LTE and WLAN Interference Suppression in CR Applications

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***Abstract*—In traditional cognitive radio approach, spectrum is divided into black and white spaces. Black space is reserved to primary users (PU) as secondary users (SU) are able to transmit in white space. A modern approach is that the black space is divided into black and grey spaces to get more capacity. Grey space leads to novel type of interference environment because of interfering signals coming from PUs and other SUs. In addition, novel CR applications like long term evolution advanced (LTE-A) and internet of things (IoT) generate interfering signals. Thus, interference suppression is needed. In this paper, the performance of the forward consecutive mean excision algorithm (FCME) interference suppression method is studied in the presence of relatively narrowband interfering signals existing in the novel CR networks. Real-world LTE and WLAN signal measurements were used to verify the usability of the FCME IS method in future CR applications.**

Keywords*–*interference suppression; grey zone; cognitive radio; LTE; WLAN; measurements.

I. INTRODUCTION

Heavily used spectrum calls for new technologies and innovations. Cognitive radio (CR) [1] [2] offers possibility to effective spectrum usage allowing secondary users (SU) to transmit at unreserved frequencies if they guarantee that primary users (PU) transmissions are not disturbed. Earlier, spectrum was divided into two zones (spaces): black and white zone. As black zone was fully reserved to PUs and off limits to secondary users, their transmission was allowed in white zones where there were no PU transmissions. The problem in this classification is that if the spectrum is not totally unused, secondary users are not able to transmit. Thus, the spectrum usage is not as efficient as it could be. Instead, spectra can be divided into three zones: white, grey (or gray) and black zone [3]. In this model, the SU transmission is allowed in white and grey spaces, as black spaces are reserved for PUs.

Cognitive radio has several novel applications. Long Term Evolution Advanced (LTE-A) is a 4G mobile communication technology [4]. LTE-A exploits cognitive radio technology and utilizes flexible and intelligent spectrum usage. Its focus is on high capacity. LTE-A enables one of the newest topics called Wide Area IoT (Internet of Things), where sensors, systems and other smart devices are connected to internet. Therein, long-range communication, long battery life and minimal amount of data, as well as narrow bandwidth are key issues. In addition, Cognitive IoT (CIoT) has been proposed to highlight required intelligence [5].

As cognitive radio technology offers more efficient spectrum use, there are many challenges. One of those is that the cognitive world is an interference-intensive environment. Especially in-band interfering signals cause problems. There are three main types of interference in CR: from SU to PU (SU-PU interference), from PU to SU (PU-SU interference), and interference among SUs (SU-SU interference) [6] [7]. The basic idea in CR is that SU must not interfere PUs. Instead, SU may be interfered by PUs or other SUs. When there are multiple PUs and SUs with different applications and technologies, cumulative interference is a problematic task [8]. In grey spaces, there is interference from PU (and possible other SU) transmissions. It is efficient to mitigate unknown interference in order to achieve higher capacity. Therefore, interference suppression (IS) methods are needed.

Interference suppression exploits the characteristics of desired / interfering signal by filtering the received signal [9]. IS techniques include, for example, filters, cyclostationarity, transform-domain methods like wavelets and short-time Fourier transform (STFT), high order statistics, spatial processing like beamforming and joint detection / multiuser detection [10]. Filter-based IS is performed in the time domain. Optimal filter (Wiener filter) can be defined only if the interference and signal of interest Power Spectral Densities (PSDs) are known. Usually, those are not known, so adaptive filtering is an option. In filter-based IS, both computational complexity and hardware costs are low but co-channel interference cannot be suppressed, and no interference with similar waveforms to signals can be suppressed. Cyclostationarity based interference suppression has low hardware complexity but medium computational complexity. This may cause challenges in real-time low-power applications. In transform domain IS, computational complexity is medium, but transform domain IS cannot be used when interference and signal-of-interest have the same kind of waveforms. However, waveform design may be used. Transform domain IS has medium computational complexity and low hardware complexity. High-order statistics based interference suppression is computationally complex, and multiple antennas/samplers are needed, so its hardware cost is high and computational complexity too. In beamforming, co-channel interference as well as interference with similar waveforms to the signal of interest can be suppressed, but because of multiple antennas, the hardware cost is high. Its computational complexity is medium.

