A Cooperative Scheme for the Coexistence of the LTE and WiFi systems

Kareem M. Metwaly
Eng. Mathematics and Physics Dept.
Alexandria University
Alexandria, Egypt
Email: kmetwaly@alexu.edu.eg

Karim G. Seddik
Electronics and Communications Eng. Dept.
American University in Cairo
AUC Avenue, New Cairo 11835, Egypt
Email: kseddik@aucegypt.edu

Mustafa Y. ElNainay
Computer and Systems Eng. Dept.
Alexandria University
Alexandria, Egypt
Email: ymustafa@alexu.edu.eg

Abstract—**Due to the increasing demand for higher data rates and the congestion in communication systems, new research is focusing on the cooperation between the two most successful communication systems, LTE and WiFi. The overall performance of a WiFi system degrades with increasing the number of served users due to collisions. We propose in this paper a novel scheme for LTE and WiFi coexistence, where an LTE femto Base Station cooperates with a WiFi Access Point to maximize both of their profits. Our proposed scheme has the advantage of relieving a congested WiFi system. Thus, this creates a time gap for the LTE system to transmit its data. In addition, we investigate the capability of WiFi and LTE systems to work simultaneously under a certain maximum interference limit. We have formulated a multi-objective optimization problem for maximizing the rate of the WiFi system and the capacity of the LTE system. We developed an algorithm based on particle swarm optimization to determine the appropriate time ratios for WiFi and LTE transmission, the transmitting power of LTE under WiFi transmission, and the number of WiFi nodes to be transferred to LTE system. Simulation results confirm the capability for LTE to transmit besides WiFi without affecting its transmission rate.**

I. Introduction

With the proliferation of technology and mobility, there is a tremendously increasing demand on mobile telecommunications and its support for higher data rates. The demand on mobile telecommunications is expected to increase by 1000 times by 2020 [1]. LTE is the most promising technology that is spectrum efficient, that enables development and enhancement. However, the mobile spectrum will be unable to cope with the increasing demand for higher transmission rates.

Currently, there is a drift toward utilizing LTE in the unlicensed bands. Qualcomm [2], Nokia [3] and many others have discussed the opportunities for LTE in the unlicensed bands and how it can utilize the unlicensed bands. WiFi systems are intended for distributed management. That is, each station takes the decision of transmission independent from other stations. However, in LTE, the decision is made by the Base Station (BS), which is responsible for the distribution of resource blocks among its stations (nodes). Therefore, LTE system uses the channel more efficiently than WiFi. This was confirmed by a field trial conducted by Lan *et. al.* in [4]. The results also clarify the importance of handling interference effect on WiFi transmission.

In this paper, we propose a novel scheme for the operation of LTE in the unlicensed band. The basic idea here is to maintain the WiFi transmission rate unaffected by the operation of LTE. This is done through relieving the WiFi system with the aid of LTE system, by moving some of the WiFi nodes to be served by the LTE system. Relieving the WiFi system will allow for some resources to be used by the LTE system (win-win situation). We formulate a multi-objective optimization problem to maximize the WiFi rate and the LTE capacity; we optimize the number of WiFi nodes to be served by the LTE system, the transmission power and the time allocation between WiFi and LTE systems. Then, we use the Particle Swarm Optimization (PSO) technique to derive the Pareto curve and choose an optimum point that keeps WiFi transmission rate unaffected.

II. Related Work

There exist a lot of research efforts toward the existence of LTE in the unlicensed bands without affecting the existing systems that use bands. Some research work examines ways to mitigate interference effect on small networks such as WiFi. Other work proposes new schemes for coordination between LTE and other networks.

Frameworks for coordination between LTE and WiFi systems are proposed by Sagari et. al. in [5] and Liu et. al. in [6]. An enhancement on [6] is presented in [7], where two models are proposed: either Dual-Band Femtocell, where LTE works on both licensed and unlicensed bands, or Integrated Femto WiFi, where LTE system acts as a WiFi system in the unlicensed bands. In addition, it presents a scheme for channel access and a framework for dynamic spectrum management.

