Power Control under QoS and Interference Constraint in Femtocell Cognitive Networks

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***Abstract*—Power control is critical for femtocell networks that allow spectrum sharing among Macrocell and Femtocell. In this paper, we derive an optimal power control strategy toward reducing the CO_2 emissions and maximize total throughput under both the probability of dropping a packet due to buffer overflow constraints at the Femtocell user equipment (FUE) and the interference constraints to the Macrocell base station (MBS) for uplink transmission. We use linear programming to solve the CO_2 emissions minimization problem. For maximizing the total throughput of FUEs, we propose a distributed power control algorithms by employing geometry convex tool. Numerical results are used to validate the analysis and demonstrate a high degree of accuracy for the derived expressions. Results indicate that the performance of the FUEs depends on not only the interference constraint of the MBS but also the delay constraint of the FUEs.**

I. Introduction

Femtocells, also known as 'home base station', are cellular network access points that connect standard mobile devices to a mobile operators network using residential DSL, cable broadband connections, optical fibres or wireless last-mile technologies [1]. Femtocell networks use femtocell an access points (FAP) regarded as a small base station which is connected to internet service provider (ISP). Femtocell user equipments (FUEs) can transmit and receive data directly to and from the macro base station (MBS) through FAPs. Hence, the channel utilization as well as the quality of service may be increased. Due to their short transmit-recive distance, femtocells can greatly lower transmit power, prolong FUEs' battery life and achieve a higher data rate. To attract FUEs by low costs, demands on femtocells will be increasing enormously. It has been predicted by ABI Research that a large deployment of femtocells is expected [2].

However, there are many challenges to be solve in femtocells network. One of the main concerns in femtocells is power control to mitigate the interference. The downlink power control and interference mitigation have been considered in the standard bodies and the literature [3], [4]. In this paper, we consider the uplink transmission from FUEs to FAPs. The higher uplink data rate FUEs has the higher profit the ISP obtains. However, FUEs also need to use more power to transmit data. The high power transmission of FUEs may make interference to the MBS and create more CO_2 emissions. Carbon footprint is a key ecological factor which is measured in carbon dioxide equivalent CO_2e and is defined as the amount of CO_2 emissions calculated according to the global warming potential (GWP-100) indicator as defined by the International

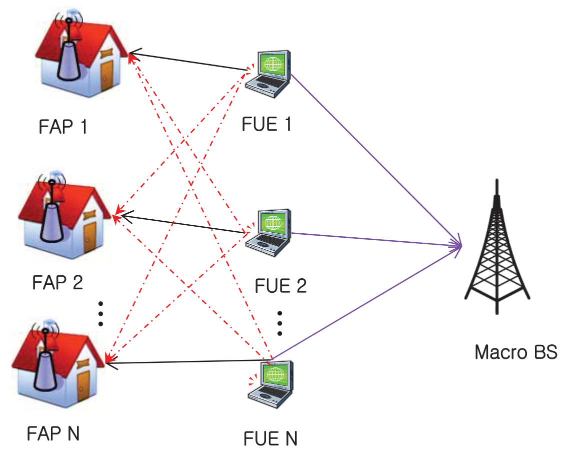

Fig. 1. System model.

Panel on Climate Change (IPCC) [5]. Based on the listed facts and figures, it can be concluded that the information and communication technology (ICT) sector in general and mobile communication in particular are not exempt from reducing their carbon footprint, and have considerable potential to decrease their global carbon footprint, especially in developing and emerging economies. Thus, FUEs' power control should be carefully considered to reducing the CO_2 emissions but still maintaining their service quality and protect the MBS's transmission.

As described in Figure 1, FUEs can access the spectrum sharing by the MBS which requires to maintain the qualify of service for the uplink of macro user equipments (MUEs). Thus, the interference generated by FUEs to the MBS should not exceed the maximum level that the MBS can tolerate. Let's denote I as the maximum interference tolerance at the MBS, which characterizes the "worst case" of the RF environment. Intuitively, we need to design power control algorithms to satisfy the MBS interference constraints [6], [7]. In addition, the probability of dropping a packet due to buffer overflow at a FUE is also important in several applications. In [15] M. Chiang turned to buffer overflow properties to be included in constraints or objective function of power control optimization.

To conclude, the main contributions of this paper are: under both the probability of dropping a packet due to buffer overflow constraints of each FUE and the interference constraint at the MBS, we formulate and design an optimization framework and give solutions for two problems as follows:

- Minimizing the total CO_2 emissions of $FUEs$: by using the linear programming, this problem can be solved in a centralized manner.
- Maximize the total throughput of FUEs with the high SINR assumption: a distributed power control (DPC) algorithm is implemented in FUEs by using geometric convex programming.

This paper is organized as follows. In section II, we introduce our system model. Then the total CO_2 emissions minimization problem is given in section III. The total throughput maximization problem is presented in section IV. Finally, conclusions are drawn in section V.

II. System model

We consider a two-tier femtocell network implementing spectrum sharing. We assume that a single central MBS which has a serving coverage R. Within the region R, there are totally N cochannel femtocells deployed by home or office users. The femtocells and the macrocell are using the same frequency bands. There is one FAP providing service for several wireless devices in each femtocell. However, for analytical tractability, we assume there is one assigned active FUE during each time slot in each femtocell, that is orthogonal uplink signaling is used in the femtocell system.