The less about the interfering signal characteristics is known, the more demanding the IS task will be. As most of the IS methods need some information about the suppressed signals and/or noise, there are some methods that are able to operate blindly. Blind IS methods do not need any *a priori* information

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about the interfering signals, their modulations or other characteristics. Also the noise level can be unknown, so it has to be estimated. Blind IS methods are well suited for demanding and varying environments.

It is crystal clear that when operating in real-world with mobile devices and varying environment, computational complexity is one of the key issues. Fast and reliable as well as cost-effective, powersave and adaptive methods are needed. In this paper, a transform domain IS method called the forward consecutive mean excision (FCME) algorithm [11] [12] is proposed to be used for interfering signal suppression (IS) in cognitive radio applications. The FCME algorithm is a blind constant false alarm rate (CFAR) -type interference suppression method that is able to suppress all kind of relatively narrowband (RNB) signals in all kind of environments and in all kind of frequency areas. Here, RNB means that the suppressed signal is narrowband with respect to the studied bandwidth. The wider the studied band is the wider the suppressed signal can be. First, cognitive radio applications and interference environment are considered. Focus is on IS in SU receiver interfered by PUs and other SUs. A scenario that clarifies the interference environment is presented. The FCME algorithm is presented and its feasibility is considered. Measurement results for LTE and WLAN signals are used to verify the performance of the FCME IS method.

This paper is organized as follows. Section II considers future cognitive applications as in Section III, interference environment in cognitive radios is studied. The FCME algorithm is presented and its feasibility is considered in Section IV. Measurement results are presented in Section V, and conclusions are drawn in Section VI.

II. Future Cognitive Applications

Future applications that use cognitive approach include, for example, LTE-A and cognitive IoT. LTE-A is an advanced version of LTE. Therein, orthogonal Frequency Division Multiplex (OFDM) signal is used. In OFDM systems, data is divided between several closely spaced carriers. LTE downlink uses OFDM signal as uplink uses Single Carrier Frequency Division Multiple Access (SC-FDMA). Downlink signal has more power than uplink signal. Thus, its interference distance is larger than uplink signals. OFDM offers high data bandwidths and tolerance to interference. As LTE uses 6 bandwidths up to 20 MHz, LTE-A may offer even 100 MHz bandwidth. LTE-A offers about three times greater spectrum efficiency when compared to LTE. In addition, some kind of cognitive characteristics are expected [13] [14] [15]. RNB interfering signals exist especially at grey zones. This calls for IS.

In the network ecosystem, it is expected that cognitive IoT [5] [16] will be the next 'big' thing to focus on. Wide-area IoT is a network of nodes like sensors and it offers connections between/to/from systems and smart devices (i.e., objects) [17] [18]. Cognitive IoT enables objects to learn, think and understand both the physical and social world. Connected objects are intelligent and autonomous and they are able to interact with environment and networks so that the amount of human intervention is minimized. Therein, the long-range (even tens of kilometers) connection of nodes via cellular connections is expected. Data sent by nodes is minimal and transmissions may seldom occur. Thus, there is no need to use wide bandwidths for a transmission. This saves power consumption but also spectrum resources. Proposed technologies include, e.g., LoRa [19], Neul [20], GSM, SigFox [21], and LTE-M [22]. As Neul is able to operate in bands below 1 GHz and LoRa as well as SigFox operate in ISM band, LTE-M operates in LTE frequencies. A common thing is that the ultra-narrowband (UNB) signals are proposed to be used. For example, in LTE-M, 200 kHz BW is to be studied. Maximum transmit power is of the order of 20 dBm. In Neul, 180 kHz band is needed. Most of those technologies are on the phase of development. In any case, it is expected that the amount of narrowband signals is growing. Thus, IS is required, especially when it is operated in mobile bands.

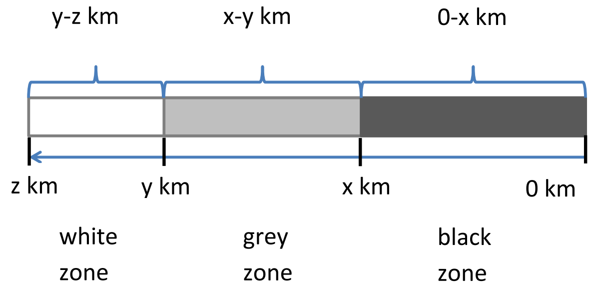

Figure 1. White, grey and black zones.

III. Interference Environment in CR

In modern CR, the spectrum is divided into three zones - white, grey and black. In Figure 1, zone classification is presented. It is assumed that PU-SU distance is >y km in the white zone, <x km in the black zone, and in the grey zone it holds that x km <PU-SU-distance <y km [23]. It means that if SU is more than y km from the PU, SU is allowed to transmit. If SU is closer than y km but further than x km from the PU, SU may be able to transmit with low power. Spectrum sensing is required before transmission and there are interfering signals so IS is needed to ensure SU transmissions. If PU-SU distance is less than x km, SU transmission is not allowed.

Interference environment differs between the zones. White space contains only noise. Therein, the noise is most commonly additive white Gaussian (AWGN) noise at the receiver's front-end, and man-made noise. This is related to the used frequency band. Grey space contains interfering signals within the noise which causes challenges. Grey space is occupied by PU (and possible other SU) signals with low to medium power that means interference with low to medium power. IS is required especially is this zone. Black space includes communications signals, possible interfering signals, and noise. In black space, there are PU signals with high power and SUs have no access.

There must be some rules that enable SUs to transmit in grey zone without causing any harm to PUs. According to [24], SU can transmit at the same time as PU if the limit of interference temperature at the desired receiver is not reached. In [2],

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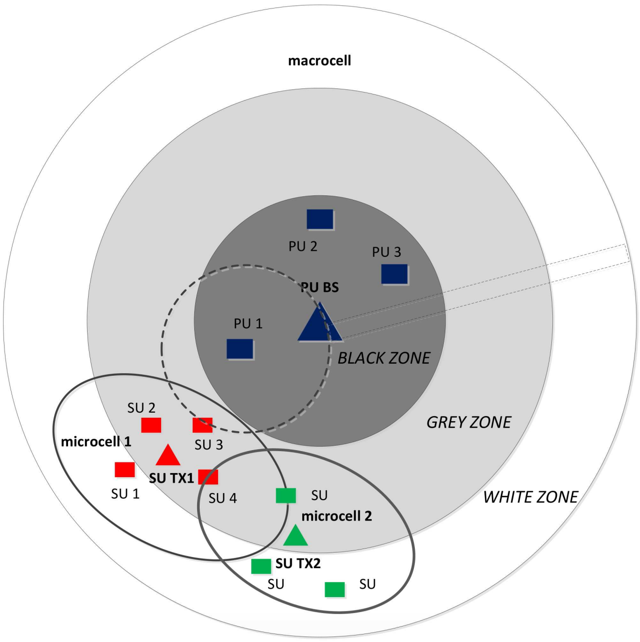

Figure 2. Scenario with one macrocell and two microcells.

it is considered the maximum amount of interference that a receiver is able to tolerate, i.e., an interference temperature model. This can be used when studying interference from SU to PU network. In [25], primary radio network (PRN) defines some interference margin. This can be done based on channel conditions and target performance metric. Interference margin is broadcasted to the cognitive radio network. In any case, the maximum transmit power of SUs is limited.

In our scenario presented in Figure 2, it is assumed that we have one PU base station (BS), several PU mobile stations and several SUs. SU terminals form microcells. Part or all of SUs are mobile and part of SUs may be intelligent devices or sensors (i.e., IoT). Between SUs, weak signal powers are needed for a transmission. One microcell can consist of, for example, devices in an office room. They can use the same or different signal types than PU. For example, in the office room case, a wireless local area network (WLAN) can be used. Between the intelligent devices (IoT), UNB signals are used. It is assumed that SUs operate at grey zone, so IS is required to ensure the quality of SU transmissions.

SUs measure signals transmitted by PU base stations and estimate relative distance to them. Using this information, SUs know whether their short range communication will cause harmful interference to the PU base station. To enable secondary transmissions under continuous interference caused by the PU base station this interference is attenuated by interference suppression.

The secondary access point knows the locations of PU terminals or SUs measure the power levels of the signals coming from PU mobile terminals in the uplink. If it is assumed that SUs know the locations of PUs, SUs do not interfere with PUs. If SUs do not know PUs locations, their transmission is allowed when received PU signal power is below some predetermined threshold. If the level of the power coming from a certain primary terminal is small, it is assumed that secondary transmission generates negligible interference towards primary terminal. However, it may happen that SUs don't sense closely spaced silent PUs.

Let us consider microcell 1 in Figure 2. There are one SU transmitter SU TX1 and four terminals SU $i, i = 1, \cdots, 4$. In addition to the intended signal from SU TX1, SU 1 receives the noise η, SU 2 receives PU downlink (PU BS) signal and the noise η, SU 3 receives PU downlink (PU BS) and PU uplink (PU 1) signals and the noise η, and SU 4 receives PU downlink (PU BS) signal, signal from other microcell's SU, and the noise η. For example, if it is assumed that PUs are in the LTE-A network and SUs use WLAN signals, receiver SU 2 has to suppress OFDM signal, receiver SU 3 has to suppress OFDM and SC-FDMA signals, and receiver SU 4 has to suppress OFDM and WLAN signals.

In addition, interfering and communication signals have to be separated from each other. The receiver has to know which signals are interfering signals to be suppressed and which signals are of interest. An easy way to separate an interfering signal from the intended signal is to use different bandwidths. For example, in LTE networks, it is known that there are 6 different signal bandwidths between 1.4 and 20 MHz that are used [4]. Especially if different signal type is used, it is easy to separate interfering signals from our information signal. It can also be assumed that interfering signal has higher power than the desired signal. However, this consideration is out of the scope of this paper.

IV. The FCME method

The adaptively operating FCME method [11] was originally proposed for impulsive interference suppression in the time domain. It was noticed later that the method is practical also in the frequency domain [12]. Earlier, the FCME method has mainly been studied against sinusoidal and impulsive signals which are narrowband ones. The computational complexity of the FCME method is $N \log_2(N)$ due to the sorting [12]. Analysis of the FCME method has been presented in [12].

The FCME method adapts according to the noise level, so no information about the noise level is required. Because the noise is used as a basis of calculation, there is no need for information about the suppressed signals. Even though it is assumed in the calculation that the noise is Gaussian, the FCME method operates even if the noise is not purely Gaussian [12]. In fact, it is sufficient that the noise differs from the signal. When it is assumed that the noise is Gaussian, $\overline{x^2}$ (=the energy of samples) has a chi-squared distribution with two degrees of freedom. Thus, the used IS threshold is calculated using [11]

$$T_h = -ln(P_{FA,DES})\overline{x^2} = T_{CME}\overline{x^2}, \tag{1}$$

where $T_{CME} = -ln(P_{FA,DES})$ is the used pre-determined threshold parameter [12], $P_{FA,DES}$ is the desired false alarm rate used in constant false alarm rate (CFAR) methods, $\overline{x^2} = \frac{1}{Q}\sum_{i=1}^{Q} |x_i|^2$ denotes the average sample mean, and

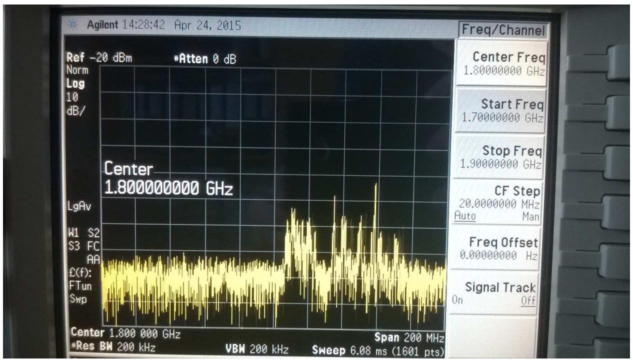

Figure 3. Agilent E4446. LTE1800 network downlink signals.

Q is the size of the set. For example, when it is selected that $P_{FA,DES} = 0.1$ (=10$\%$ of the samples are above the threshold in the noise-only case), the threshold parameter $T_{CME} = -ln(0.1) = 2.3$. The FCME method rearranges the frequency-domain samples in an ascending order according to the sample energy, selects 10% of the smallest samples to form the set Q, and calculates the mean of Q. After that, (1) is used to calculate the first threshold. Then, Q is updated to include all the samples below the threshold, a new mean is calculated, and a new threshold is computed. This is continued until there are no new samples below the threshold. Finally, samples above the threshold are from interfering signal(s) and suppressed.

The FCME algorithm is blind and it is independent of modulation methods, signal types and amounts of signals. It can be used in all frequency areas, from kHz to GHz. The only requirements are that (1) the signal(s) can not cover the whole bandwidth under consideration, and (2) the signal(s) are above the noise level. The first requirement means that the FCME method can be used against RNB signals. For example, 10 MHz signal is wideband when the studied bandwidth is that 10 MHz, but RNB when the studied bandwidth is, e.g., 100 MHz. In fact, it is enough that the interfering signal does not cover more than 80% of the studied bandwidth. However, the narrower the interference is, the better the FCME method operates [26].

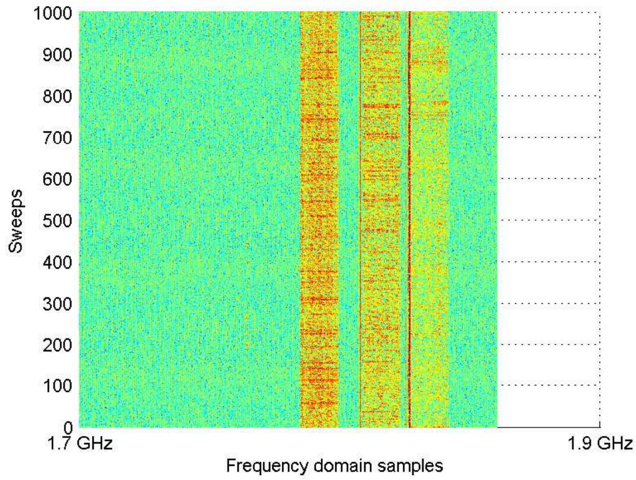

Figure 4. LTE1800 network frequencies. Spectrogram of downlink signals present.

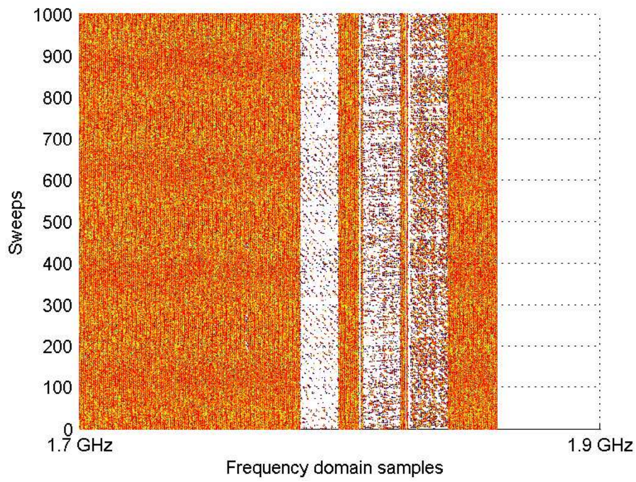

Figure 5. LTE1800 network frequencies. Spectrogram of suppressed downlink signals. The FCME method was used.

V. Measurements

The interference suppression performance of the FCME method against RNB signals was studied using real-world wireless data. The results are based on real-life measurements. Measurements were performed using spectrum analyzer Agilent E4446 [27] (Figure 3). Three types of signals were studied, namely the LTE uplink, LTE downlink, and WLAN signals. All those signals are commonly used wireless signals. Both LTE1800 network frequencies and WLAN signals were measured at the University of Oulu, Finland. IS was performed using the FCME method with threshold parameter 4.6, i.e., desired false alarm rate $P_{FA,DES} = 1\% = 0.01$ [12].

LTE1800 network operates at 2×75 MHz band so that uplink is on $1.710 - 1.785$ GHz and downlink is on $1.805 - 1.880$ GHz [28]. LTE downlink uses OFDM signal as uplink uses SC-FDMA. LTE assumes a small nominal guard band (10% of the band, excluding 1.4 MHz case).

One measurement at $1.7 - 1.9$ GHz containing 1000 time domain sweeps and 1601 frequency domain points is seen in Figure 4. Therein, only downlink signaling is present. Downlink signals have larger interference distance than uplink signals. Interfering signals cover about 30% of the studied bandwidth. In Figure 5, situation after the FCME IS is presented. It can be seen that the signals have been suppressed. On uplink signal frequencies where no signals are present (600 first frequency domain samples), average noise value is -99 dBm before and after IS.

