Cognitive radio-based solutions for spectrum scarcity in Palestine

Ali Jamoos*, Osama Najajri and Ahmed Abdou

Department of Electronic and Communication Engineering,
Al-Quds University,
Jerusalem, Palestine
Email: ali.jamoos@staff.alquds.edu
Email: o.najar.89@hotmail.com
Email: aabdou@staff.alquds.edu
*Corresponding author

Abstract: In this paper, we study the feasibility of implementing cognitive radio (CR) secondary network either on the primary Palestinian second generation (2G) global system for mobile communication (GSM) network or on the ultra-high frequency (UHF) television (TV) band. Particularly, we propose solutions for spectrum scarcity based on the three CR paradigms, namely: interweave CR, underlay CR, and overlay CR. In the first solution, an interweave CR system is suggested to efficiently utilise the so-called TV white spaces in the UHF TV band allocated for Palestine. In the second solution, an underlay CR system based on code division multiple access (CDMA) is introduced to underlay the primary GSM system. In the third solution, an overlay CR system is proposed based on orthogonal frequency division multiplexing (OFDM) to share the same spectrum band with the primary GSM system. It is confirmed that the proposed solutions can solve the spectrum scarcity and limit the interference levels, and consequently improve system capacity.

Keywords: spectrum scarcity; cognitive radio; global system for mobile communication; GSM; TV white space; code division multiple access; CDMA; orthogonal frequency division multiplexing; OFDM; Palestine.

Reference to this paper should be made as follows: Jamoos, A., Najajri, O. and Abdou, A. (2019) 'Cognitive radio-based solutions for spectrum scarcity in Palestine', *Int. J. Mobile Network Design and Innovation*, Vol. 9, No. 1, pp.14–23.

Biographical notes: Ali Jamoos received his BSc degree in Electronic Engineering from Al-Quds University, Jerusalem in 1996; his MSc degree in Communications from Jordan University of Science and Technology (JUST), Jordan in 2000; his PhD degree in Signal Processing and Communications from Bordeaux 1 University, France in 2007. His research interests are in the field of signal processing for wireless communications with focus on mobile fading channel modelling, estimation and equalisation, multicarrier techniques, wireless sensor networks, cognitive radio, mobile network planning and optimisation. He is an IEEE senior member. Currently, he is an Associate Professor at the Department of Electronic and Communication Engineering at Al-Quds University.

Osama Najajri obtained his BSc in Communication and Electronic Engineering from Palestine Polytechnic University, Hebron, Palestine in 2012 and MSc in Communication and Electronic Engineering from Al-Quds University, Jersulaem, Palestine in 2017. He has been working as teaching assistant (2012–2015). Currently, he is a vocational teacher at Kufur Nima Industrial School-Ramallah in communication department. He is concerned with research on Wireless and Mobile Communications.

Ahmed Abdou received his BSc degree in Electronic Engineering from Al-Quds University (Palestine) in 2004, his MSc degree in Electronic and Communication Engineering from Al-Quds University in 2008, and his PhD degree in Signal Processing and Communication from Bordeaux 1 University (France) in 2014. His research interests are in the field of communication systems and signal processing for wireless communications and channel estimation techniques, and cognitive radio. He got many awards and scholarship during his study and in his current job as an assistant professor in signal processing and communication as well as the director of innovation department at Al-Quds University.

This paper is a revised and expanded version of a paper entitled 'Developing a secondary mobile network in the Palestinian GSM band using cognitive radio' presented at IEEE AEECT, Amman, 11–13 October 2017.

1 Introduction

The traffic on cellular data networks is growing rapidly in the world, leading to high demand for mobile communication spectrum. With the increasing number of wireless devices, the available radio spectrum becomes insufficient to achieve this demand. At the same time, the available literature shows that spectrum utilisation varies from 15% to 85% at different geographic locations at a given time (FCC, 2002). In particular, the spectrum assigned to Palestine is very limited due to the restrictions imposed by Israel through Oslo accords[1] (World Bank Group: Transport and ICT, 2016). The mobile operators in Palestine are still based on global system for mobile communication (GSM) which is the European standard for second generation (2G) mobile system. Indeed, the number of channels allocated to the Palestinian mobile operators (Jawwal and Wataniya) through Oslo accords is limited to 47 channels (out of 922 channel) to conduct 2G services in both the GSM900 and GSM1800 bands as shown in Table 1. This amounts to about only 5.1% of the global GSM channels. Therefore, the cellular network in Palestine is overcrowded. For this reason, the radio frequency (RF) engineers at the Palestinian mobile operators are elaborating on optimising the RF planning of the network so as to increase the capacity and reduce the interference caused by the massive reuse of limited number of channels (Mkheimer and Jamoos, 2012).

Table 1 Number of GSM channels allocated to the two Palestinian mobile operators.

GSM bands	*Total number of channels*	*Number of channels allocated to Palestinian mobile operators*	
		Jawwal	*Wataniya*
GSM850	124	0	0
GSM900	124	24	9
GSM1800	374	0	14
GSM1900	300	0	0
Total	922	47	

Note: Jawwal and Wataniya.

Recently, only two channels are released by Israel to the Palestinian mobile operators to run 3G services. Nevertheless, these limited numbers of channels are not sufficient to provide high data rate internet services for the Palestinian community. The effective solution for the mobile networks in Palestine is to increase the spectrum bandwidth and upgrade the network towards higher levels of mobile generations (3G and 4G). However, this solution is not allowed to be implemented at least till now.

As the demand for advanced broadband wireless technologies and services increases, traditional static spectrum regulation policies are becoming obsolete. In order to meet the needs and optimise the use of the resources, novel technologies are required and could benefit from the unused spectrum. In that context, cognitive radio (CR) has been firstly proposed by Mitola and Maguire (1999) to access the spectrum opportunistically and dynamically. It is an intelligent wireless communication system capable of changing its transceiver parameters based on interaction with the external environment in which it operates (Haykin, 2005; Akyildiz et al., 2008). CR is a key enabling technology for dynamic spectrum access (DSA) that allows secondary system (SS) to operate in the existing licensed spectrum without harmful interference (Akyildiz et al., 2006). The authors in Xiao et al. (2013) have discussed the technical solutions to expand the 4G long-term evolution (LTE) spectrum using CR technology from both research and implementation perspectives. In Lin and Viswanathan (2013), a novel solution is considered to provide GSM connectivity within 4G LTE system through an efficient overlay dynamic spectrum refarming. In this approach, the operators can refarm their GSM spectrum to LTE while still providing some GSM connectivity to their low data rate customers. An overview of important trends, regulatory reform initiatives, and research challenges that manage and utilise radio spectrum is presented in Bhattarai et al. (2016). Millimeter wave (mmW) is another promising technology that will enable high capacity and data rates demands of future 5G cellular communication systems. The wide bandwidth of mmW spectrum provides a solution of spectrum crowding as discussed in the survey by Rangan et al. (2014).

