from the Japanese Ministry of Internal Affairs and Communications valid for Iizuka region in Kyushu. In these experiments we replaced sophisticated signal generators with two USRPs



a) Front view



b) Side view

Fig 7 Experimental evaluation of the analog cancellation procedure in a realistic outdoor environment

synchronized from a shared external 10MHz clock. Under these conditions, we measured maximum analog interference cancellation of 20dB.

3.2. Numerical Evaluation of the Digital Domain Cancellation Procedure

In the simulations we assume that the self-interference SU signal and the PU signal are transmitted simultaneously. The

TABLE 2 Computer Simulation Parameters

Parameter	Value
Modulation	OFDM,QPSK
Number of symblos at OFDM	10
Number of pilot symbols at OFDM	2
Number of FFT points (per symbol)	512
Number of guard intervals	100
Fading environment	Rayleigh fading
Number of channel taps	8
Number of trials	5000

parameters used for the simulations are summarized in Table 2. To accommodate for analog domain cancellation measured in the reverberation chamber and outdoor we reduce the SU signal power by 25dB and 20dB, respectively. Then, we superpose Gaussian noise to this signal and scale it with an "unknown" channel coefficient. This signal is then used to estimate the channel loss using MMSE-RLS described in Section 2.2.

At this stage, we can numerically create a replica signal that cancels self-interference using the estimated channel state. A 40 dB attenuation of the secondary signal is achieved by subtracting the replica from the output of analog cancellation. The signal is then processed by the energy detection sensing algorithm under the assumption of false alarm probability P_{fa} = 0.15. This value is selected since it corresponds to the probability of false alarm in the case of PU detection right before the MMSE-RLS estimation and digital domain cancellation. A false alarm occurs when an SU transmission or receiver thermal noise is wrongly interpreted as a PU transmission. Therefore, it is the probability of detecting a PU (observed in the additional independent set of simulations) in case of the "null-hypothesis". Here the null-hypothesis corresponds to erroneously detecting the PU which is not present since the signal contains only the thermal noise and the self-interference signal processed by the analog cancellation subsystem.

We compare detection performance under four scenarios: 1) cancellation only in digital domain and energy detection; 2) cancellation both in analog as well as digital domain and energy detection; 3) energy detection applied to the superposition of the PU and the SU signals; and 4) energy detection applied to the PU signal only. The results are presented in Fig. 8.

The results indicate that, assuming 100kHz bandwidth, the PU signal equal to or stronger than -130dBm can be detected by the energy detector with P_d = 100% success rate in case when the self-interference signal is not present. At the opposite extreme, when energy detection is applied to the superposed PU and SU signals, the PU power of at least -80dBm is needed for 100% detection rate. However, if energy detection is applied to the signal preprocessed with both analog and digital cancellation, this detection rate is achievable for PU signal strengths as low as -120dBm under the same conditions.

It can be observed that the analog cancellation provides additional 10dB processing gain. By comparing Figs. 8a and 8b we observe 2dB performance degradation due to 5dB reduction in analog cancellation. Overall, Fig. 8 illustrates that the proposed system can detect very weak PU signals in presence of self-interference, with less than 10dB performance degradation in comparison to the case when QP is imposed on the SU transmitter.

As a sanity check, as expected, at low signal powers the detection rate approaches the 15% false alarm rate.

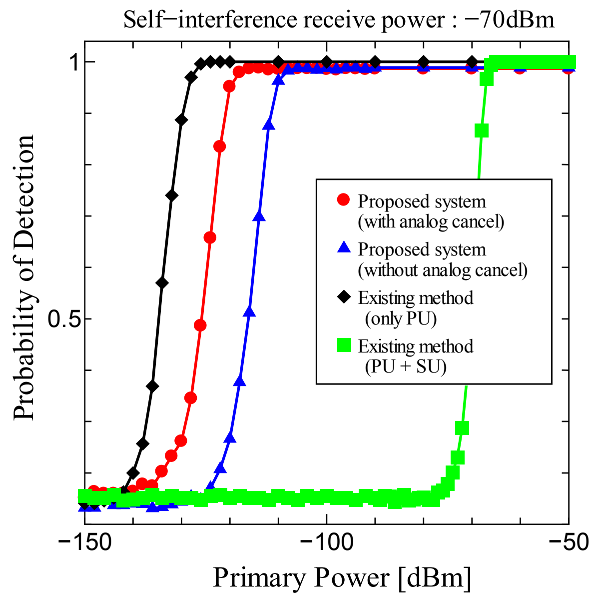
4. CONCLUSION

In this paper we proposed and evaluated a spectrum sensing system, primarily designed for vehicular environment, which can detect a primary user with high probability without the need to terminate SU transmission to perform sensing. Interference to the incumbent users is reduced because the proposed system can detect the primary user presence even when communicating with other secondary users. Since sensing is carried out on a secondary node simultaneously with transmission, the system treats its transmission as the self-interference signal which is attenuated by processing first in the analog and than in the digital domain.

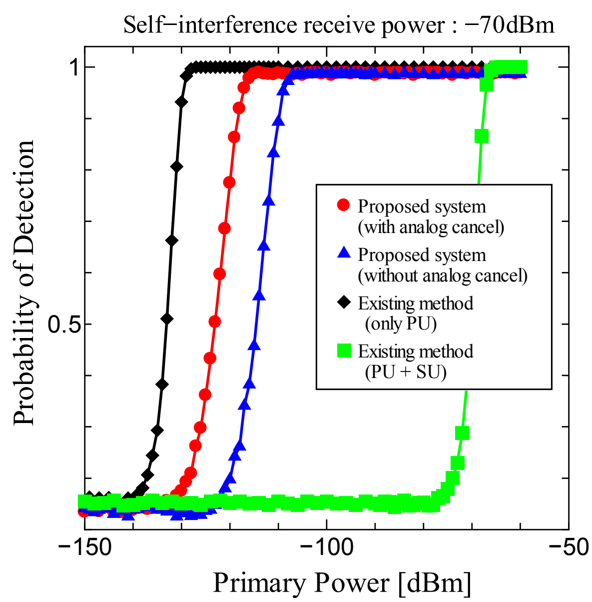
First, the sensor front end saturation by the strong secondary signal is prevented by signal cancellation in the analog domain at the sensor antenna. This is achieved by transmitting the inverted phase replica of the secondary signal. The analog domain replica is transmitted from an antenna which is much closer to the sensing antenna than the transmitting antenna. Therefore, the replica can be transmitted with much lower power in order not to affect significantly the secondary transmission range.

At the second stage, self-interference cancellation in the digital domain achieves better performance by estimating the channel gain between the transmitting and sensing antenna. This estimation is implemented using the MMSE-RLS iterative algorithm. After subtracting the replica of the secondary signal scaled by the channel gain coefficient, the resulting signal is passed to the energy detector.

The two-stage experimental and numerical performance analysis we performed indicates less than 10 dB penalty in comparison to energy detection applied while the secondary transmitter is quiet. At the same time, since the proposed system does not require scheduling of quiet periods for sensing both the primary and the secondary users can benefit from its implementation. Since the secondary transmitter does not have to wait for the end of transmission to perform sensing, interference to the primary users is reduced. In addition to this, without the quiet periods channel utilization for secondary users is increased.



a) 25dB analog cancellation



b) 20dB analog cancellation

Fig 8 Self-interference cancellation performance assuming a) 25dB and b) 20dB analog cancellation

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