In Figure 6, first line (sweep) of the previous case is presented more closely. The FCME thresholds after two cases are presented. In the first case, the FCME is calculated using

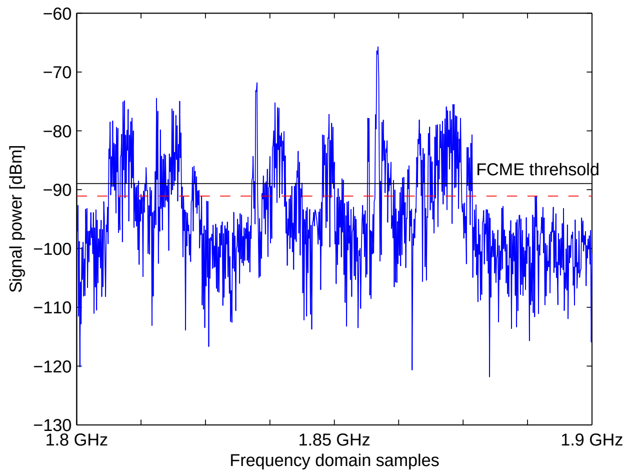

Figure 6. IS using the FCME method for LTE downlink signals. Upper threshold when the FCME calculated on $1.8 - 1.9$ GHz, lower threshold (dashed line) when the FCME calculated on $1.7 - 1.9$ GHz.

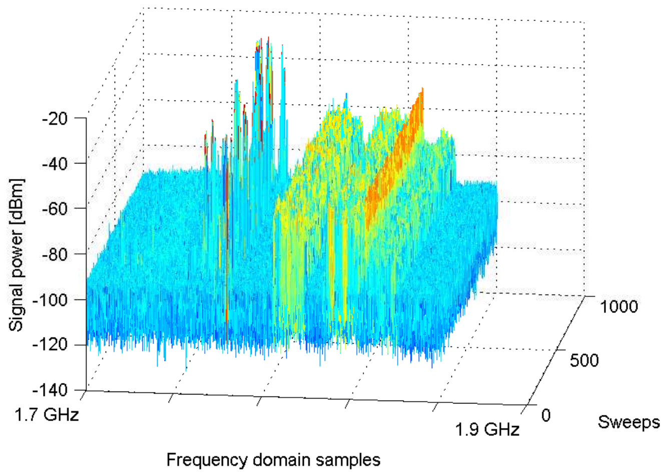

Figure 7. LTE1800 network frequencies. Uplink and downlink signals present.

frequencies $1.8 - 1.9$ GHz (downlink). Interfering signals cover about 60% of the studied bandwidth. The threshold is -89 dBm (upper line). In the second case, the threshold is calculated using both uplink and downlink frequencies $1.7-1.9$ GHz when there is no uplink signals (like case in Figure 4), i.e., SU is so far away from PU that only downlink signals are present. Interfering signals cover about 30% of the studied bandwidth. In that case, the threshold is -91 dBm (lower dashed threshold). It can be noticed that when the studied bandwidth is doubled and this extra band contains only noise, we get 2 dB gain.

Next, both uplink and downlink signals are present. There were 2001 frequency domain points and 1000 time sweeps. Figure 7 presents one measurement at $1.7 - 1.9$ GHz. Both uplink and downlink signals are present. In Figure 8, one snapshot when both uplink and downlink signals are present is presented. Therein, both signals are suppressed.

In the WLAN measurements, $2.4-2.5$ GHz frequency area was used. There were 1000 sweeps and 1201 frequency domain data points. In Figure 9, one snapshot is presented when there is a WLAN signal present and the FCME algorithm is used to perform IS. As can be seen, the WLAN signal is found.

Next, the desired false alarm rate ($P_{FA,DES}$) values are compared to the achieved false alarm rate (P_{FA}) values in the noise-only case. Figure 10 presents one situation when there is only noise present. According to the definition of the FCME method, threshold parameter 4.6 means that 1% of the samples is above the threshold when there is only noise present. Here, there are 1201 samples so $P_{FA,DES} = 1\% = 12$ samples. In Figure 10, 12 samples are over the threshold, so $P_{FA,DES} = P_{FA}$. We had 896 measurement sweeps in the noise-only case at WLAN frequencies. Therein, minimum 1 sample and maximum 19 samples were over the threshold as the mean was 10 samples and median value was 9 samples. Those were close of required 12 samples. Note that the definition has been made for pure AWGN noise.

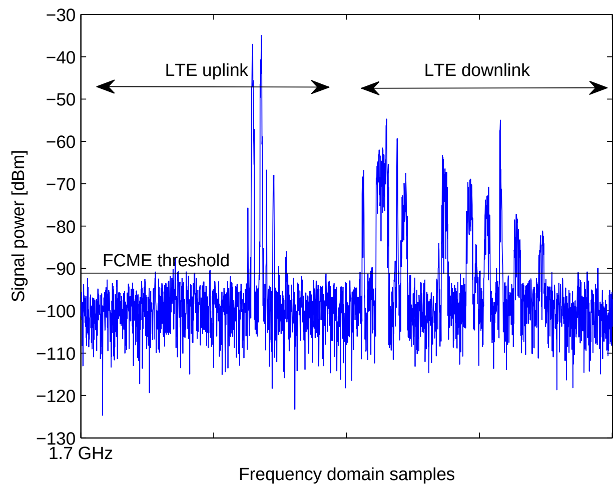

Figure 8. LTE1800 network frequencies. Uplink and downlink signals present. IS using the FCME method.

VI. CONCLUSION

In this paper, the performance of the forward consecutive mean excision (FCME) interference suppression method was studied against relatively narrowband interfering signals existing in the novel cognitive radio networks. Focus was on interference suppression in secondary user receiver suffering interfering signals caused by primary and other secondary users. Real-world LTE and WLAN measurements were performed in order to verify the performance of the FCME method. It was noted that the FCME method is able to suppress LTE OFDM and SC-FDMA signals as well as WLAN signals.

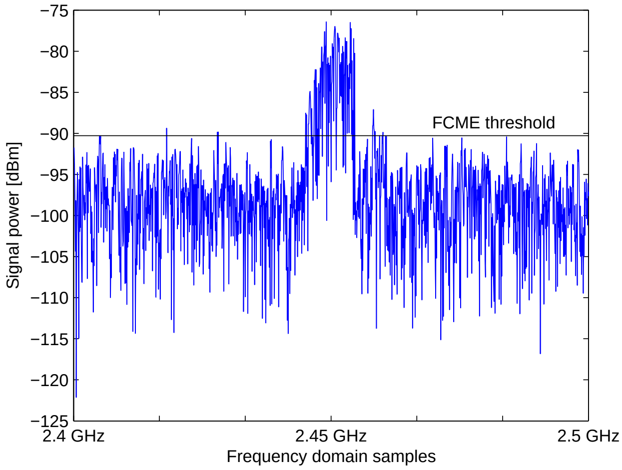

Figure 9. IS using the FCME method at frequencies 2.4-2.5 GHz where WLAN signals exist. Threshold is -90 dBm.

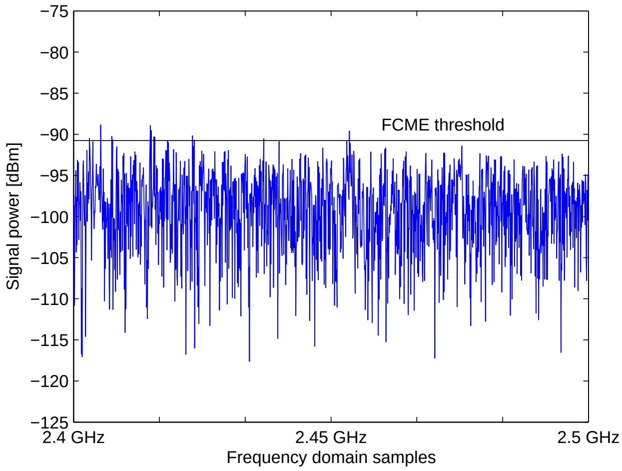

Figure 10. IS using the FCME method at frequencies 2.4-2.5 GHz where are no signals present. Threshold is -91 dBm. $1\% = 12$ samples are above the threshold, as expected.

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