Recently, we have suggested to develop a secondary mobile network in the Palestinian GSM band using overlay CR (Abdou et al., 2017). In this paper, we propose to extend the results in Abdou et al. (2017) by suggesting three different approaches to expand mobile network spectrum in Palestine based on three CR paradigms: interweave CR, underlay CR and overlay CR (Goldsmith et al., 2009). In the first approach, the so-called television white spaces (TVWS) in the Palestinian ultra-high frequency (UHF) band are suggested to be used by an interweave 3G or 4G CR secondary mobile system. In the second approach, 3G secondary CR mobile network based on code division multiple access (CDMA) is proposed to underlay the existing primary 2G GSM network. In the third approach, a 4G mobile system based on orthogonal frequency division multiplexing (OFDM) is suggested as an overlay CR SS to coexist with the existing 2G GSM primary system (PS). In the later approach, the interference expression due to the SS at the PS receiver and the interference expression due to the PS at the SS receiver are firstly derived. Then, to eliminate these interferences, a precoding technique based on zero forcing beam forming (ZFBF) is inserted at the SS transmitter, while a postcoding is introduced at the SS receiver.

The rest of the paper is organised as follows. Section 2 overviews the three types of CR networks: interweave CR, underlay CR and overlay CR. The proposed overlay CR system is introduced in Section 3. Simulation results are illustrated in Section 4. Finally, conclusion remarks are drawn in section 5.

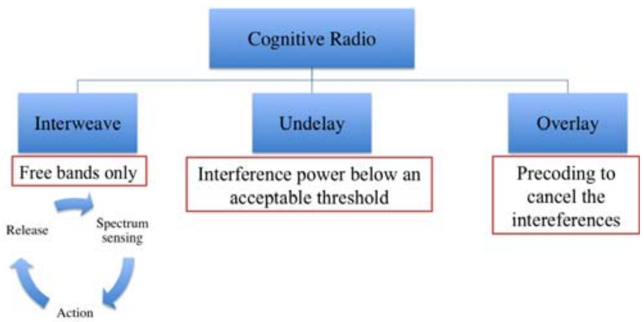
2 Review of CR networks

CR is a software defined radio coupled with cognitive capabilities, where it can sense the spectrum, understand the RF environment, learn from past experience, decide when and how it can access the spectrum and then act accordingly (Haykin, 2005). In that case, two systems must coexist:

- The PS, which is a system already in operation using a license of the spectrum such as GSM or LTE system, etc. It cannot be modified.
- The SS, which aims at using the free resources of the PS in order to transmit its own data.

They respectively involve the so-called primary users (PU) and secondary users (SU) who have to share the spectrum. This can be done in various ways and has led to three main families of CR systems (Goldsmith et al., 2009): the so-called nterweave CR, underlay CR and overlay CR modes as shown in Figure 1.

Figure 1 CR paradigms (see online version for colours)



2.1 Interweave CR

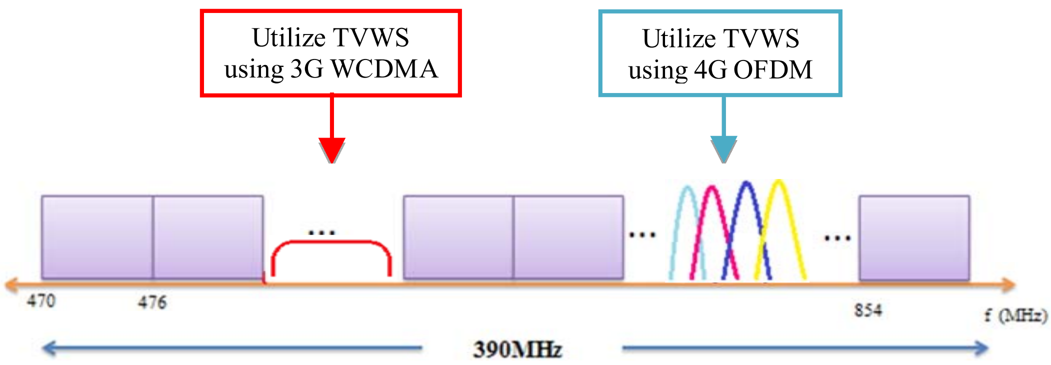
In interweave CR paradigm, the SU can transmit only on a spectrum band where the PU is not active, and has to move onto different bands over time. Interweave platform takes advantage of temporary frequency voids, referred to as spectrum holes that are unused by the licensed PS (Kouassi et al., 2013; Senthuran et al., 2014). This requires spectrum sensing techniques in order to avoid SU degrading the performance of PU. Several spectrum sensing schemes have been proposed to efficiently find PS holes to be used for CR communications (Alizadeh et al., 2015).

To bring the concept of interweave CR into practice, the Federal Communications Commission (FCC) in USA had decided to open up TVWS for unlicensed utilisation (FCC, 2008). TVWS refers to large portions of RF spectrum, in the very high frequency (VHF) and UHF bands, which will become vacant after the switch-over from analogue to digital TV (Nekovee, 2010; Sachs et al., 2010). In Masonta et al. (2012), several field studies and measurements on spectrum occupancy within the VHF and UHF TV bands were conducted in South Africa using a CR platform. These studies found that hundreds of MHz of spectrum is available as a result of traditional analogue TV coverage planning, and it is believed that the switch-over to digital TV will free even more spectrum bands.

Some researchers have studied the translation of the IEEE 802.11 networks into the TV spectrum bands (Bahl et al., 2009). The same idea has also been investigated by the Office of Communications (OfCom) (2009) in the UK. In Stevenson et al. (2009), the IEEE 802.22 standard has been released for wireless regional area network (WRAN) using the TVWS. In the last decade, there has been a large amount of interest in expanding the broadband wireless network spectrum with CR technology using the new TVWS (Xiao et al., 2013). It is believed that LTE 4G mobile network can take advantage of TVWS propagation characteristics and cover large geographical areas with less number of base stations, besides enabling operators to offer cheaper mobile broadband services to more consumers, especially in rural areas (Xiao et al., 2013).

In this paper, we suggest to use the concept of interweave CR so as to expand the spectrum available for Palestinian mobile operators. Particularly, the available TVWS in the Palestinian UHF band can be used to implement a 3G or 4G mobile network as shown in Figure 2. Nevertheless, this introduces a number of technical challenges like spectrum sensing, requirement of new wireless physical and media access control (MAC) layer designs (Shellhammer et al., 2009).

Figure 2 Suggested 3G or 4g interweave CR transmission into TVWS of the Palestinian uhf band (see online version for colours)



2.2 Underlay CR

The underlay CR paradigm allows SU to operate if the interference they cause to PU is below a given threshold in which the SU cannot significantly interfere with the communication of PU. In that case, a SU can spread its signal over a very wide bandwidth such that the interference power spectral density (PSD) is below the noise floor at any PU location.

Several undelay CR methods have been proposed in the literature (Le and Hossain, 2008; Son et al., 2009; Zhang et al., 2013; Jasbi and So, 2016). The most preferable multiple access techniques for underlay CR systems are those based on spread spectrum signalling such as CDMA and multicarrier CDMA (MC-CDMA) (Le and Hossain, 2008; Jasbi and So, 2016). Indeed, there are two main advantages when using CDMA for underlay transmission. Firstly, spread spectrum signaling results in low PSD similar to the power level of the background noise. Secondly, spread spectrum signaling has high interference suppression capabilities particularly for narrow-band interfering signals.

In this paper, to efficiently utilise the available 24 channel (from 910.2MHz to 915MHz) allocated for ‘Jawwal’ Palestinian mobile operator in the GSM900 band, we suggest to implement an underlay CR system based on wideband CDMA (WCDMA) into the existing 2G GSM system as shown in Figure 3.

According to Figure 3, which shows only the up-link frequencies, the total bandwidth allocated for ‘Jawwal’ Palestinian mobile operator is 4.8MHz. This bandwidth can be used for the underlay transmission of one WCDMA channel.

2.3 Overlay CR

In overlay CR, the SS simultaneously transmits with the PS while mitigating the interferences, by taking into account that some *a priori* information of the PU is known at the SU transmitter. Sophisticated encoding techniques can be defined to cancel or mitigate the interference at the PU receiver from SU transmitter and the interference from PU transmitter at the SU receiver. Examples of existing interference cancelation methods are ZFBF (Abdou et al., 2013), interference alignment (IA) (Liang et al., 2016), dirty paper coding (DPC) (Costa, 1983), and block diagonalisation (Lee and Lee, 2011). Each method requires *a priori* knowledge at the SU. Thus, in DPC the exchanged messages at the PU side have to be known. In IA, *a priori* information about the PU channels must be known by the SU. ZFBF has lower complexity as compared with other techniques. Also, it maximises the signal to noise ratio (SNR) due to spatial diversity. This motivates us to use ZFBF to be performed at the SS.

In recent years overlay CR has been widely investigated in the literature. In Jasbi and So (2016), a hybrid transmission system that exploits both overlay and underlay CR is proposed using MC-CDMA due to its interference rejection and diversity exploitation capabilities. The merits and challenges of CR based on OFDM technology is investigated in Mahmoud et al. (2009). The authors present some of the requirements for CR and explain how OFDM can fulfil these requirements. In Mukherjee et al. (2015), transmitter architecture for OFDM-based overlay CR has been introduced to reduce the spectral leakage of SU. The PSD of the scheme has been calculated and compared with other spectral precoding schemes. A comparison of two types of multicarrier communications: conventional OFDM with cyclic prefix (CP) and filter bank multicarrier (FBMC)-based CR networks in terms of the average channel capacity, which depends on the resource allocation strategy adopted by the CR system is proposed in Zhang et al. (2010). Simulation results show that FBMC can achieve higher channel capacity than OFDM. In Abdou et al. (2013), an overlay CR based on FBMC/OQAM is proposed for the SU whereas the PU is based on OFDM, and a ZFBF interference cancellation method was considered. Simulation results confirmed that the FBMC-based CR is superior to OFDM-based CR in terms of the spectral efficiency and bit error rate (BER). In the following section, we propose an overlay CR system based on OFDM to coexist with the Palestinian 2G GSM PS.

3 Proposed overlay CR system

Our proposed system is based on an overlay CR platform where the existing Palestinian 2G GSM system is considered as PS and a 4G system based on OFDM is suggested as SS (see Figure 4).

In that case, the PS and the SS are considered to be a single-input single-output (SISO) system and multiple-input multiple-output (MIMO) system, respectively. We derive the interference expression due to SS at the PS receiver as well as the interference expression due to PS at the SS receiver. To cancel the interferences, a precoding based on ZFBF is considered at the SS transmitter, while a postcoding is employed at the SS receiver as will be introduced in the following subsections.

Figure 3 Suggested WCDMA underlay CR transmission in the Palestinian GSM900 band (see online version for colours)

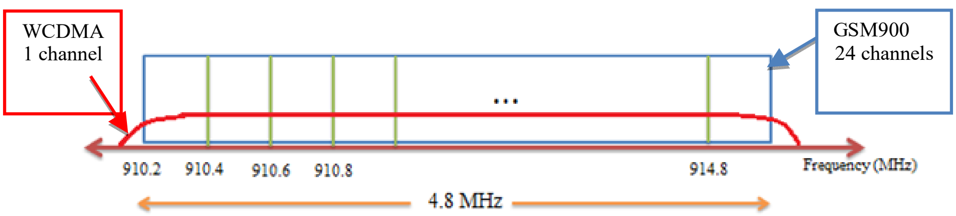


Figure 4 Proposed overlay CR based on GSM as PS and OFDM as SS (see online version for colours)

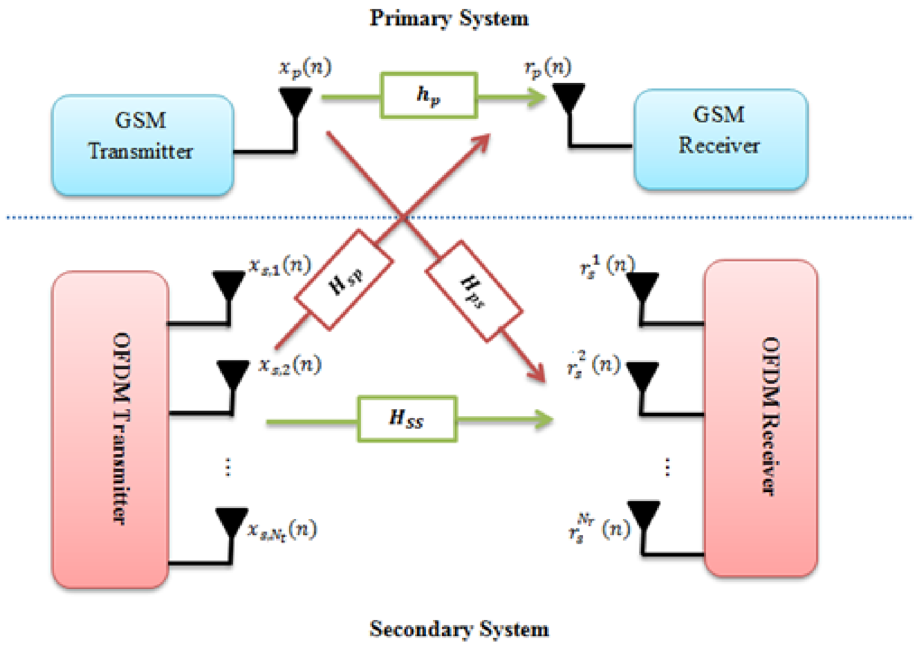
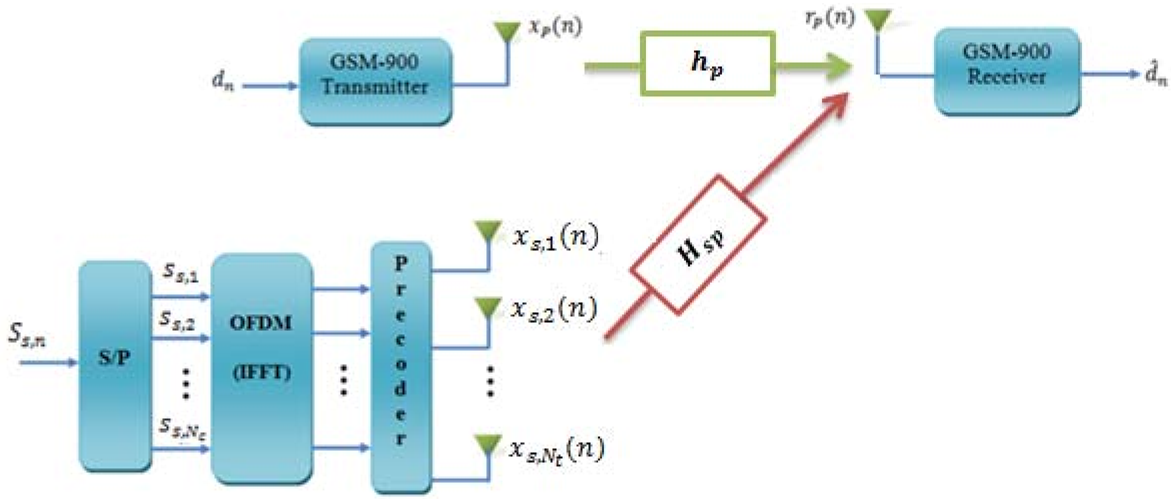


Figure 5 Interference cancellations at PS receiver (see online version for colours)



3.1 *Interference cancellation at PS receiver*

In this subsection, the transmitted symbols at SS transmitter are pre-coded before transmission. The received signal at the GSM receiver is corrupted by interference from SS since they transmit in the same band. The key of interference cancellation at PS receiver is the use of a precoding in the SS transmitter. In this model, we propose to use precoding after the process of IFFT in OFDM system. In order to apply a precoding technique to mitigate the interferences, we consider a multiple-input single-output (MISO) case at SS. Thus, the secondary data is transmitted over several numbers of antennas. Figure 5 describes the precoding scheme for interference cancellation at PS receiver side.

The received signal $r_p(n)$ can be expressed as:

$$r_p(n) = h_p(n) * x_p(n) + \sum_{a=1}^{N_t} h_{sp,a}(n) * x_{s,a}(n) + w(n) \tag{1}$$

where $x_p(n)$ is the transmitted Gaussian minimum shift keying (GMSK) signal of the GSM PS, and $x_{s,a}(n)$ is the transmitted signal of the SS (OFDM) on the a^{th} antenna. In addition, $h_p(n)$ is the channel impulse response on the $x_p(n)$, $h_{sp,a}(n)$ is the channel effect on the $x_{s,a}(n)$ and $w(n)$ is the additive white Gaussian noise at the primary receiver. It should be noted that the number of antennas at SS transmitter, N_t, is related to the number of multipath taps, L_p, where the number of antenna is at least greater than number of multipath taps by one, i.e., $N_t \geq L_p + 1$.

The discrete-time transmitted GMSK signal from the PS can be written as follows:

$$x_p(n) = A_c \cos\left(2\pi f_c + \varphi(n)\right) \tag{2}$$

where A_c is the amplitude of the signal, f_c is the RF of the carrier and the discrete phase φ(n) contains the information is given by:

$$\varphi(n) = \frac{\pi}{2}\sum_{i=-\infty}^{\infty} d(i)\, p\left(n - iN_s\right) \tag{3}$$

with the data $d(i) \in \{\pm 1\}$, $p(n)$ related to the pulse shape of the modulation scheme and N_s the number of sample in a bit period.

The interference due to SS transmission in the band of the PS is represented by:

$$i(n) = \sum_{a=1}^{N_t} h_{sp,\,a}(n) * x_{s,\,a}(n) \tag{4}$$

The a^{th} signal from SS, under the assumption that all the symbols to be equal on each antenna, can be written as:

$$x_{s,\,a}(n) = z_a x_s(n) \tag{5}$$

where z_a is the preceded data or beamformer of a^{th} antenna and $x_s(n)$ is the OFDM symbol with N_c subcarriers, it is related to digital data $X_s(m)$ according to IFFT process as follows:

$$x_s(n) = \frac{1}{\sqrt{N_s}}\sum_{m=0}^{N_c-1} X_s(m) e^{j2\pi\frac{mn}{N_c}} \tag{6}$$

Thus, the interference can be written as:

$$i(n) = \sum_{a=1}^{N_t}\sum_{k=0}^{L_p-1} h_{sp,\,a}(n) z_a x_s(n-k) \tag{7}$$

In GSM system, the number of taps in multipath fading channel denoted by L_p is usually set to 5. Therefore, the minimum required number of antenna is $N_t = 6$. With these two values we get:

$$\begin{aligned} i(n) = {} & z_1\begin{bmatrix} h_{sp,1}(0)x_s(n) + h_{sp,1}(1)x_s(n-1) \\ + \cdots + h_{sp,1}(4)x_s(n-4) \end{bmatrix} \\ & + z_2\begin{bmatrix} h_{sp,2}(0)x_s(n) + h_{sp,2}(1)x_s(n-1) \\ + \cdots + h_{sp,2}(4)x_s(n-4) \end{bmatrix} \\ & \vdots \\ & + z_{N_t}\begin{bmatrix} h_{sp,N_t}(0)x_s(n) + h_{sp,N_t}(1)x_s(n-1) \\ + \cdots + h_{sp,N_t}(4)x_s(n-4) \end{bmatrix} \end{aligned} \tag{8}$$

In that case, $i(n)$ can be rewritten in a matrix form as follows:

$$i = \boldsymbol{z}\boldsymbol{H}_{\boldsymbol{sp}}\boldsymbol{x}_{\boldsymbol{s}} \tag{9}$$

where

$$z = \left[z_1, z_2, \ldots, z_{N_t}\right] \tag{10}$$

In addition, $\boldsymbol{H}_{sp}$ is the $N_t \times L_p$ matrix that contains all interfering channels:

$$\boldsymbol{H}_{sp} = \begin{bmatrix} h_{sp,1}(0) & \cdots & h_{sp,1}\left(L_p - 1\right) \\ \vdots & \ddots & \vdots \\ h_{sp,N_t}(0) & \cdots & h_{sp,N_t}\left(L_p - 1\right) \end{bmatrix} \tag{11}$$

The $L_p \times 1$ is vector x_s contains the transmitted secondary data can be written as follows:

$$x_s = \left[x_s(n) \quad x_s(n-1) \quad \ldots \quad x_s\left(n - \left(L_p - 1\right)\right)\right]^T \tag{12}$$

The beamformer vector, z, is designed to set (9) to zero, i.e., the interference is cancelled. In that case, (9) can be written as:

$$\boldsymbol{z}\boldsymbol{H}_{sp}\boldsymbol{x}_s = 0 \tag{13}$$

Since the data should not be zero, then we should find z that satisfies the following:

$$\boldsymbol{H}_{sp}^H \boldsymbol{z}^H = \boldsymbol{0} \tag{14}$$

where $\boldsymbol{H}_{sp}^H$ and $\boldsymbol{z}^H$ are the Hermitian matrices of $\boldsymbol{H}_{sp}$ and z, respectively.

The nontrivial solution of this equation can be done through the singular value decomposition (SVD) property of the channel matrix $\boldsymbol{H}_{sp}^H$ where $N_t \geq L_p + 1$. It is well known that the SVD of matrix $\boldsymbol{H}_{sp}^H$ can be written as:

$$\boldsymbol{H}_{sp}^H = \boldsymbol{U}\boldsymbol{\Sigma}\boldsymbol{V}^{\boldsymbol{H}} \tag{15}$$

where $\boldsymbol{U}$ and $\boldsymbol{V}$ are orthogonal matrices, $\boldsymbol{U} = \boldsymbol{H}_{sp}^H\boldsymbol{H}_{sp}$ and $\boldsymbol{V} = \boldsymbol{H}_{sp}\boldsymbol{H}_{sp}^H$. $\boldsymbol{\Sigma}$ is $L_p \times N_t$ pseudo-diagonal matrix contains the positive eigenvalues of $\boldsymbol{H}_{sp}^H$. It can written as follows:

$$\boldsymbol{\Sigma} = \begin{bmatrix} \sigma_1 & \cdots & 0 & 0 & \cdots & 0 \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ 0 & \cdots & \sigma_{L_p} & 0 & \cdots & 0 \end{bmatrix} \tag{16}$$

Using SVD, by multiplying $\boldsymbol{H}_{sp}^H$ with $\boldsymbol{V}_q$, the q^{th} rightmost column of V, where $q > L_p + 1$, so we get:

$$\boldsymbol{H}_{sp}^H\boldsymbol{V}_q = 0 \Rightarrow z^H = \boldsymbol{V}_q \tag{17}$$

3.2 *Interference cancellation at SS receiver*

The received signal at the OFDM receiver is corrupted by interference from primary transmitter since they transmit in the same band. In this model, we consider a MIMO at SS. Thus, the secondary data is transmitted over several numbers of antennas. Recalling Figure 4, the secondary received signal at the j^{th} antenna can be written as:

$$r_s^j(n) = \sum_{q=1}^{N_t} h_{ss,\,q}^j(n) * x_{s,\,q}(n) + i_{ps}^j(n) + w^j(n) \tag{18}$$

where $h_{ss,q}^{j}(n)$ is the channel gain that is affected on the signal of the q^{th} transmitter antenna at the j^{th} receive antenna, $w^j(n)$ is the additive noise at the j^{th} receive antenna and $i_{ps}^{j}(n)$ is the interference from primary transmitter on the secondary receiver at the j^{th} receive antenna.

We can write the total interference of the PS on SS as following:

$$\begin{aligned} i_{ps}(n) &= \sum_{j=1}^{N_r} i_{ps}^{j}(n) = \sum_{j=1}^{N_r} h_{ps}^{j}(n) * x_p(p) \\ &= \sum_{j=1}^{N_r} \sum_{m=0}^{L_p-1} h_{ps}^{j}(m) x_p(n-m) \end{aligned} \quad (19)$$

It is clear that $i_{ps}(n)$ can be written in matrix form as:

$$\boldsymbol{i}_{ps} = \boldsymbol{H}_{ps} \boldsymbol{x}_p \quad (20)$$

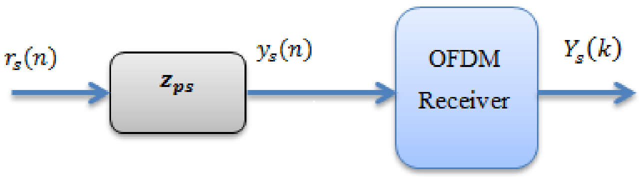
where

$$H_{ps} = \begin{bmatrix} h_{ps}^{1}(0) & \cdots & h_{ps}^{1}(L_p-1) \\ \vdots & \ddots & \vdots \\ h_{ps}^{N_r}(0) & \cdots & h_{ps}^{N_r}(L_p-1) \end{bmatrix} \quad (21)$$

and $x_p = [x_p(n)\ x_p(n-1) \ldots x_p(n-L_p+1)]^T$.

We look to force the interference to be zero at the SS receiver. In that case, we should generate a postcoding, z_{ps}, on the SS received signal as shown in Figure 6 in order to cancel the interference, i.e., $i_{ps} = 0$.

Figure 6 Post-coding at SS receiver (see online version for colours)



Therefore, ZFBF at SS receiver can also be applied as follows

$$\boldsymbol{i}_{ps} = \boldsymbol{z}_{ps} \boldsymbol{H}_{ps} \boldsymbol{x}_p = \boldsymbol{0} \quad (22)$$

Since the data should not be zero, then we should find z_{ps} that satisfies the following:

$$\boldsymbol{z}_{ps} \boldsymbol{H}_{ps} = \boldsymbol{0} \rightarrow \boldsymbol{H}_{ps}^{H} \boldsymbol{z}_{ps}^{H} = \boldsymbol{0} \quad (23)$$

The nontrivial solution of this equation can be done through the SVD property of the channel matrix $\boldsymbol{H}_{ps}^{H}$ where $N_r \geq L_p + 1$ as discussed in last subsection. It is well known that the SVD of matrix $\boldsymbol{H}_{ps}^{H}$ can be written as:

$$\boldsymbol{H}_{ps}^{H} = \boldsymbol{U \Sigma V}^{H} \quad (24)$$

Using SVD, by multiplying $\boldsymbol{H}_{ps}^{H}$ with $\boldsymbol{V}_q$, the q^{th} rightmost column of $\boldsymbol{V}$, where $q > L_p + 1$, so we get:

$$\boldsymbol{H}_{ps}^{H} \boldsymbol{V}_q = 0 \Rightarrow \boldsymbol{z}_{ps}^{H} = \boldsymbol{V}_q \quad (25)$$

According to Figure 6, $y_s(n)$ can be written as:

$$y_s(n) = \boldsymbol{z}_{ps} r_s(n) \quad (26)$$

In matrix form, y_s, can be written as:

$$\boldsymbol{y}_s = \boldsymbol{z}_{ps} \boldsymbol{H}_{ss} x_s + \boldsymbol{z}_{ps} \boldsymbol{i}_{ps} + \boldsymbol{z}_{ps} \boldsymbol{w} \quad (27)$$

It should be noted that the term $\boldsymbol{z}_{ps}\boldsymbol{i}_{ps}$ will be cancelled based on SVD design for z_{ps}. The post-coding vector, z_{ps}, $1 \times N_r$ complex values vector. Thus, we can multiply j^{th} receive signal with a component of this vector, z_{ps}^{j}, $j = 1, \ldots, N_r$. For sake of simplicity, let we assume that $x_s(n) = \{x_{s,q}(n)\}_{q=1}^{N_t}$, then we can write the received signal on j^{th} antenna after post-coding process as:

$$y_s^j(n) = x_s(n) * \sum_{q=1}^{N_t} z_{ps}^{j} h_{ss,q}^{j}(n) + z_{ps}^{j} i_{ps}^{j}(n) + z_{ps}^{j} w^j(n) \quad (28)$$

Define $y_s(n) = \Sigma_{j=1}^{N_r} y_s^j(n)$, then:

$$\begin{aligned} y_s(n) &= \sum_{j=1}^{N_r} \left(x_s(n) * \sum_{q=1}^{N_t} z_{ps}^{j} h_{ss,q}^{j}(n) \right) + i_{ps}(n) + w(n) \\ &= x_s(n) * \sum_{j=1}^{N_r} \sum_{q=1}^{N_t} z_{ps}^{j} h_{ss,q}^{j}(n) + v(n) \end{aligned} \quad (29)$$

where $i_{ps}(n) = \Sigma_{j=1}^{N_r} z_{ps}^{j} i_{ps}^{j}(n)$ is the cancelled interference term, i.e., it is the same as $\boldsymbol{z}_{ps}\boldsymbol{i}_{ps}$. The additive noise $w(n) = \Sigma_{j=1}^{N_r} z_{ps}^{j} w^j(n)$ and $v(n) = i_{ps}(n) + w(n)$.

The received signal after *FFT* can be written as:

$$Y_s(k) = X_s(k) H_{ss}(k) + V(k) \quad (30)$$

where $H_{ss}(k) == FFT\{\Sigma_{j=1}^{N_r} \Sigma_{q=1}^{N_t} z_{ps}^{j} h_{ss,q}^{j}(n)\}$ and $V(k)$ = $FFT\{v(n)\}$.

The equalised signal, $\hat{X}_s(k)$, can be implemented by ZF equaliser and it can be written as:

$$\hat{X}_s(k) = Y_s(k) H_{ss}^{*}(k) \quad (31)$$

4 Simulation results

In this section, a comparative simulation study is carried-out in-terms of BER performance between two overlay CR systems.

a An overlay CR system where OFDM is used at the PS as well as at the SS. We call it OFDM-OFDM CR (Abdou et al., 2013.)

b The proposed overlay CR system where the GSM-900 is considered as PS and OFDM is the SS. We call it GSM-OFDM CR.

The two systems are also compared with theoretical BER of quadrate phase shift keying (QPSK) and GMSK over Rayleigh fading channel.

In OFDM system, we assume $N_c = 64$ subcarriers are all used and the CP length is set to $L_{cp} = 16$. Both are known by the SU. A QPSK modulation is used in the OFDM system whereas GMSK modulation is used for GSM with bandwidth bit period product of 0.3. In addition, the channels are first assumed to be perfectly known. The number of channel paths (taps) in GSM signal is assumed to be $L_p = 5$. According to the constraints $L_p + 1 \leq N_t$ and $L_p + 1 \leq N_r$ we choose the number of antenna at each secondary transmitter and receiver to be six. Two methods for channel equalisation in GSM system are tested. Namely, the zero forcing (ZF) channel equaliser and the minimum mean square error (MMSE) channel equaliser.

Figure 7 shows the BER performance of GSM-OFDM CR system with two equaliser techniques for GSM system. It can be shown that the BER performance using MMSE equaliser is better than using ZF equaliser especially when E_b/N_0 is greater than approximately 12 dB.

Figure 7 BER of GSM-OFDM CR system where the GSM receiver is based on ZF and MMSE (see online version for colours)

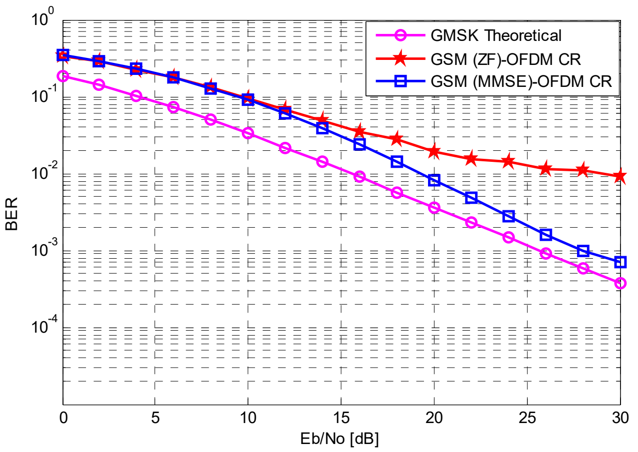


Figure 8 BER of OFDM-OFDM CR and GSM-OFDM CR with ZF and MMSE channel equalisation (see online version for colours)

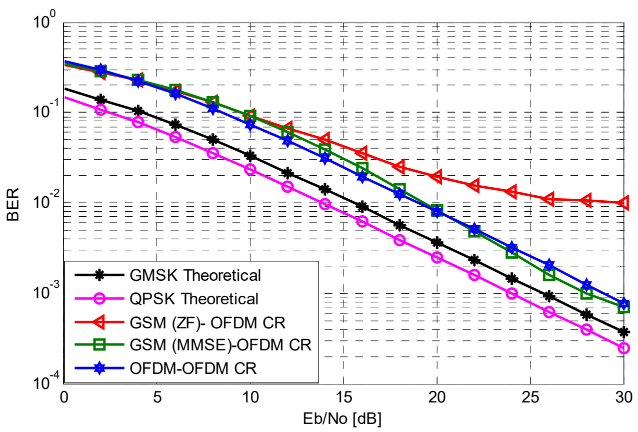


Figure 8 shows the BER performance of OFDM-OFDM CR compared with GSM-OFDM CR using two channel equalisation techniques (ZF and MMSE) for GSM. One can notice that the performance of CR system where the PS is OFDM is better than when it is considered as GSM system when using ZF channel equalisation scheme. In that case, the BER of OFDM-OFDM CR is superior to GSM-OFDM CR when E_b/N_0 is approximately great the 10 dB. Nevertheless, when the GSM receiver is based on MMSE channel equaliser the performance of the two CR configurations is approximately the same.

In Figure 8, the channels between PU and SU are assumed to be known. However, in practice these channels need to be estimated and tracked in order to design the ZFBF. In the following, we investigate the sensitivity of the proposed system to channel estimation error (CEE) where 10% error on the channel is introduced.

The BER performances for GSM (ZF)-OFDM CR, GSM (MMSE)-OFDM CR, and OFDM-OFDM CR with and without CEE are shown in Figure 9, Figure 10, and Figure 11, respectively. It can be noticed that the BER increased when there is a CEE. Nevertheless, the proposed system is robust to CEE.

Figure 9 BER performance for GSM (ZF)-OFDM CR with and without CEE (see online version for colours)

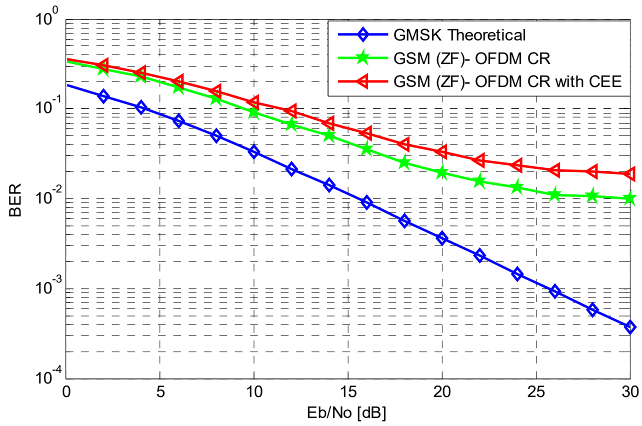


Figure 10 BER performances for GSM (MMSE)-OFDM CR with and without CEE (see online version for colours)

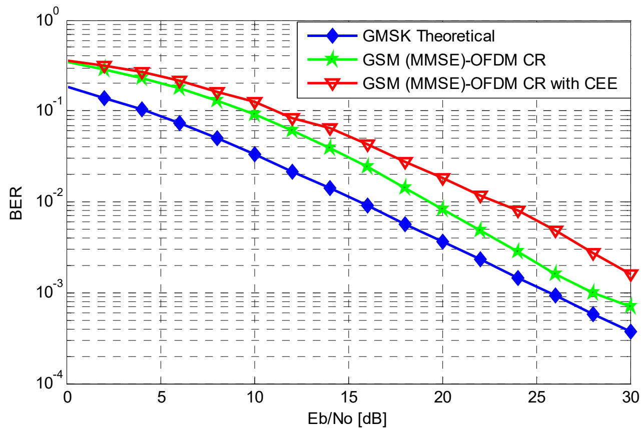


Figure 12 shows the BER performance for GSM-OFDM CR compared with the OFDM-OFDM CR, in the presence of CEEs where a 10% error is introduced on the channel. It can be noticed that the performance of CR system where the PS is OFDM is better than when it is GSM system with ZF equalisation scheme. However, with MMSE equaliser the performance of the two CR configuration is approximately the same. In addition, one can notice that the proposed system is robust to CEE.

Figure 11 BER performance for OFDM-OFDM CR with and without CEE (see online version for colours)

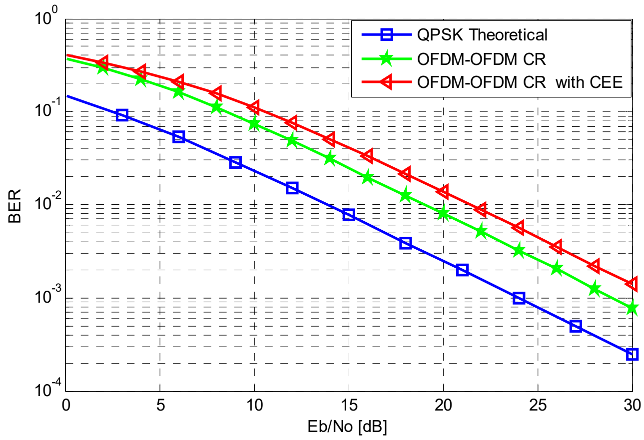
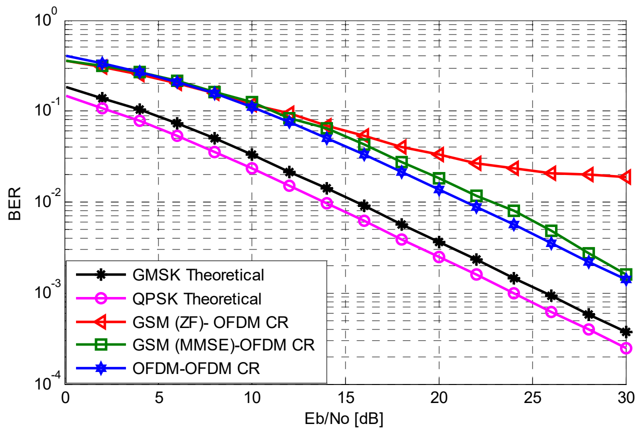


Figure 12 BER for GSM-OFDM CR compared with the OFDM-OFDM CR, in the presence of CEE (see online version for colours)



5 Conclusions

In this paper, the three CR paradigms (interweave, underlay, overlay) are firstly reviewed. Based on these three CR paradigms, three solutions are then suggested for the spectrum scarcity of mobile systems in Palestine. Particularly, in the first solution, an interweave CR mobile system is suggested to be implemented in the TVWS of the Palestinian UHF band. In the second solution, an underlay CR mobile system based on WCDMA is suggested to share the spectrum of the Palestinian GSM primary band. In the third solution, an overlay CR mobile system based on OFDM is proposed to coexist with the currently operated Palestinian GSM system. In the later solution, the interference expression due to the SS at the PS receiver and the interference expression due to the PS at the SS receiver are firstly derived. Then, to eliminate these interferences, a precoding technique based on ZFBF is inserted at the SS transmitter, while a postcoding is introduced at the SS receiver. Simulation results confirm the efficiency of the proposed overlay CR system as compared with existing systems.

References

Abdou, A., Ferre, G., Grivel, E. and Najim, M. (2013) ‘Interference cancellation in multiuser hybrid overlay cognitive radio’, *Proceeding of the EUSIPCO*, pp.1–5, September.

Abdou, A., Najajri, O. and Jamoos, A. (2017) ‘Developing a secondary mobile network in the Palestinian GSM band using cognitive radio’, *Proceeding of the IEEE AEECT*, 11–13 October, Amman.

Akyildiz, I.F., Lee, W.Y., Vuran, M.C. and Mohanty, S. (2006) ‘Next generation/dynamic spectrum access/cognitive radio wireless networks: a survey’, *Computer Networks Journal*, Elsevier, September, Vol. 50, No. 13, pp.2127–2159.

Akyildiz, I.F., Lee, W.Y., Vuran, M.C. and Mohanty, S. (2008) ‘A survey on spectrum management in cognitive radio networks’, *IEEE Communications Magazine*, April, Vol. 46, No. 4, pp.40–48.

Alizadeh, A., Bahrami, H., Maleki, M. and Sastry, S. (2015) ‘Spatial sensing and cognitive radio communication in the presence of a K-user interference primary network’, *IEEE Journal on Selected Areas in Communications*, May, Vol. 33, No. 5, pp.741–754.

Bahl, P., Chandra, R., Moscibroda, T. and Murty, R. (2009) ‘White space networking with Wi-Fi like connectivity’, *Proceedings of ACM SIGCOMM*, Barcelona, Spain.

Bhattarai, S., Park, J., Gao, B., Bian, K. and Lehr, W. (2016) ‘An overview of dynamic spectrum sharing: ongoing initiatives, challenges, and a roadmap for future research’, *IEEE Transactions on Cognitive Communications and Networking*, June, Vol. 2, No. 2, pp.110–128.

Costa, M. (1983) ‘Writing on dirty paper’, *IEEE Transaction on Information Theory*, Vol. 29, No. 3, pp.439–441.

Federal Communication Commission (FCC) (2002) *Spectrum Policy Task Force Report*, ET Docket No. 02-155, Technical Report Series, November.

Federal Communications Commission (2008) ‘FCC adopts rules for unlicensed use of television white spaces’, *Media Release*, USA, November.

Goldsmith, A., Jafar, S., Maric, I. and Srinivasa, S. (2009) ‘Breaking spectrum gridlock with cognitive radios: an information theoretic perspective’, *Proceeding of the IEEE*, May, Vol. 97, No.5, pp.894–914.

Haykin, S. (2005) ‘Cognitive radio: brain-empowered wireless communications’, *IEEE Journal on Selected Areas in Communications*, February, Vol. 23, No. 2, pp.201–220.

Jasbi, F. and So, D. (2016) ‘Hybrid overlay/underlay cognitive radio network with MC-CDMA’, *IEEE Transactions on Vehicular Technology*, April, Vol. 65, No. 4, pp.2038–2047.

Kouassi, B., Slock, D., Ghauri, I. and Deneire, L. (2013) ‘Enabling the implementation of spatial interweave LTE cognitive radio’, *Proceeding of the EURASIP-European Signal Processing Conference (EUSIPCO)*, pp.1–5.

Le, L.B. and Hossain, E. (2008) ‘Resource allocation for spectrum underlay in cognitive radio networks’, *Wireless Communications, IEEE Transactions on*, December, Vol. 7, No. 12, pp.5306–5315.

Lee, K. and Lee, I. (2011) 'MMSE based block diagonalization for cognitive radio MIMO broadcast channels', *IEEE Transactions on Wireless Communications*, October, Vol. 10, No. 10, pp.3139–3144.

Liang, B. Huang, H. and Jing, X. (2016) 'Dynamic power allocation for spectrum sharing in interference alignment (IA)-based cognitive radio', *The 16th International Symposium on Communications and Information Technologies (ISCIT)*, September, pp.646–650.

Lin, X. and Viswanathan, H. (2013) 'Dynamic spectrum refarming with overlay for legacy devices', *IEEE Transactions on Wireless Communications*, October, Vol. 12, No. 10, pp.5282–5293.

Mahmoud, H., Yucek, T. and Arslan, H. (2009) 'OFDM for cognitive radio: merits and challenges', *IEEE on Wireless Communication*, April, Vol. 16, No. 2, pp.6–15.

Masonta, M.T., Johnson, D. and Mzyece, M. (2012) 'The white space opportunity in Southern Africa: measurements with Meraka cognitive radio platform', Popescu-Zeletin, R. et al. (Eds.): *Springer Lecture Notes*, Part 1, Vol. 92, pp.6–73.

Mitola, J. and Maguire, G. (1999) 'Cognitive radio: making software radios more personal', *IEEE Personal Communications*, August, Vol. 6, No. 4, pp.13–18.

Mkheimer, B. and Jamoos, A. (2012) 'Evaluation and optimization of GSM network in Jenien city, Palestine', *International Journal of Mobile Network Design and Innovation*, December, Vol. 4, No. 4, pp.201–213.

Mukherjee, M., Chang, R. and Kumar, V. (2015) 'OFDM-based overlay cognitive radios with improved spectral leakage suppression for future generation communications', *2015 IEEE Wireless Communications and Networking Conference (WCNC)*, March, pp.434–439.

Nekovee, M. (2010) 'A survey of cognitive radio access on TV white spaces', *Hindawi International Journal of Digital Multimedia Broadcasting*, 11, Article ID: 236568 [online] http://dx.doi.org/10.1155/2010/236568.

Office of Communication (2009) *Statement on Cognitive Access to Interleaved Spectrum*.

Rangan, S., Rappaport, T. and Erkip, E. (2014) 'Millimeter wave cellular wireless networks: potentials and challenges', *Proceeding of the IEEE*, March, Vol. 102, No. 3, pp.366–385.

Sachs, J., Maric, I. and Goldsmith, A. (2010) 'Cognitive cellular systems within the TV spectrum', *Proceeding 2010 IEEE Symposium on New Frontiers in Dynamic Spectrum*, April, pp.1–12.

Senthuran, S., Anpalagan, A., Hyung, Y., Karmokar, A. and Das, O. (2014) 'An opportunistic channel access scheme for interweave cognitive radio systems', *Journal of Communications and Networks*, Vol. 16, No. 1, pp.56–66.

Shellhammer, S., Sadek, A. and Zhang, W. (2009) 'Technical challenges for cognitive radio in the TV white space spectrum', *Information Theory and Applications Workshop*, February, pp.323–333.

Son, K., Jung, B.C., Chong, S. and Sung, D.K. (2009) 'Opportunistic underlay transmission in multi-carrier cognitive radio systems', in *IEEE Wireless Commun. Net. Conf. (WCNC)*, April, pp.1–6.

Stevenson, C., Chouinard, G., Lei, Z.D., Hu, W.D., Shellhammer, S. and Caldwell, W. (2009) 'IEEE 802.22: the first cognitive radio wireless regional area network standard', *IEEE Communications Magazine*, Vol. 47, No. 1, pp.130–138.

World Bank Group: Transport and ICT (2016) *The Telecommunication Sector in the Palestinian Territories: A Missed Opportunity for Economic Development; Note for the Palestinian Ministry of Telecommunications and Information Technology*, Technical Report, January.

Xiao, J., Hu, R., Qian, Y., Gong, L. and Wang, B. (2013) 'Expanding LTE network spectrum with cognitive radios: from concept to implementation', *IEEE Wireless Communications*, April, Vol. 20, No. 2, pp.12–19.

Zhang, H., Ruyet, D., Roviras, D. and Sun, H. (2010) 'Capacity analysis of OFDM/FBMC based cognitive radio networks with estimated CSI', *Proceeding of the International Conference on Cognitive Radio Oriented Wireless Networks Communications (CROWNCOM)*, pp.1–5.

Zhang, L., Yang, H. and Mazen, H. (2013) 'Area spectral efficiency of underlay cognitive radio transmission over Rayleigh fading channels', *Proceeding of the IEEE Wireless Communications and Networking Conference (WCNC)*, July, pp.2988–2992.

Notes

1 Oslo accords: are a set of agreements between the government of Israel and the Palestine Liberation Organization (PLO) signed in 1993.