Some research is targeted toward treating the coexistence as a competition and models it using game theory such as [8] and [9]. Some other research proposes fairness-based schemes for the coexistence such as [10] and [11]. Bennis et. al. propose a game theoretic model for offloading delay-tolerant data traffic from Small-Cell Base Stations (SCBSs) to WiFi in [8]. In addition, they present a machine learning framework for self-organized SCBSs using reinforcement learning and cross learning. On the other hand, a proportional fairness scheme is presented in [10], where an optimization problem for maximizing the capacity given a certain number of WiFi

stations and LTE stations is proposed. In [11], Salem and Maaref propose an algorithm for user equipment centric joint association and channel selection. Abdel-Rahman et. al. make use in [12] of doubling the spectrum efficiency through full-duplex WiFi transmission. In [13], Ratasuk et. al. discuss three different scenarios, either a single operator at multiple 20 MHz channels, a single operator at a single 20 MHz channel, or multiple operators at the same 20 MHz channel. In [14], Jeon et. al. mathematically analyze the effect of interference on the quality of service of both LTE and WiFi stations. Attar et. al. discuss in [15] radio resource management schemes, such as selfish schemes using Listen Before Talk (LBT) or collaborative schemes.

However, the most relevant work to ours would be that in [16]. Chen et. al. present a model for relieving WiFi system through moving some WiFi stations to the LTE system. Though, conversely, they do not study the advantage of allowing simultaneous transmission of both WiFi and LTE systems, which we consider in this paper. Our model is more general as we optimize the time allocated for simultaneous transmission of the WiFi and LTE stations; if the optimum allocated time for simultaneous transmission is zero, our system reduces to the one in [16].

As stated above, there is barely a little work in the field of merging underlay coexistence with time division coexistence, in other words, to have the opportunity for LTE to transmit while WiFi is transmitting, and also to have a dedicated time slot for LTE transmission. Most contributions that present a model for simultaneous transmission of LTE and WiFi systems do not investigate the benefits of cooperative coexistence of both systems.

III. SYSTEM MODEL

Our system model consists of an LTE femto Base Station (fBS) which serves N_l LTE nodes and a WiFi Access Point (AP) which serves N_w WiFi nodes. The assumption of one fBS and one AP is adopted to simplify modeling and analysis of the system. Nevertheless, the model can be readily extended to add a number of WiFi APs and/or a number of LTE fBSs. However, it requires modeling of the fairness of each AP and fBS and also modeling for how these diversely connected systems organize and schedule their transmissions.

Nowadays, most of the electronic devices support LTE and WiFi transmission. Therefore, we depend on this in our model. However, compared to [16], we assume that there are some WiFi nodes that support WiFi transmission only and their number is n_w. The rest of WiFi nodes support LTE transmission and their number is $n_l = N_w - n_l$.

We assume that the Signal to Interference and Noise Ratio (SINR) between a transmitting node A and a receiving node B, subject to an interference from node C, is equal to

$$SINR_{AB/C} = \Gamma_{AB/C} = \frac{h_{AB}P_A}{h_{CB}P_C + \sigma_n^2} \qquad (1)$$

where σ_n^2 is the noise variance, P_A and P_C are the transmitted powers from nodes A and C, respectively, and h_{AB} and h_{CB}
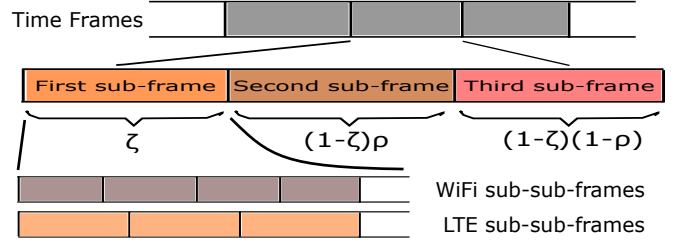

Fig. 1. Explanation of Time Division between WiFi and LTE system

represent the channel strength between nodes A to B and C to B, respectively. We assume that $h_{AB} = C_o d_{AB}^{-\gamma}$, where C_o represents the path loss constant and γ is the path loss exponent. For simplification, we assume that the channel is constant over the transmission time. However, the model can be extended to include these variations.

The fBS should sense the existence of nearby APs and identify their attached nodes and their capabilities to communicate through LTE. However, this assumption is not practical. Therefore, we suggest that there will be a neutral or governmental authority that coordinates and monitors WiFi activity and LTE requirements. This coordinator is capable of managing the spectrum and distribute resources to achieve a better overall performance for both systems; also, it is responsible for maintaining synchronization between them. The coordinator will typically divide the channel into time frames with each consisting of three different sub-frames. Each sub-frame contains several LTE and WiFi sub-sub-frames. Therefore, Each system will operate normally and independently from the other one except at the transitions between sub-frames, which the coordinator is responsible for when to occur. The structure of the time division is depicted in Fig. 1 and can be described as follows.

1) **First Sub-Frame**: WiFi and LTE transmit simultaneously. The LTE system will transmit with a certain power so that the interference on the most vulnerable WiFi node will not exceed its interference limit. If the transmission of LTE will have an effect on WiFi nodes, then the highest priority will be given for WiFi to transmit.

2) **Second Sub-Frame**: LTE helps the WiFi system by handling the transmission of some of its nodes. Thus, the WiFi system is relieved and a higher rate can be achieved. The WiFi system is idle in this sub-frame.

3) **Third Sub-Frame**: LTE transmits the data of its nodes. The LTE system will have full control of the channel to transmit the data of its nodes without having to be cautious about the interference from or to the WiFi system. The reason is that the WiFi system is idle in this time sub-frame.

Finally, we assume that WiFi nodes, which support LTE transmission and have the strongest channel to the fBS, have the highest priority to be assigned to the fBS, if needed. This is to have the least interference effect on WiFi transmission and to have the highest channel gain between the fBS and its

attached WiFi nodes. In the subsequent subsections, we will discuss the modeling of the data rate for both LTE and WiFi.

A. WiFi Transmission Data Rate

Each of the WiFi nodes uses the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol to mitigate collisions. However, some collisions may occur and their number increases with increasing N_w (the total number of WiFi nodes) and the transmission probability of each user. In addition, there is a part of the time when the WiFi system is idle because there is no node transmitting. Assume that if a collision occurs, its duration will be constant and equal to T_c. Also, if there is no transmitting WiFi node at the moment, no node will request to transmit for a certain amount of time that is equal to T_σ; the possible data rate of WiFi node i is equal to [16]

$$R_{WiFi}^{(i)}(n) = \frac{P_{tr} P_s \mathbb{E}[p] n^{-1}}{(1 - P_{tr}) T_\sigma + P_{tr} P_s T_s^{(i)} + P_{tr} (1 - P_s) T_c}, \tag{2}$$

where

$$P_{tr} = 1 - (1 - \kappa)^n \text{ and } P_s = \kappa(1 - \kappa)^{n-1}/P_{tr}, \tag{3}$$

where P_{tr} is the probability of at least one user is transmitting, P_s is the probability of a successful transmission, that is only one user is transmitting at a time, κ is the transmission probability of a single user, n is the number of WiFi nodes, $\mathbb{E}[p]$ is the expected length of a WiFi packet, and $T_s^{(i)}$ is the expected duration of a successful transmission for node i which can be assumed to be equal to

$$T_s^{(i)} = \frac{\text{Packet Length}}{\text{Ergodic Capacity}} = \frac{\mathbb{E}[p]}{B \log(1 + \Gamma^{(i)})} \tag{4}$$

where B is the transmission bandwidth and $\Gamma^{(i)}$ is the Signal to Interference and Noise Ratio for node i as in (1).

It is noted that when the time of a collision is zero, $T_c = 0$, and the time for an empty frame is zero, $T_\sigma = 0$, then the data rate of a WiFi node is equal to the Ergodic capacity divided by the number of users:

$$R_{WiFi}^{(i)}(n) = \frac{B}{n} \log(1 + \Gamma^{(i)}). \tag{5}$$

B. LTE Transmission Data Rate

In LTE transmission, there is no possibility for any collision, because the Base Station is responsible for dividing the resources between nodes. Consequently, we use Shannon's capacity to characterize the LTE capacity. However, the model can be extended to different capacity calculations.

$$R_{LTE}^{(i)}(n) = \frac{\rho B}{n} \log(1 + \Gamma^{(i)}) \tag{6}$$

where ρ is the time ratio of LTE transmission and it is bounded by $0 \leq \rho \leq 1$, B is the transmission bandwidth, n is the number of LTE transmitting nodes, and $\Gamma^{(i)}$ is the signal to interference and noise ratio for node i as in (1).

IV. MULTI-OBJECTIVE OPTIMIZATION PROBLEM FORMULATION

In our system model, we are interested in maximizing two objectives, the sum rate of the LTE nodes and the sum rate of the WiFi nodes. However, maximizing one might lead to the minimization of the other. The problem can be modeled as follows.

$$\text{Maximize}_{\tau, \rho, n, I} \quad C_{LTE} = \tau \sum_{i=1}^{N_l} \frac{B}{N_l} \log\left(1 + \Gamma_l^I(d_i)\right)$$
$$+ (1 - \tau)\rho \sum_{i=1}^{N_l} \frac{B}{N_l} \log\left(1 + \Gamma_l(d_i)\right) \tag{7.1}$$

$$\& \quad C_{WiFi} = \tau \sum_{j=1}^{n} R_{WiFi}^{(i)}(n)$$
$$+ (1-\tau)(1-\rho) \sum_{j=1}^{N_w - n} \frac{B}{N_w - n} \log(1 + \Gamma_{wl}(r_j)) \tag{7.2}$$

$$\text{Subject to} \quad \tau_{\min} \leq \tau \leq 1 \tag{7.3}$$
$$0 \leq \rho \leq 1 \tag{7.4}$$
$$n_w \leq n \leq N_w \tag{7.5}$$
$$0 \leq I \leq I_{\max} \tag{7.6}$$
$$(1 - \tau)(1 - \rho) \geq \sum_{j=1}^{N_w - n} \frac{R_{WiFi}^{(i)}(N_w)}{\frac{B}{N_w - n} \log\left(1 + \Gamma_{wl}(r_j)\right)} \tag{7.7}$$
$$\tau \geq \sum_{i=1}^{n} \frac{R_{WiFi}^{(i)}(N_w)}{R_{WiFi}^{(i)}(n)} \tag{7.8}$$

where $R_{WiFi}^{(i)}(n)$ is as in (2), d_i is the distance between LTE node i and fBS $\forall i = 1, 2, \cdots, N_l$, r_j is the distance between WiFi node j and fBS $\forall j = 1, 2, \cdots, N_w$, τ is the time ratio taken for the first sub-frame, ρ is used to divide the remaining time into the second and the third sub-frames, n is the number of WiFi nodes transmitting to the AP, I_{max} is the maximum allowable interference limit for the WiFi system, Γ_l^I is the SINR for LTE nodes subject to the interference from WiFi nodes, Γ_l is the Signal to Noise Ratio (SNR) between LTE nodes and the fBS without interference from WiFi nodes, and Γ_{wl} is the SNR between WiFi nodes and the fBS. The time division structure is explained in Fig. 1.

Constraint (7.3) states the possible range of the time ratio that the first sub-frame can take, if $\tau = 1$ then LTE and WiFi systems always work simultaneously. The minimum value for τ is $\tau_{min} \geq 0$, which puts a lower bound on the first sub-frame. This lower bound is not a necessity, but it could be advisable to make sure that the AP can access the channel for at least a certain amount of time. Constraint (7.4) bounds the value of ρ so its maximum is at 1, which means that the third sub-frame is disregarded and its minimum is at 0, which means that the second sub-frame is disregarded. Constraint (7.5) guarantees that the number of transferred users to the

fBS does not exceed n_l and, also, to bound the total number of WiFi nodes by N_w. Constraint (7.6) limits the interference so that the WiFi system could work properly. Constraints (7.7) and (7.8) assure fairness for WiFi nodes by lower bounding the rate of each WiFi node by the rate before LTE transmission.

V. IMPLEMENTATION

The optimization problem is too difficult to be solved using the Karush Kuhn Tucker (KKT) conditions. In addition, the Hessian matrix of C_{LTE} is not negative semi-definite to guarantee its concavity. Hence, we use a meta-heuristic technique to solve it. More specifically, we use the Particle Swarm Optimization (PSO) technique to generate the Pareto-optimal curve of our two objectivesfor different values of the distances between the LTE fBS and the WiFi AP. Then, we choose a point on the Pareto-optimal curve that maximizes LTE capacity constrained by the conservation of the capacity of the WiFi system as shown in **Algorithm 1**.

Algorithm 1 Multi-Objective PSO Algorithm

Input: Data in Tables I and II
Output: C_{LTE}, C_{WiFi}, τ, ρ, n and I
1: **for** each separation value between AP & fBS **do**
2:     **for** each generation of nodes (N_{dis}) **do**
3:         Generate $Population$, satisfying (7.3), (7.4), (7.5) & (7.6) and calculate C_{LTE} & C_{WiFi}.
4:         Calculate objectives for each particle, Obj_l and Obj_w.
5:         Check domination of $Particles$ and define $Leaders$.
6:         Create $Grid$ and Place $Leaders$ in it.
7:         **for** $iteration = 1$ to N_{it} **do**
8:             **for** Each Particle **do**
9:                 Select a suitable $Leader$ of a $Cell$ in the $Grid$.
10:                Calculate $Particle$'s $Velocity$ and $Position$.
11:                Check $Constraints$ Violation and calculate C_{LTE}, C_{WiFi}, Obj_l & Obj_w.
12:                Apply $Mutation$ and check if $Position$ is better than $Best$. If better, replace.
13:             **end for**
14:             Update $Leaders$, $Grid$ & w_{new}
15:             Check if $Leaders$ size $> N_{lead}$, remove extra.
16:         **end for**
17:         Choose the optimum $Particle$
18:     **end for**
19:     Calculate averages of C_{LTE} and C_{WiFi}
20: **end for**
21: **return** P

The values of Obj_l and Obj_w are as follows,

$$Obj_l = C_{LTE} - penalty * (<dif_1> + <dif_2>) \quad (8)$$

$$Obj_w = C_{WiFi} - penalty * (<dif_1> + <dif_2>). \quad (9)$$

dif_1 and dif_2 are the differences between the left-hand sides and the right-hand sides of the equations (7.7) and (7.8), respectively and $<X> = max(0, X)$.

The algorithm solves a number of optimization problems, each for a certain separation between the AP and the fBS. We solve each optimization problem several times for several random generations of the distribution of LTE and WiFi nodes, which are generated uniformly in the range of the coverage of the AP (r_{max}) and fBS (d_{max}), respectively. Then, we obtain the average of these solutions. In each generation of nodes, we create a four-dimensional population of particles that span the feasible region. The feasible region is the region containing the combined possible values of τ, ρ, n and I which satisfy the constraints (7.3), (7.4), (7.5), and (7.6) but not necessarily satisfying constraints (7.7) and (7.8). Therefore, to guarantee the satisfaction of those two remaining constraints, we subtract a penalty value from our two objectives; the LTE and WiFi transmission rates. The penalty is linearly proportional to how much a particle diverges from satisfying each of the two constraints as in (8) and (9). In case a particle satisfies all constraints, the penalty would be equal to zero.

To obtain the optimum values of the objectives, the algorithm iterates for a certain number of times. In each iteration, the new position of each particle, i.e., the new different values of τ, ρ, n and I, are calculated. The calculations are based on relocating a particle to be closer to its own best and a selected leader. Leaders are the non-dominated particles in the previous iteration. By non-dominated, we mean that there is no other particle that has a greater value of one of the two objectives without having a lower value of the other. In other words, if p_l is a leader, S_p is the set of all generated particles and Obj_l and Obj_w are our objectives, then, $\forall p \in S_p$ that satisfy $Obj_l(p) \geq Obj_l(p_l)$, $Obj_w(p)$ must be less than $Obj_w(p_l)$. Similarly, $\forall p \in S_p$ that satisfy $Obj_w(p) \geq Obj_w(p_l)$, $Obj_l(p)$ must be less than $Obj_l(p_l)$.

VI. SIMULATION RESULTS

The simulation parameters of the LTE and WiFi systems, and PSO are given in Table I and Table II, respectively. The parameters of PSO are based on a MATLAB code developed by [17]. These parameters ensure that the generated particles span the entire feasible set. Most of the parameters of the communication systems are chosen according to [16]. However, due to the effect of the transmission probability κ, on the performance of the system, we study the effect of changing κ on the transmission rates of WiFi and LTE systems. In addition, we investigate the effect of changing the number of users on the performance of both systems. Moreover, we plot examples of the trade-off curves for low and high separation to elaborate the different diverse behavior of the system.

A graph of the transmission rates of C_{LTE} and C_{WiFi} versus the transmission probability κ is shown in Fig. 2. This graph does not study the mutual interference effect between the two systems. However, it provides an insight into the effect of changing κ on C_{WiFi}. We, thereby, are able to choose an appropriate value of κ. The transmission rate of the WiFi system has only one peak at $\kappa = 0.9$ and it decreases monotonically until it reaches 0 at $\kappa = 0$ or 1. κ plays a significant role in determining the gain of using our model. By approaching the value $\kappa = 0.9$, the benefit of using our model decreases because WiFi transmission rate gets closer to that of LTE and thus the gain of relieving the WiFi system decreases.

TABLE I
SYSTEM PARAMETERS

Bandwidth(B)	20 MHz
Number of LTE nodes (N_l)	30
Number of WiFi nodes (N_w)	10
Number of WiFi nodes, that supports LTE (n_l)	7
Number of WiFi nodes, that don't supports LTE (n_w)	3
LTE transmitting Power (P_l)	30 dBm
WiFi transmitting Power (P_w)	30 dBm
Noise Variance (σ_n^2)	-95 dBm
Maximum Allowed Interference to WiFi (I_{max})	10 dBm
Minimum Value of τ (τ_{min})	0
Transmission Probability for a WiFi node (κ)	0.9
Expected Packet Length for a WiFi transmission ($\mathbb{E}[p]$)	1500 Bytes
Time Duration of a Collision (T_c)	20 μs
Time Duration of an Empty Frame (T_σ)	20 μs
Path Loss Exponent (γ)	5
Path Loss Coefficient (C_o)	0.16
WiFi AP Cell Coverage for WiFi nodes (r_{max})	10 m
LTE Cell Coverage for LTE nodes (d_{max})	30 m

TABLE II
PARTICLE SWARM OPTIMIZATION PARAMETERS

| Population Size (N_{pop})	200
Leaders Size (N_{lead})	100
Number of Iterations for a certain distance (N_{dis})	5
Number of Iterations for the algorithm (N_{it})	200
Number of Grids per Dimension (N_{grid})	7
Mutation Rate (μ_{rate})	0.4
Deletion Selection Pressure (γ_s)	2
Leader Selection Pressure (β_s)	2
Inflation Rate (α_{rate})	30
Inertia Weight (w)	0.5
Inertia Weight Damping Rate (w_{damp})	0.99
Personal Learning Coefficient (C_1)	1
Global Learning Coefficient (C_2)	2
tolerance	0.9
penalty	1e10
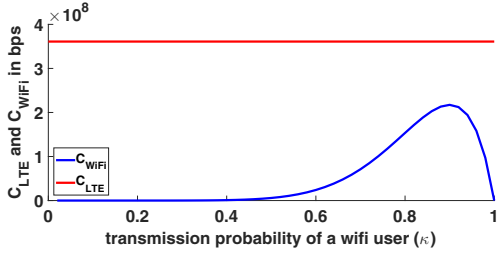
Fig. 2. Trans. rates of LTE and WiFi vs. trans. probability

The same applies to the noise variance. By increasing the noise variance, the benefit of using our model decreases.

In Figures 3, 4, 5, and 6, we apply our algorithm to plot the transmission rates of LTE and WiFi. The value of κ is set to be 0.7 in Figures 3 and 5 and 0.9 in Figures 4 and 6. In Figures 5 and 6, we changed the number of WiFi nodes
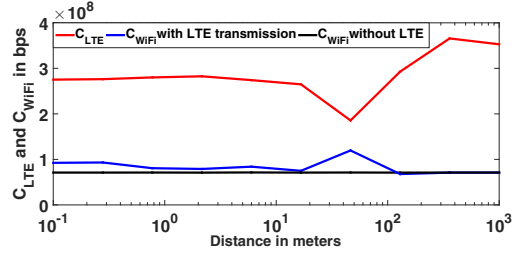

Fig. 3. Trans. rates of LTE and WiFi vs. separating distance for $\kappa = 0.7$
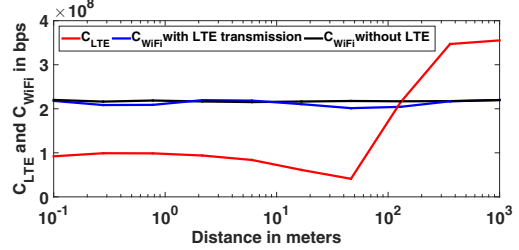

Fig. 4. Trans. rates of LTE and WiFi vs. separating distance for $\kappa = 0.9$
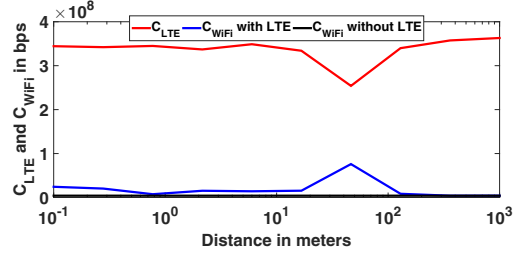

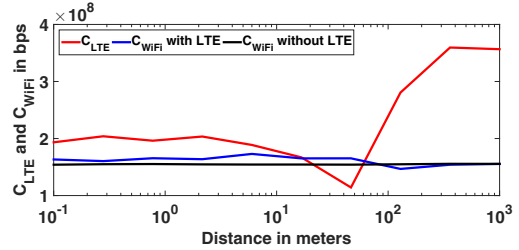Fig. 5. Trans. rates of LTE and WiFi vs. separating distance for $\kappa = 0.7$, $N_w = 20$, $n_l = 14$ and $n_w = 6$

Fig. 6. Trans. rates of LTE and WiFi vs. separating distance for $\kappa = 0.9$, $N_w = 20$, $n_l = 14$ and $n_w = 6$

to be $N_w = 20$, which are divided into WiFi nodes that support LTE $n_l = 14$ and WiFi nodes that do not support LTE $n_w = 6$. The performance of the WiFi system is impacted severely by increasing N_w from 10 to 20. Hence, by increasing congestion, the benefits of our scheme are manifested. In addition, our scheme benefits more by changing κ to reduce the transmission rate of WiFi. Conclusively, those figures prove that by increasing the gap between LTE and WiFi transmission rates, the gain of using our scheme increases.

Each of the WiFi and the LTE systems can be considered isolated from each other with high separation between AP and fBS. In other words, the interference effect is negligible. Consequently, in Fig. 3, C_{WiFi} and C_{LTE} saturate at high separation. In other words, the values of C_{LTE} and C_{WiFi}
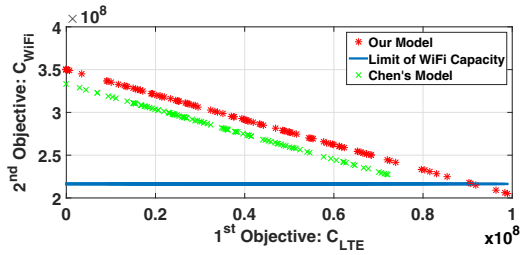
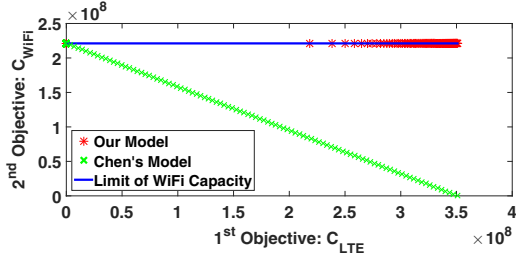Fig. 7. Pareto curve with $\kappa = 0.9$ and $l = 0$

Fig. 8. Pareto curve with $\kappa = 0.9$ and $l = 1000$

do not vary significantly from $200m$ to $1000m$. The same applies for Figures 4, 5 and 6. The slight change in the values of transmission rates, for high separation, is due to different generations of the distribution of nodes besides the slight effect of interference between the two systems.

The performance of the LTE system is always at its lowest at a separation around $l = 50m$. This is expected at this value of l, because the separation is not high enough to lessen the effect of interference and at the same time the separation is not small enough to transfer WiFi nodes to the LTE system.

Examples of trade-off curves of our two objectives, C_{LTE} and C_{WiFi}, are shown in Fig. 7, where the fBS coincides with the AP ($l = 0$), and in Fig. 8, where the separation between the fBS and the AP is equal to $1000m$ (i.e., the fBS and the AP can be considered to be isolated). In both of those figures, we compare our performance with the performance of [16] shown in green. The blue line indicates the original WiFi transmission rate without the existence of the LTE system. As shown in Fig. 7, C_{LTE} and C_{WiFi} values are inversely proportional, i.e., increasing the value of one leads to the reduction of the value of the other. However, in Fig. 8, variations in our model for the values of C_{WiFi} are quite indistinctively small and the values almost follow a horizontal line. This is due to the high separation and thus the negligible effect of the interference of the LTE system on the WiFi system. As expected in both of the figures, our system achieves a higher end data rate for both systems as compared to the system in [16]; as mentioned above, the system is [16] is a special case of our system with $\tau = 0$. Also, for the case of isolated fBS and AP, the system in [16] shows trade-off between the WiFi and LTE rates, due to dividing the time between the two transmissions, which is not the case in our work where the two systems use the entire time for simultaneous transmission as there is no interference. Finally, note that in Fig. 7, the WiFi rate can increase even if the LTE rate is zero since some of the WiFi nodes can be offloaded to the fBS, which is not the case in Fig. 8.

VII. CONCLUSION

In this paper, we have discussed the capability of LTE to operate, coherently and effectively, with a nearby WiFi system in the unlicensed band. The LTE system relieves the WiFi system and, thus, gets a dedicated time for its transmission. We have modeled the problem as a two-objectives optimization problem. PSO was used for solving the problem and producing the trade-off curve between LTE and WiFi transmission rates. An appropriate point on the curve can be chosen that guarantees the WiFi rate. Simulation results indicated the effectiveness of the proposed cooperative coexistence scheme. The proposed scheme outperforms a previously proposed scheme where the time is divided between the WiFi and LTE systems, by allowing simultaneous transmission of the two systems.

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