Under the above framework, Figure 2 presents the uplink transmission model for this two-tier femtocell networks for a given time slot. Let $h_{n,n}$ denotes the channel gain between FUE_n and FAP_n. Likewise, $h_{m,n}$ denotes the channel power gain between FUE_n and FAP_m. g_n is the channel gain between FUE_n and the MBS. Moreover, let σ^2 be the variance of Additive White Gaussian Noise at $FUEs$ as the environment noise, which is assumed to be constant for simplicity. Let P denote a vector of power levels for $FUEs$, i.e., $P = [P_1, P_2, ..., P_n]$. Thus, the interference constraint in femtocell network is to keep the aggregate interference from all FUEs to the MBS below I, i.e.,

$$\sum_{n=1}^{N} g_n P_n \leq I. \tag{1}$$

The signal-to-interference-noiseratio (SINR) at the FAP_n is given as follows

$$SINR_n(P) = \frac{h_{n,n} P_n}{\sum\limits_{m \neq n}^{N} h_{n,m} P_m + \sigma^2}. \tag{2}$$

The transmit rate R_n of FUE_n is a variable which is correlated to the node modulation scheme and the simultaneous SINR at FAP_n. According to [9], we have:

$$R_n = log(1 + SINR_n). \tag{3}$$

The FUE_n first buffers the received packets in a queue and then transmits these packets at a rate R_n set by the $SINR_n$ on the egress link. The rate R_n is determined by the transmit

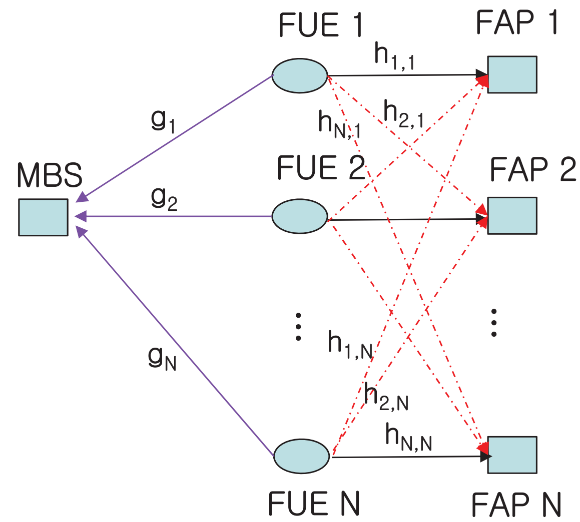

Fig. 2. Uplink transmission model.

powers vector P. A FIFO queuing discipline is used here for simplicity. The packets arrival process of FUE_n is assumed to be a Poisson distribution with parameter λ_n and to have an exponentially distributed length with parameter π_n. Using the model of an M/M/1 queue as in [10], the probability of FUE_n having a backlog of $N_n = k$ packets to transmit is well-known to be $Prob\{N_n = k\} = (1 - \rho)\rho^k$ where $\rho = \frac{\lambda_n}{\pi_n R_n(P)}$. The probability Pr^{BO} of dropping a packet due to buffer overflow at a node is also important in several applications. It is again a function of power vector P and can be written as $Pr_n^{BO} = Prob\{N_n > B_n\} = \rho^{B_n+1}$ where B_n is the buffer size of FUE_n's queue. For each FUE_n, let's set an upper bound $Pr_n^{BO,max}$ on the buffer overflow probability also gives a posynomial lower bound constraint in power vector P as follows

$$\left(\frac{\lambda_n}{\pi_n log(1 + SINR_n(P))}\right)^{B_n+1} \leq Pr_n^{BO,max}. \tag{4}$$

Let denote $\Omega_n = \left(e^{\frac{\lambda_n}{\pi_n (P_n^{BO,\max})^{\frac{1}{B_n+1}}}} - 1\right)^{-1}$,thus we have a equivalent inequality as follows

$$\frac{1}{SINR_n(P)} \leq \Omega_n, \tag{5}$$

where Ω_n is a constant when all the parameters of femtocell network are fixed.

III. Minimize CO_2 Emissions

In this section, we formulate the power control problem to minimize the total CO_2 emissions of all $FUEs$ and give a solution for this problem.

In [8], the authors stated that the CO_2 emissions from mobile communication depends on the kind of power supply for mobile devices in place of Li-ion battery. The key point is the CO_2 emission coefficients of each individual renewable energy source. Let denote c_n is the CO_2 emission coefficients of FUE_n, thus the total CO_2 emission of all $FUEs$ is given as

$$\text{total CO}_2 \text{ emission} = \sum_{n=1}^{N} c_n P_n. \tag{6}$$

Thus, the total CO_2 emission minimization problem can be formulated as follows

$$\begin{aligned} \min_{\mathbf{P}} \quad & \sum_n c_n P_n & (7)\\ \text{s.t.} \quad & \sum_{n=1}^{N} g_n P_n \le I \\ & \sum_{m\neq n}^{N} h_{n,m} P_m + \sigma^2 \le h_{n,n} P_n \Omega_n, \forall n, \\ & P_n^{\min} \le P_n \le P_n^{\max}, \forall n, \end{aligned}$$

The (7) could be solved by linear programming by adding some slack variable and surplus variable. