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Partially overlapping filtered multitone with reconfigurable antennas in uncoordinated networks

Mustafa Harun Yılmaz [a,*], Selçuk Köse [a], Nowrin H. Chamok [b], Mohammod Ali [b], Hüseyin Arslan [a,c]

[a] Department of Electrical Engineering, University of South Florida, Tampa, FL, United States
[b] Department of Electrical Engineering, University of South Carolina, Columbia, South Carolina
[c] School of Engineering and Natural Sciences, Istanbul Medipol University, Beykoz, İstanbul, Turkey

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ABSTRACT

Partially overlapping tones (POT) have recently been offered as a promising solution with the aim of decreasing the interference induced on the users for uncoordinated networks. Since each user causes interference on other users while utilizing the same resources, a reduction on this destructive interference can be achieved with POT concept. In this study, a game theoretical partially overlapping filtered multitone scheme is proposed. Partially overlapping is performed in both frequency and space domains. While intentional carrier frequency shift is introduced in frequency, reconfigurable antennas are utilized to achieve partially overlapping in space domain. Within a game theoretical framework, when users search for the frequency shift ratio, they also select the antenna state to increase the system utility. When the users act simultaneously, joint behavior makes it increasingly difficult to reach the Nash equilibrium (NE). To address this problem, a sequential game algorithm is utilized. As a result, the NE is proved theoretically with potential games and simulations. With this joint partially overlapping game in frequency and space domains, it is demonstrated that the capacity gain at system level is improved significantly.

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1. Introduction

Due to the unprecedented increase in the wireless usage demand, researchers have primarily focused on spectrally efficient solutions. As one of the most efficient solutions, orthogonal frequency-division multiplexing (OFDM) has been proposed to satisfy this demand. In coordinated networks, OFDM provides high spectral efficiency. However, in uncoordinated networks which can consist of non-cooperative small cells which include one base station (BS) and multiple users in each, and are not controlled by a central unit in one possible scenario, OFDM is highly vulnerable to interference coming from other users due to the asynchronous transmission which is leading to loss of orthogonality. Moreover, since all the small cells utilize the same band in uncoordinated networks, they produce destructive interference between each other.

Recently, partially overlapping tones (POT) concept has been introduced in [1] to mitigate the interference coming from other users in uncoordinated networks. In the POT concept, intentional carrier frequency shift (CFS) is performed by every non-cooperative users with the aim of exploiting the gaps in between subcarriers. The allocated resources to two uncoordinated users i and j are illustrated in Fig. 1(a) and Fig. 1(b) (solid curve) where i and j are assigned at the same time. Before j is provided with a frequency shift, both users fully overlap each other, i.e., they fully interfere with each other. To decrease the interference, j introduces some CFS (dashed curve) as shown in Fig. 1(b). Partially overlapping scheme can therefore be achieved at the subcarrier level to reduce the cross interference as depicted in Fig. 1(c). This scheme can be considered for both orthogonal and non-orthogonal waveforms. However, when this concept is utilized in uncoordinated networks, POT will give rise to non-orthogonality among non-cooperative users regardless of what type of waveform is employed in the whole system.

If all users introduce the same amount of CFS at the same time, partially overlapping would not be achieved since the users would still fully overlap each other. In this case, all users will capture the same interference. To overcome this issue, we propose game theoretical partially overlapping filtered multitone (POFMT) technique. As a scheme, filtered multitone (FMT) is utilized due to certain advantages over OFDM such as providing flexibility in spectrum

* Corresponding author.
E-mail addresses: myilmaz@mail.usf.edu (M.H. Yılmaz), kose@usf.edu (S. Köse), chamok@email.sc.edu (N.H. Chamok), alimo@cec.sc.edu (M. Ali), arslan@usf.edu (H. Arslan).

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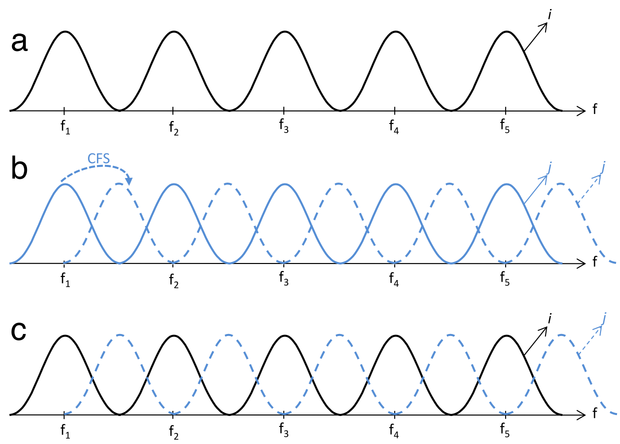


Fig. 1. Users *i* and *j* fully overlap by allocating the same resources at the same time in (a) and (b)(solid curves), respectively. *j* performs CFS to decrease the interference in (b) (dashed curve). *i* and *j* partially overlap in (c).

band usage, not requiring synchronization between transmissions in both ends of a link, and not necessitating the cyclic prefix usage [2]. While game theory (GT) is utilized to determine the frequency shift ratio (FSR) in the frequency domain, it is also used to select the antenna state (radiation pattern) of reconfigurable antenna (RA) to achieve partially overlapping in the space domain. In RAs, the antenna characteristics can be reconfigured electrically or mechanically. In the fixed directions, different radiation patterns can be generated with RAs. Also, they have the capability to work in different operating frequencies [3] which can provide additional degree of freedom in the user equipment. The main motivation to use these antennas in this study is their physical sizes which make them employable in user equipments and capability of generating multiple states. Therefore, in several studies, RAs are utilized to solve various issues such as to increase the system performance [4–6], to increase the diversity gain with coding scheme [7] and degree of freedom in full duplex systems [8], for sub-channel allocation [9]. Multiple-input multiple-output (MIMO) technology can also be used to form multiple states. Due to the challenges such as minimum distance requirement between two antennas, MIMO technology is currently not feasible for mobile devices working in frequencies below 6 GHz. RA therefore becomes a possible future solution for small devices.

1.1. Related work

Various solutions have been proposed in the literature to handle/decrease the interference, and hence, increase the system capacity in uncoordinated networks. One group of studies focuses on the game theoretical resource allocation techniques. Since GT investigates the interactions between two or more nodes and can provide a solution among uncoordinated players (users), it has been utilized extensively in the resource allocation studies. S-modular games are used in [10,11] to carry out the subcarrier allocation and power control, respectively. [12–15] utilized the Stackelberg games, which is based on the leader and followers scenario, to perform resource allocation. the Stackelberg games are also utilized to provide secure communication in physical layer in [16,17].

When there are multiple primary and secondary networks, this game can be utilized . While a cooperative game approach is used in [18], potential games are proposed with resource allocation and load balancing literature in [19,20] and [21], respectively.

Another group of studies focuses on the partially overlapping channels (POC) [22] and [23] to reduce the interference in WiFi networks where there are three non-overlapping channels among the eleven available channels. POC is utilized when there are more than three users in a WiFi network. For example, for four users case, instead of using non-overlapping channels of 1, 6 and 11, channels 1, 4, 7 and 11 are proposed to be used in a partially overlapping manner. Similar approach is introduced in [24] for cellular networks. Also, in [25–27], POC concept is utilized to increase the capacity. In [28], a game theoretical POC is proposed where players are trying to find the least aggregated interference channel. Cooperative games are used among access points in [29] to increase throughput, and hence, to decrease the interference.

1.2. Proposed scheme and contributions

In this study, POFMT with RAs is proposed within a game theoretical framework. To the best of our knowledge, RAs have not been utilized with POT in the literature. In the previous study [30], POFMT concept with only orthogonal waveforms was investigated in the system level without utilizing the RAs. In this study, non-orthogonal waveforms are introduced since they have been offered for 5G and beyond [31]. Additionally, RAs are also utilized to introduce the space domain partially overlapping and to further improve the system performance. A joint FSR and antenna state selection game is proposed. While users search for the FSR to reduce the interference from other users in the environment, they also determine the antenna state where the highest utility can be achieved for the relevant FSR. The existence of Nash equilibrium (NE) in this game is proved with simulations and theoretically with potential games because of having finite improvement property (FIP) which guarantees the NE convergence. As demonstrated with simulation results, POFMT scheme with RAs outperforms OFDM in terms of capacity in the system.

The contributions can be summarized as follows:

1. System level implementation and analysis of POT are introduced in the uncoordinated networks.
2. Orthogonal and non-orthogonal waveforms are investigated under POT concept with various subcarrier spacing and filter roll-off and dispersion parameter values. The results are compared with OFDM.
3. RA is utilized to achieve the partially overlapping in space domain. Joint FSR and antenna state selection is introduced for orthogonal and non-orthogonal waveforms. The results are compared with omni-directional antenna usage.

The remainder of this paper is organized as follows. In Section 2, the system model is introduced where the transmission, channel, and reception models are given within the system model. The problem formulation with potential games is explained in Section 3. The game algorithm with the uniqueness of NE is introduced in Section 4. Section 5 entails numerical results of the proposed approach. Conclusions are drawn in Section 6.

2. System model

We consider an uplink scenario which has multiple small BSs and users. We also consider that the small BSs are randomly distributed in a given area as seen in Fig. 2. It is assumed that each small BS serves to a single user. We also consider that users are equipped with RAs while small BSs use omni-directional antenna. Users are assumed to be able to introduce an intentional frequency shift compared to the other links.

2.1. Transmission model

Similar to [32], the transmitted signal of ith user, $i \in \mathcal{I}$, where $\mathcal{I}$ is the set of users, is given by

$$x_i(t;\varphi) = \sum_{m=-\infty}^{\infty} \sum_{k=0}^{N-1} X_{kmi} g(t-mT) e^{j2\pi k(f_0+\varphi)t}, \tag{1}$$

where N is the total number of subcarriers, X_{kmi} is the modulated symbols on the kth subcarrier of mth symbol, f_0 is the subcarrier spacing, T is the symbol duration, $g(t)$ is the prototype filter, and $\varphi \in [0, f_0]$ is the frequency shift introduced by ith user, which aims to reduce the interference coming from other users with the concept of POFMT.

2.2. Channel model

We consider utilizing an antenna model given in 3GPP standards [33] as an RA. This model captures different large scale attenuations with respect to the νth RA state, $\nu \in \Lambda$ where Λ is the state set of antenna, and is given by

$$A_\nu(\theta) = -\min\left[12\left(\frac{\theta}{\theta_{3dB}}\right)^2, A_{\max}\right]. \tag{2}$$

where θ is the angle between the direction of relevant BS and the boresight direction, $-180° \leqslant \theta \leqslant 180°$, θ_{3dB} is the 3 dB beamwidth of the antenna, and $A_{\max}$ is the maximum attenuation. In this study, we consider fixed boresight directions towards where the antenna can generate the radiation pattern. For instance, when an RA generates three beams, and the angle between beams is 60°, then, the boresight directions become 0°, 60°and −60°. With the consideration of small scale Rayleigh fading, channel impulse response for the νth antenna state is given as $h(t,\tau;\nu) = \sum_{\ell=0}^{L-1} \varrho_\ell(t;\nu)\delta(t-\tau_\ell)$ where ℓ is the path index, L is the total number of paths, τ_ℓ is the delay of the ℓth tap, and $\varrho_\ell(t)$ is the path gains. The channels of ith intended user and jth interfering user are denoted with $h_i(t,\tau;\nu)$ and $h_j(t,\tau;\nu)$.

The received signal strength (RSS) of the user is calculated as $RSS = P_{tx}+G-PL$ where P_{tx} is the transmit power, G is the transmit antenna gain, and PL is the path loss. The transmit antenna gain can be calculated as $G = G_{tx} + A_\nu(\theta)$ where G_{tx} is the constant antenna gain given in [33] and $A_\nu(\theta)$ is the attenuation.

2.3. Reception model

The received signal of small BS of the ith user is expressed as

$$y_i(t;\varphi,\nu) = \int_\tau \int_\varphi H_i(\tau;\varphi,\nu) x_i(t-\tau;\varphi) e^{j2\pi(f_0+\varphi)t} d\varphi d\tau$$
$$+ \sum_{j\in\mathcal{I}, j\neq i} \int_\tau \int_\varphi H_j(\tau;\varphi,\nu) x_j(t-\tau;\varphi) e^{j2\pi(f_0+\varphi)t} d\varphi d\tau$$
$$+ w(t), \tag{3}$$

where j is the interfering users index, $w(t)$ is the additive white Gaussian noise, $H_i(\tau;\varphi,\nu)$ and $H_j(\tau;\varphi,\nu)$ are the Fourier transformations of $h_i(t,\tau;\nu)$ and $h_j(t,\tau;\nu)$, respectively. The location of the users with respect to their corresponding small BS is critical in terms of RA state. If the direction of the interfering users' antenna state ν is not towards the ith small BS, lower interference power is captured when compared to the case where all users are equipped with the omni-directional antenna. Thus, in order to obtain the received symbol, the received signal is projected onto the corresponding received filter as

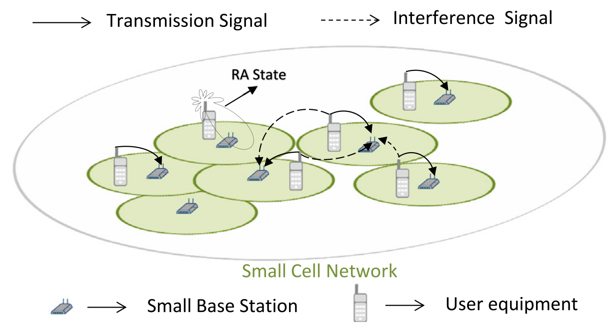


Fig. 2. System view. In uncoordinated network structure, the system has multiple small BSs with a single user. Also, each user has RA which can form a state in one direction.

$$\tilde{X}_{lni}(\varphi,\nu) = \left\langle y_i(t;\varphi,\nu), g(t-nT)e^{j2\pi l(f_0+\varphi_i)t}\right\rangle$$
$$= \int_t r_i(t,\tau;\varphi,\nu) g(t-nT) e^{-j2\pi l(f_0+\varphi_i)t} dt$$
$$+ \sum_{\substack{j\in\mathcal{I},\\ j\neq i}} \sum_{n=-\infty}^{\infty} \sum_{l=0}^{N-1} \int_t r_j(t,\tau;\varphi,\nu) g(t-nT)$$
$$\times\ e^{-j2\pi l(f_0+\varphi_i)t} dt + w(t), \tag{4}$$

where $r_i(t,\tau;\varphi,\nu) = \int_\tau \int_\varphi H_i(\tau;\varphi,\nu) x_i(t-\tau;\varphi) e^{j2\pi(f_0+\varphi)t} d\varphi d\tau$. As it can be seen in (4), small BS employs the same frequency shift of ith user in order to receive the symbol properly. Otherwise, the transmit pulse shape will be captured partially, which can degrade the performance tremendously in terms of capacity. Alternatively, the same situation provides significant advantage against the interfering users that introduce different amount of frequency shift φ_j. Since the interfering signal is captured based on φ_j, the signal-to-interference-plus-noise ratio (SINR) of the ith user is increased significantly. Therefore, SINR of small BS of the ith user can be expressed as

$$SINR_i = \frac{P_i(\varphi_i,\nu_i)}{P_j(\varphi_i,\nu_j) + w(t)}. \tag{5}$$

In (5),

$$P_i(\varphi_i,\nu_i) = \mathbb{E}\left[\left|\int_t r_i(t,\tau;\varphi,\nu) g(t-nT) \times e^{-j2\pi l(f_0+\varphi_i)t} dt\right|^2\right], \tag{6}$$

and

$$P_j(\varphi_i,\nu_j) = \sum_{\substack{j\in\mathcal{I},\\ j\neq i}} \sum_{n=-\infty}^{\infty} \sum_{l=0}^{N-1} \mathbb{E}\left[\left|\int_t r_j(t,\tau;\varphi,\nu)\right.\right.$$
$$\left.\left.\times\ g(t-nT) e^{-j2\pi l(f_0+\varphi_i)t} dt\right|^2\right] \tag{7}$$

3. Problem formulation

We consider joint FSR and antenna state selection among users in uncoordinated networks within the game theoretical framework. GT is a mathematical tool which provides a solution method in an uncoordinated environment. It investigates the interactions between two or more agents. Since it relies on the strategic thinking, for uncoordinated networks, GT can be exploited by the users which are defined as players and denoted with i. The strategies are given as the FSR and antenna state selection and can be denoted with $s_i = \{\varphi_i, \nu_i\}$, $s_i \in S_i$ where S_i is the strategy set of player i.

Finally, the utility function is defined as the capacity of the player i and expressed as

$$U_i(\varphi_i, \nu_i) = \log_2(1 + SINR_i). \tag{8}$$

Thus, the game $\mathcal{G}$ can be described with three components as $\mathcal{G} = \langle \mathcal{I}, S_i, U_i \rangle$. So, the NE can be formulated as

$$U_i(s_i^*, s_{-i}^*) \geq U_i(s_i, s_{-i}^*) \quad \forall i \in \mathcal{I}, \forall s_i, s_{-i} \in S \tag{9}$$

where s_{-i} represents the strategies for all players except i, '*' shows the equilibrium point, and S is the strategy profile of all players.

3.1. Potential game formulation

A game is considered as potential game when a function called potential function exists. This function reflects the change of one player's utility function with respect to its unilateral deviation. [34] defines a game as an ordinal potential game as in the following.

Definition 1. A game $\mathcal{G}$ is said to be an ordinal potential game if it admits an ordinal potential. A function V is an ordinal potential for $\mathcal{G}$ if, for all, $i \in \mathcal{I}$

$$U_i(s_i', s_{-i}) - U_i(s_i, s_{-i}) > 0 \text{ iff } V(s_i', s_{-i}) - V(s_i, s_{-i}) > 0 \quad \forall s_i, s_i' \in S_i. \tag{10}$$

where s_i' indicate the change in the strategy of player i.

Ordinal potential games guarantee that there is at least one pure NE. In this study, the potential function is defined as follows [32]

$$V(S) = \log_2\left(\sum_{b\in\mathcal{I}} \mathbb{E}\left[\left|\int_t r_b(t, \tau; \varphi, \nu) g(t - nT) \times e^{-j2\pi l(f_0+\varphi_b)t} \mathrm{d}t\right|^2\right] + w_0\right) \tag{11}$$

where $S = (\{\varphi_i, \nu_i\}, \{\varphi_{-i}, \nu_{-i}\})$.

3.2. Convergence to Nash equilibrium

Every finite potential game has a FIP [35]. A path in strategy set S is defined as a sequence of $\gamma = \{s_0, s_1, s_2, \ldots\}$. For a finite path, there are initial and terminal points of γ as s_0 and the last element and the game is played sequentially. In our scheme, players play with their best response correspondences, i.e., no player would select the strategy which will provide smaller utility, and hence, smaller potential function. Therefore, if it is considered that the newly selected and previous strategies are s_1 and s_0, respectively, the relation between these strategies in terms of the utility will be $U_i(s_1) > U_i(s_0)$, when there is a profit in terms of having higher utility for player to change the strategy. Hence, it is considered for γ to have an improvement path. This property will have an effect on the potential function and the relation between the potential functions will become $V(s_0) < V(s_1) < \cdots$. This can be explained mathematically as follows.

After separating the ith player's received signal power, the potential function $V(\{\varphi_i, \nu_i\}, \{\varphi_{-i}, \nu_{-i}\})$ which is defined in (11) can be expressed as

$$\begin{aligned} V(\{\varphi_i, \nu_i\}, \{\varphi_{-i}, \nu_{-i}\}) &= \log_2\Bigg(\sum_{\substack{b\in\mathcal{I},\\ b\neq i}} \mathbb{E}\left[\left|\int_t r_b(t, \tau; \varphi, \nu) g(t - nT) e^{-j2\pi l(f_0+\varphi_b)t} \mathrm{d}t\right|^2\right] \\ &\quad + \mathbb{E}\left[\left|\int_t r_i(t, \tau; \varphi, \nu) g(t - nT) e^{-j2\pi l(f_0+\varphi_i)t} \mathrm{d}t\right|^2\right] + w_0\Bigg), \end{aligned} \tag{12}$$

When player i changes its strategy from $\{\varphi_i, \nu_i\}$ to $\{\varphi_i', \nu_i'\}$, the potential function $V(\{\varphi_i', \nu_i'\}, \{\varphi_{-i}, \nu_{-i}\})$ would be

$$\begin{aligned} V(\{\varphi_i', \nu_i'\}, \{\varphi_{-i}, \nu_{-i}\}) &= \log_2\Bigg(\sum_{\substack{b\in\mathcal{I},\\ b\neq i}} \mathbb{E}\left[\left|\int_t r_b(t, \tau; \varphi, \nu) g(t - nT) e^{-j2\pi l(f_0+\varphi_b)t} \mathrm{d}t\right|^2\right] \\ &\quad + \mathbb{E}\left[\left|\int_t r_i(t, \tau; \varphi, \nu) g(t - nT) e^{-j2\pi l(f_0+\varphi_i)t} \mathrm{d}t\right|^2\right]' + w_0\Bigg), \end{aligned} \tag{13}$$

Since the strategies of all users except i remain unchanged, the difference between potential functions, i.e., the difference obtained from the subtraction of (12) from (13), would be bigger than zero and is expressed as

$$V(\{a_i', \nu_i'\}, \{a_{-i}, \nu_{-i}\}) - V(\{a_i, \nu_i\}, \{a_{-i}, \nu_{-i}\}) > 0 \tag{14}$$

Eq. (14) shows that our scheme is an ordinal potential game. So, the NE existence is proved. This also indicates that our scheme has the FIP, and, as shown in Figs. 7(b) and 8(b), it converges to NE.

4. FSR and antenna state selection scheme

In this scheme, the players compete to maximize their capacity given in (8) by selecting the best FSR and antenna state. A player first chooses the FSR from the set of $\varphi = [0, f_0]$ when transmitting the signal defining in (1). By introducing the shift, the player looks for a position where it captures the least interference. When the transmitted signal $x_i(t; \varphi_i)$ is received by the small BS in a given antenna state, the received signal $y_i(t; \varphi, \nu)$ is projected onto the corresponding filter to obtain the received symbol $\tilde{X}_{lni}(\varphi, \nu)$ given in (4). Interference signals coming from other players are also obtained from the corresponding small BS with its receiver filter in a same way. Then the small BS computes the SINR and utility defining in (5) and (8), respectively, and sends the payoff report to the player. The small BS performs this scheme for every antenna state with all FSRs. Based on the payoff reports, the player selects the one which provides the highest utility. Every player follows the same procedures. To reach NE, sequential game algorithm is utilized. In this algorithm, each player plays the game in a round robin manner iteratively until the NE is reached. The detailed explanation of this game can be seen in Table 1.

4.1. Uniqueness of Nash equilibrium

As mentioned in Section 3.2, every finite potential game has a FIP [35]. In our scheme, players play with their best response correspondences. Therefore, the relation in utility functions which have the newly selected strategy s_1 and previous strategy s_0 will become $U_i(s_1) > U_i(s_0)$.

In this study, we consider joint FSR and antenna state selection scheme in uncoordinated networks. Each player play with their best responses when they select the FSR and antenna state. Every player adheres the sequential game algorithm. In this game, each player plays in a round robin manner, i.e., each player waits its turn to play. As explained in Table 1, a player first introduces an FSR and searches for the best antenna state for this corresponding FSR. When the player searches through all the FSRs, it picks the best FSR and antenna state which provide the highest capacity gain. Then, the next player (and all others) follows the same algorithm until the NE is reached. By keeping playing with this algorithm, the system will converge to a unique NE. Since the players play with their best response correspondences, it can be guaranteed that the best equilibrium is reached with the this algorithm and the game converges to a unique NE.

Table 1
FSR and Antenna State Selection Scheme.

#	Sequential Game Algorithm
1	Assign the same FSR and antenna state to each player
2	*for* iterations $= \{1,2,\ldots\}$
3	*for* $i = \{1,2,\ldots\}$
4	*for* $\varphi = \{\varphi_{i,1}, \varphi_{i,2}, \ldots\}$
5	introduce an FSR
6	*for* $\Lambda = \{\nu_{i,1}, \nu_{i,2}, \ldots\}$
7	select an antenna state of player i
8	calculate $\mathbb{E}\left[\left\| \int_t r_i(t,\tau;\varphi,\nu) g(t-nT) \times e^{-\mathrm{j}2\pi l(f_0+\varphi_i)t} \mathrm{d}t \right\|^2\right]$ (player i's received signal power)
9	calculate $\sum_{j\in\mathcal{I}, j\neq i} \sum_{n=-\infty}^{\infty} \sum_{l=0}^{N-1} \mathbb{E}\left[\left\| \int_t r_j(t,\tau;\varphi,\nu) \times g(t-nT) e^{-\mathrm{j}2\pi l(f_0+\varphi_i)t} \mathrm{d}t \right\|^2\right]$ (interfering players' received signal power)
10	calculate $U_i(\varphi,\Lambda)$
11	*end*
12	*end*
13	pick the highest payoff from the set of $U_i(\varphi,\Lambda)$ **if** the payoff selected in previous iteration is the highest one, don't change the strategy
14	update the antenna state and FSR indexes for player i
15	*end*
16	*end*

5. Performance evaluation

In this section, performance results are provided to show the performance of the system with the POFMT in uncoordinated networks. The results can be categorized into two groups: (1) To demonstrate the advantages of POT concept in frequency domain over OFDM, each user is equipped with omni-directional antenna. The performance results with omni-directional antenna is shown in Figs. 3–6. (2) Joint partially overlapping in frequency and space domain performance results are depicted in Figs. 7–10. Here, we do not consider mobility for users. All of the simulation parameters are listed in Table 2 where the parameter values for RA and the path loss model are taken from [36] and [33], respectively. The path loss model employed in this study is $PL(\text{dB}) = max(15.3 + 37.6\log_{10}R, 38.46 + 20\log_{10}R) + 0.7d_{2D} + qL_{iw} + L_{ow}$, where R is the distance between transmitter and receiver, d_{2D} is the total distance inside the houses, q is the number of walls separating houses between transmitter and receiver, L_{iw} is the penetration loss of wall separating houses, and L_{ow} is the penetration loss of outdoor walls of houses. As a filter, to obtain non-orthogonal waveform, we use the Gaussian filter (GF), which is distributed in both time and frequency domain in an optimum way and defined as [1]

$$h_{GF}(t) = (2\rho)^{1/4} e^{-\pi\rho t^2} \tag{15}$$

where ρ is the dispersion adjustment parameter of the pulse in time and frequency.

Table 2
Simulation Parameters.

Simulation Parameters	Parameter Value
Power of user equipment (UE)	23 dBm
Number of subcarriers	16
Maximum antenna attenuation	20 dBm
Maximum antenna gain	12 dBi
Antenna beamwidth	120
Modulation Order	QPSK
d_{2D}	20 m
q	1
L_{iw}	5 dB
L_{ow}	20 dB

To attain orthogonal signal, we utilize a band limited root raised cosine filter (RRCF) with a roll-off factor β. The response of the filter is

$$h_{RRCF}(t) = \begin{cases} \left(1-\beta+4\dfrac{\beta}{\pi}\right), & t = 0 \\ \dfrac{\beta}{\sqrt{2}}\left[\left(1+\dfrac{2}{\pi}\right)\sin\left(\dfrac{\pi}{4\beta}\right)+\left(1-\dfrac{2}{\pi}\right)\cos\left(\dfrac{\pi}{4\beta}\right)\right], & t = \pm\dfrac{T}{4\beta} \\ \dfrac{\sin\left[\pi\frac{t}{T}(1-\beta)\right]+4\beta\frac{t}{T}\cos\left[\pi\frac{t}{T}(1+\beta)\right]}{\pi\frac{t}{T}\left[1-\left(4\beta\frac{t}{T}\right)^2\right]}. \end{cases} \tag{16}$$

We consider that all transceiver pairs use the same filter for a given scenario.

5.1. POFMT for various filter roll-off and dispersion parameter values

SINR distributions of the orthogonal waveform with various filter roll-off values and OFDM signal are shown in Fig. 3. Orthogonal waveform is labeled as RRCF in the legend. It is noted that for OFDM, it is considered that all available resources are utilized by all in fully overlapping manner throughout the paper. As seen from Fig. 3, when β value increases, the SINR values of RRCF decrease. This is basically because the higher β values spread over the frequency more. Although there is a considerable amount of the subcarrier spacing (i.e., 1.5), the gap in between two consecutive subcarriers diminishes. The intended users therefore can capture more interference from other users. As compared to OFDM, POFMT with RRCF provides higher SINR gain.

In Fig. 4, the comparison of the SINR distributions of the non-orthogonal waveform and OFDM is shown. Non-orthogonal waveform is labeled as GF in the legend. As indicated in Fig. 4, when the value of ρ decreases, the system can achieve higher SINR gain. The aim in this analysis is to show the effect of partially overlapping with various ρ values when the subcarrier spacing is equal to 1, i.e., when no intentional gap is introduced between subcarriers. If $\rho = 1$, the SINR distribution of GF would be very close to the SINR distribution of OFDM. The difference between these two distributions is negligible. On the other hand, when $\rho = 0.2$, a high amount of gain can be achieved. As indicated in [1], when the value of ρ decreases, the subcarriers shrink in frequency, which leads to increasing gap in between subcarriers. While lower ρ values provide less interference on other players, they increase the self-interference. This causes higher inter-symbol interference on each player. So, this trade-off needs to be taken into account in the system design.

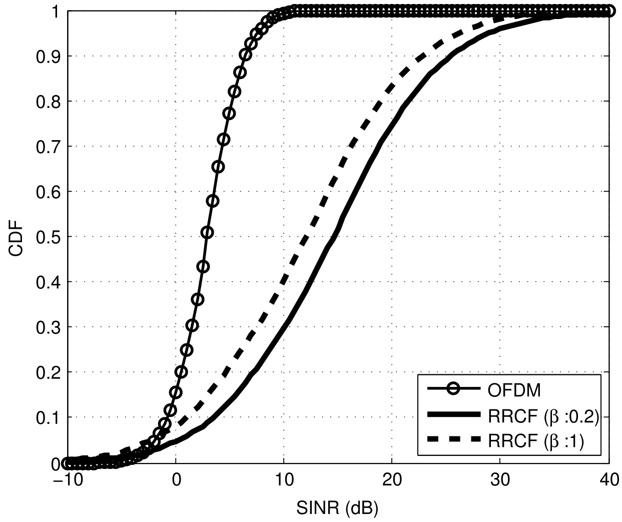


Fig. 3. CDF of the SINR values achieved in orthogonal waveforms with RRC filter for various the roll-off values. When subcarrier spacing is constant, increasing the filter roll-off decreases the SINR gain.

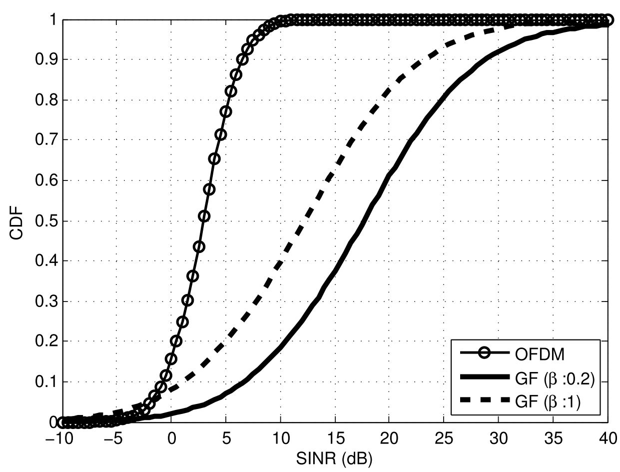


Fig. 4. CDF of the SINR values achieved in non-orthogonal waveforms with Gaussian filter for various the roll-off values. When subcarrier spacing is constant, increasing the filter control parameter decreases the SINR gain in non-orthogonal waveforms with Gaussian filter.

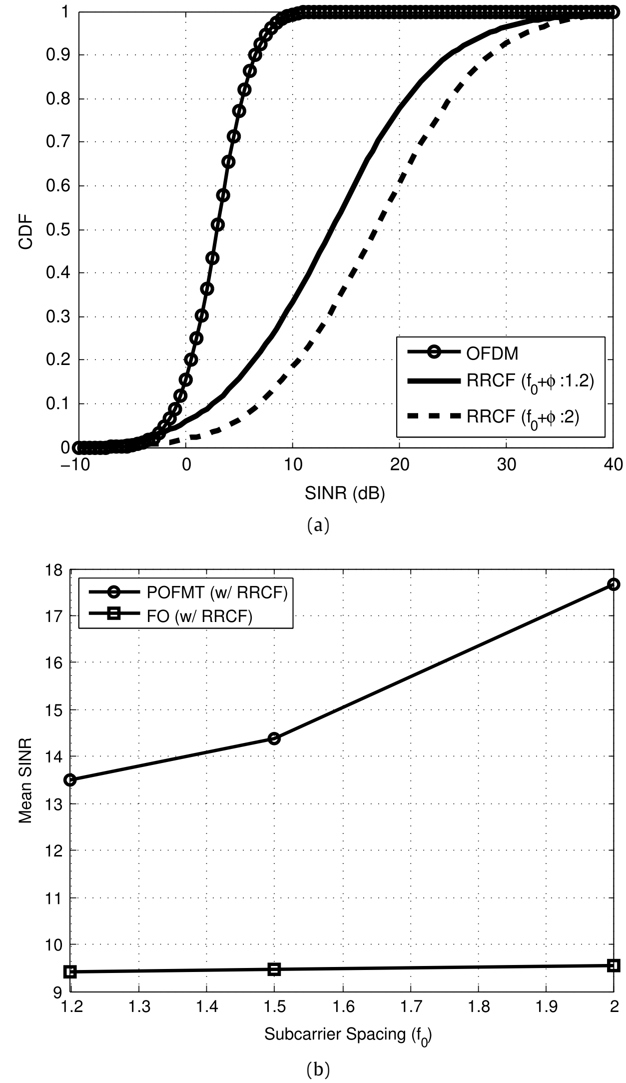
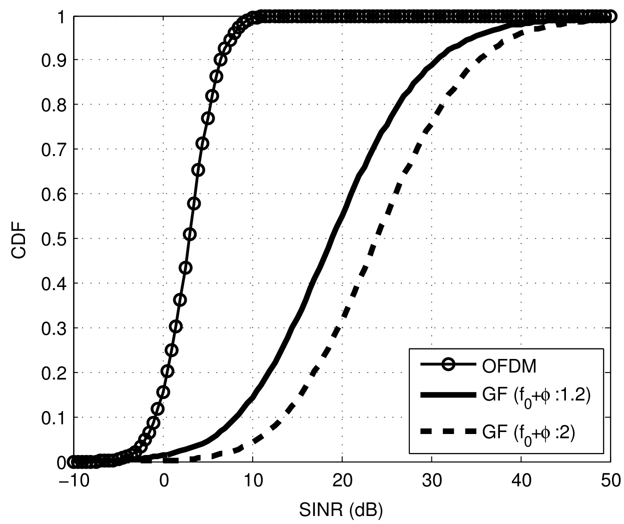


Fig. 5. CDF of the SINR values achieved in orthogonal waveforms with RRC filter for various the subcarrier spacing values. (a) When filter roll-off is constant, increasing the subcarrier spacing increases the SINR gain. (b) When the subcarrier spacing increases, i.e., in other words, when the bandwidth usage rises, mean SINR level also increases.

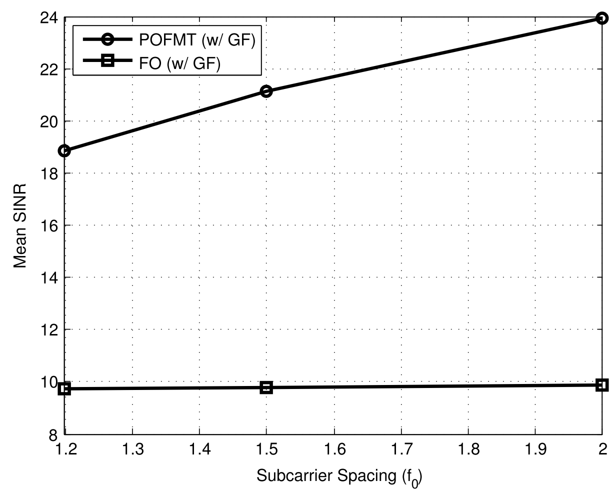
5.2. POFMT for various subcarrier spacing

Orthogonal waveforms have an important feature, which is to keep the signal energy same before and after passing through the receiver filter [1]. This is advantageous for the signal transmitted from the legitimate transmitter. However, if the signal is coming from the interfering source, it becomes disadvantageous. Therefore, to reduce the energy of the signal taken from the interfering user, subcarrier spacing is utilized with partially overlapping technique. Fig. 5(a) shows the effect of POFMT in terms of the interference mitigation in orthogonal waveforms for various subcarrier spacing values. As seen in this figure, when the subcarrier spacing increases, the system gives higher performance gain in terms of SINR if the filter roll-off value is constant. It is basically because the higher subcarrier spacing leaves more gap between subcarriers, and hence, the intended user captures less interference from the other users who are not fully overlapped. Alternatively, since there is no spacing between subcarriers in OFDM scheme, it gives the least SINR gain.

When a system is designed, it would be desirable to use high subcarrier spacing with the expense of higher bandwidth occupation since increasing subcarrier spacing decreases the interference. Fig. 5(b) shows the bandwidth usage in terms of mean SINR level for orthogonal waveforms. As seen in the figure, x-axis is labeled as subcarrier spacing which is multiplied with the bandwidth of individual subcarrier to find how much bandwidth is used. For instance, if a bandwidth of a subcarrier is 15 kHz as being in 3GPP standards and there are 16 subcarriers, total bandwidth usage is said to be 240 kHz and 360 kHz for subcarrier spacings of 1 and 1.5, respectively, without considering the guard bands. As seen in Fig. 5(b), when more bandwidth is allocated in POT case, mean SINR gain increases in both schemes. If the same bandwidth as occupied with OFDM scheme is desired to be used, some subcarriers need to be turned off. In this case, there would be a slight loss in bandwidth usage. This introduces the tradeoff within POFMT technique. One will either use a complex interference reduction method in receiver without losing from the bandwidth [1] or select the significant interference mitigation with slightly higher bandwidth usage.



(a)



(b)

Fig. 6. CDF of the SINR values achieved in non-orthogonal waveforms with Gaussian filter for various the subcarrier spacing values. (a) When filter control parameter is constant, increasing the subcarrier spacing increases the SINR gain. (b) When the subcarrier spacing increases, i.e., in other words, when the bandwidth usage rises, mean SINR level also increases.

Similarly, in Fig. 6(a), the SINR distributions of OFDM and non-orthogonal schemes with various subcarrier spacing values are given while the filter control parameter is constant. Similar to orthogonal scheme, SINR gains increase with the higher subcarrier spacing values. Significant gain can be achieved when $f_0 = 2$. Fig. 6(b) depicts the mean SINR variation for different subcarrier spacing values. This figure also proves the higher performance gain achievement depending on the higher f_0 values.

For fully overlapping (FO) case, bandwidth increment does not make any difference in system gain because the gaps are not utilized by the players. Moreover, more bandwidth is occupied unnecessarily. These figures also indicate the benefit of POFMT technique over conventional FO case. For the same amount of bandwidth usage, proposed technique outperforms in terms of SINR.

5.3. POFMT with reconfigurable antenna

In this study, POFMT is investigated in both frequency and space domains. To exploit the space domain, RAs are utilized within the partially overlapping concept. In Figs. 7 and 8, the advantages of RA over conventional omni-directional antenna are shown when POFMT in frequency domain is performed with both antenna types. We also compare the algorithm with our RA to another RA named as planar inverted-F antenna (PIFA) which is traditionally used in handheld devices [37,38]. Figs. 7a and 8a show the distribution of the capacity values of orthogonal and non-orthogonal schemes, respectively. Since RAs can form a state in fixed and different directions, it can help to decrease the interference induced on intended players. At the same time, if the serving BS is in the boresight direction, RA can provide higher antenna gains. Therefore, when joint partially overlapping in frequency and space domains is performed, the system performance can be improved further in terms of capacity.

As given in Table 2, the antenna we utilized has 120° beamwidth while the PIFA has 150° beamwidth. In general, when the beamwidth increases, the antenna gain decreases. So, the maximum gain in utilized antenna and PIFA is 12 dBi and 3 dBi, respectively. On the other hand, since, based on the LTE standards, we assumed that the antenna gain for omni-directional antenna is 5 dBi, the capacity results for both omni-directional and PIFA overlap. While the PIFA causes less interference from its sidelobes and backlobes, since the antenna gain in the main beam is lower than the omni-directional antenna, the gain attained from the interference reduction is compensated with the loss obtained from the lower antenna gain.

It is important to note that proposed algorithm provides slightly weaker performance in lower capacity values. Since an RA can form beams in fixed directions, beams can only be propagated within certain angles. The antenna we utilized can direct beams from 60°, 0° and −60°, i.e., only the angles from 120° to −120° can be covered by RA beams. RA would have sidelobes in all the other directions (angles). Hence, the serving BS could be directed towards the sidelobes of the RA of its user. In this case, the low capacity gains are achieved.

Finally, Figs. 7b and 8b show the mean capacity values in each iteration of the algorithm in orthogonal and non-orthogonal schemes, respectively. NE existence can be proved with these figures. The increment from omni-directional antenna and PIFA usage cases to RA usage can be clearly seen in these figures. When the RAs are used with partially overlapping concept, the system capacity can be increased further. These results show that the POFMT with RAs is the candidate solution against the significant interference problem in the uncoordinated networks.

5.4. Price of anarchy

Price of anarchy (PoA) shows the effectiveness of the algorithm against its optimum counterpart. It can be defined as the ratio of the worst equilibrium to optimum value of the system [39]. The aim is to measure how close the derived equilibrium of the proposed game theoretical algorithm to optimum solution. The equilibrium has already been defined in (9) for the utility function given in (8). The objective function can be expressed as the maximization of the sum capacity of the system as follows,

$$\max_{\varphi_i^{v_i}} \sum_{i\in\mathcal{I}} \log_2(1+SINR_i) \tag{17}$$

subject to:

$$\varphi_i \in \{0, f_0\}, \qquad \sum_{i\in\mathcal{I}} \varphi_i \leqslant f_0 \tag{18}$$

Thus, PoA can be defined as

$$PoA = \frac{\Phi_{Equ}}{\Phi_{Opt}} \tag{19}$$

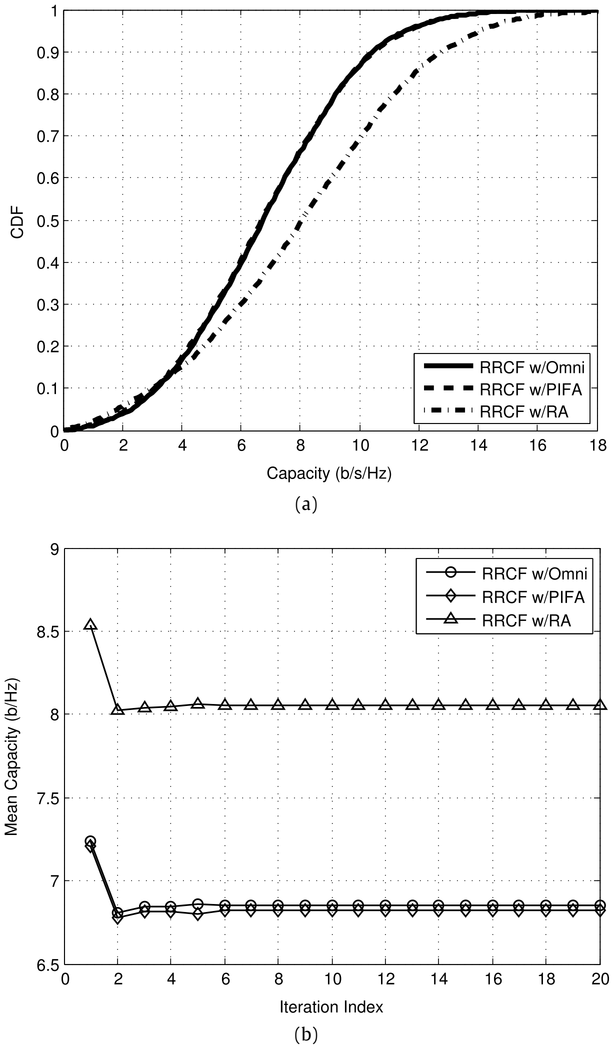


Fig. 7. Mean capacity values in each iteration for orthogonal waveforms with RRC filter. (a) When RAs are used within POT concept, the system gain can be increased further in orthogonal schemes. (b) The system with orthogonal scheme and RA can reach the NE.

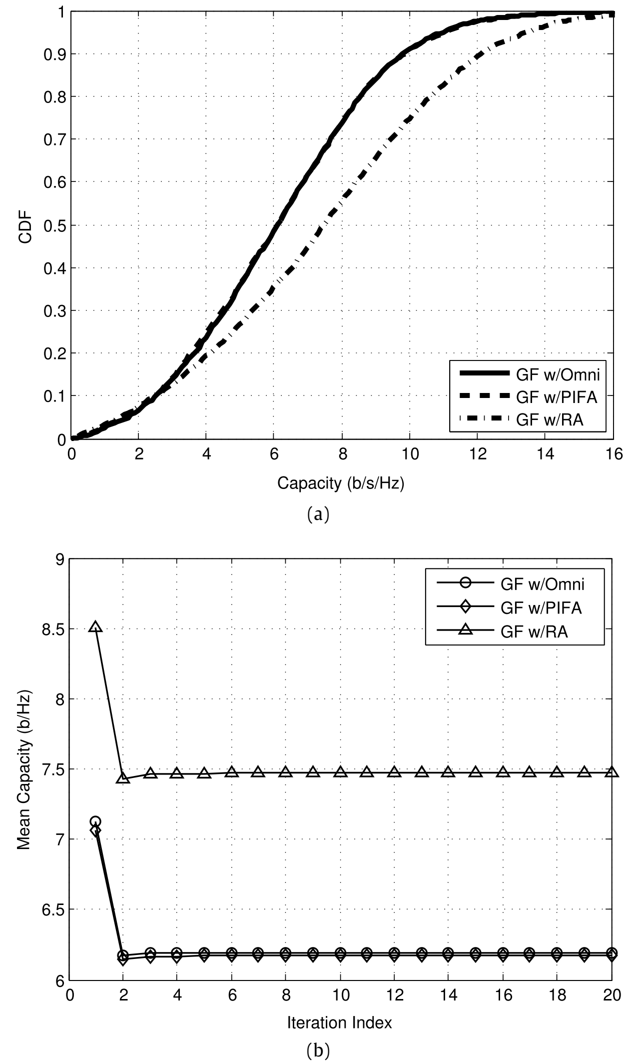


Fig. 8. Mean capacity values in each iteration for non-orthogonal waveforms with Gaussian filter. (a) When RAs are used within POT concept, the system gain can be increased further in non-orthogonal schemes. (b) The system with non-orthogonal scheme and RA can reach the NE.

where Φ_{Equ} and Φ_{Opt} show the worst case equilibrium and optimum points, respectively.

Figs. 9 and 10 show the PoA histograms for both orthogonal and non-orthogonal waveforms, respectively. To obtain PoA, it is considered that the system has two small BSs with one user in each. In order to find the optimum value, exhaustive search algorithm is utilized in this study. Totally, 1000 realizations are performed. In every realizations, 10 iterations are performed for game theoretical algorithm, and the equilibrium is obtained in each realization where the equilibrium and optimum values are computed. As indicated in Figs. 9 and 10, PoA values become bigger than 0.5 in most of the time.

6. Conclusion

In orthogonal frequency-division multiple accessing technique, resources are allocated accordingly to manage the interference between users when the whole network is controlled by a central unit. However, in uncoordinated networks, it is impossible to establish coordination among users, which leads to increasing interference in the shared environment. To decrease the interference in uncoordinated networks, POFMT was proposed within game

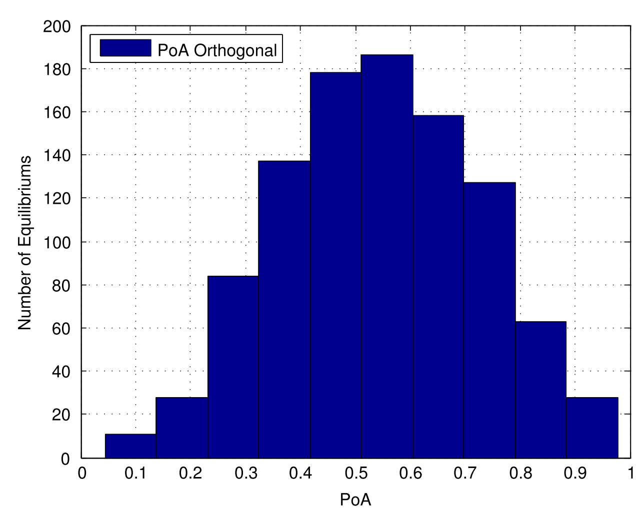


Fig. 9. The efficiency of the proposed algorithm for the orthogonal waveforms based on PoA analysis.

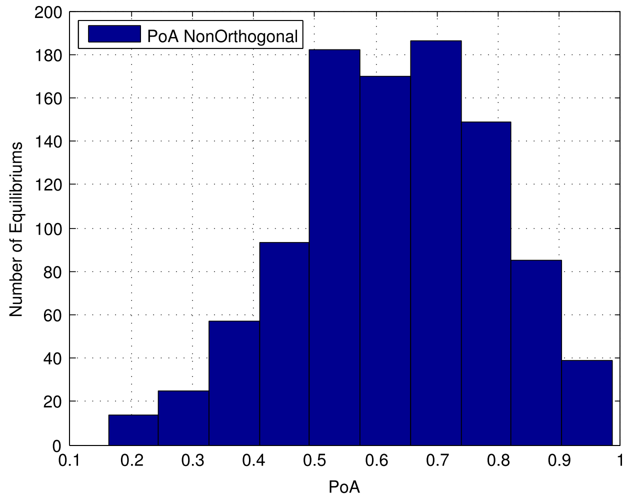


Fig. 10. The efficiency of the proposed algorithm for the non-orthogonal waveforms based on PoA analysis.

theoretical framework in this study. As players, users introduced joint partially overlapping in frequency and space domains. While frequency domain partially overlapping was fulfilled by giving intentional CFS, RAs were utilized to introduce space domain partially overlapping. The system was evaluated with various subcarrier spacing and filter control parameter values to show the advantages of partially overlapping in only frequency domain. It is found that increasing subcarrier spacing decreases the interference in the system. Also, when the filter control parameter decreases, the system gain increases. With the utilization of RAs, the system performance is shown to increase further. By utilizing the partially overlapping concept, a new network design can be considered in uncoordinated networks.

There are several extensions in this topic beyond what is presented in this study. One possible extension is the time domain synchronization when there are multiple users served by one BS, i.e., there will be multiple small BSs with multiple users. In this type of scenario, users have to satisfy the time synchronization with their single BS. Another extension can be given with RA. In this study, it is assumed that only uncoordinated users are equipped with RAs. In cognitive heterogeneous networks, the scenario where primary users, secondary and primary BSs are all equipped with smart antenna, i.e., either with RA or MIMO, or any combination of them in the network needs further investigation.

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Mustafa Harun Yılmaz was born in Bursa, Turkey. He received his B.Sc. degree from the department of electronic and computer teaching from Gazi University in Ankara, Turkey in 2007 and M.Sc. degree from Southern University and A&M College in Baton Rouge, Louisiana in 2010.

He is currently working towards the Ph.D. degree as a Graduate Research Assistant in the department of Electrical Engineering from University of South Florida in Tampa, Florida. His research interests are interference coordination, interference management, resource allocation in OFDMA systems, signal identification and physical layer security.

Selçuk Köse received the B.S. degree in electrical and electronics engineering from Bilkent University, Ankara, Turkey, in 2006, and the M.S. and Ph.D. degrees in electrical engineering from the University of Rochester, Rochester, NY, respectively, in 2008 and 2012.

He is currently an Assistant Professor at the Department of Electrical Engineering, University of South Florida, Tampa, FL. He was a part-time engineer at the Scientific and Technological Research Council (TUBITAK), Ankara, Turkey in 2006. He was with the Central Technology and Special Circuits Team in the enterprise microprocessor division of Intel Corporation, Santa Clara, CA in 2007 and 2008. He was with the RF, Analog, and Sensor Group, Freescale Semiconductor, Tempe, AZ in 2010. His current research interests include the analysis and design of high performance integrated circuits, on-chip dc–dc voltage converters, and interconnect related issues with specific emphasis on the design, analysis, and management of on-chip power delivery networks, 3-D integration, and hardware security.

Dr. Kose received the National Science Foundation CAREER Award in 2014, University of South Florida College of Engineering Outstanding Junior Research Achievement Award in 2014, and Cisco Research Award in 2015. He is currently serving on the editorial boards of the Journal of Circuits, Systems, and Computers and Microelectronics Journal. He is a member of the technical program committee of a number of conferences.

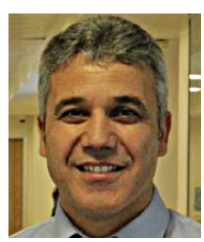
Nowrin Hasan Chamok received the B.Sc. degree in electrical engineering from the Bangladesh University of Engineering and Technology, Dhaka, Bangladesh, in 2009, and the M.E. degree in electrical engineering from the University of South Carolina, Columbia, SC, USA, in 2014.

He has been a Graduate Research Assistant with the Microwave Engineering Laboratory, Department of Electrical Engineering, University of South Carolina, since 2011. He has authored or co-authored several journal and conference papers. His current research interests include the fundamental research of broadband multifunctional metamaterial, pattern reconfigurable array design for handheld terminals, and body-worn antenna design.

Mohammod Ali received the B.Sc. degree in electrical and electronic engineering from the Bangladesh University of Engineering and Technology, Dhaka, Bangladesh, in 1987, and the M.A.Sc. and Ph.D. degrees in electrical engineering from the University of Victoria, Victoria, BC, Canada, in 1994 and 1997, respectively.

From 1998 to 2001, he was with Ericsson Inc., Research Triangle Park, NC, USA. Since 2001, he has been with the Department of Electrical Engineering, University of South Carolina, Columbia, SC, USA, where he is currently a Professor. He was a Visiting Research Scientist with the Motorola Corporate EME Research Laboratory, Plantation, FL, USA, in 2004. More recently, he was a Summer Faculty Fellow with the Air Force Research Laboratory (AFRL), Wright-Patterson Air Force Base (WPAFB), Dayton, OH, USA, in 2010 and 2011. He spent a year on sabbatical leave with AFRL, WPAFB, from 2013 to 2014. He has authored or coauthored over 160 publications and holds eight U.S. patents. His specific research interests include in the fields of new active device (MEMS, GAN devices, varactors, and VO2) integration with antennas and phase shifting structures; novel materials (structural composites, fabrics, liquid metal) and their exploitation to design antennas, dc bias networks, and power supply routes; 3-D printing of metamaterials for antennas as well as radomes; RF heating or energy focusing using both low and high frequency techniques; the application of magnetic materials into RF structures for antennas, co-site interference reduction, and metamaterials; and beamforming/MIMO in the handheld and base stations for 5G and beyond. His current research interests include conformal antennas, reconfigurable antennas, broadband structural load bearing antennas, metamaterials and metasurfaces, aircraft antennas and their coupling reduction, MIMO antennas, and wireless power transfer and wireless sensors.

Dr. Ali was a recipient of the 2003 National Science Foundation Faculty Career Award. He was also a recipient of the College of Engineering and Computing Young Investigator Award, the Research Progress Award, and the Samuel Litman Distinguished Professor Award from the University of South Carolina in 2006, 2009, and 2011, respectively. He was the Technical Program Co-Chair of the IEEE Antennas and Propagation Society's International Symposium in Charleston, SC, USA, in 2009. He was an Associate Editor of the *IEEE Antennas and Wireless Propagation Letters* from 2008 to 2013. He serves on the Technical Program Committee of the IEEE Antennas and Propagation Society's (APS) International Symposium. He has organized specials session for the IEEE IWAT conference and the IEEE APS Symposia in the past. He has also served on the Technical Program Committee of the IEEE SmartGrid Conference, the European Association for Antennas and Propagation Conference, and the APMC Conference. He serves on the Editorial Boards of the *International Journal of RF and Microwave Computer-Aided Engineering and the International Journal of Antennas and Propagation* (Hindawi).



Hüseyin Arslan received his B.S. degree from Middle East Technical University (METU), Ankara, Turkey in 1992; M.S. and Ph.D. degrees in 1994 and 1998 from Southern Methodist University (SMU), Dallas, Tx. USA. From January 1998 to August 2002, he was with the research group of Ericsson Inc., NC, USA, where he was involved with several project related to 2G and 3G wireless communication systems. Since August 2002, he has been with the Electrical Engineering Dept. of University of South Florida, Tampa, FL, USA, where he is a Professor. In December 2013, he joined Istanbul Medipol University to found the Engineering College, where he has been working as the Dean of the School of Engineering and Natural Sciences. He has also been serving as the director of the Graduate School of Electrical, Electronics And Cyber Systems in the same university. In addition, he has worked as part time consultant for various companies and institutions including Anritsu Company, Savronik Inc., and The Scientific and Technological Research Council of Turkey.

Dr. Arslans research interests are related to advanced signal processing techniques at the physical and medium access layers, with cross-layer design for networking adaptivity and Quality of Service (QoS) control. He is interested in many forms of wireless technologies including cellular radio, wireless PAN/LAN/MANs, fixed wireless access, aeronautical networks, underwater networks, in vivo networks, and wireless sensors networks. His current research interests are on physical layer security, signal intelligence, cognitive radio, small cells, powerline communications, smart grid, UWB, multi-carrier wireless technologies, dynamic spectrum access, co-existence issues on heterogeneous networks, aeronautical (high altitude platform) communications, in vivo channel modeling and system design, and underwater acoustic communications. He has served as Technical Program Committee Chair, Technical Program Committee Member, Session and Symposium Organizer, and Workshop Chair in several IEEE conferences. He is currently a member of the editorial board for the IEEE Transactions on Cognitive Communications and Networking, the Physical Communication Journal (Elsevier), and the Journal of Electrical and Computer Engineering (Hindawi). He has also served for eight years as a member of the editorial board for the Wiley Wireless Communication and Mobile Computing Journal.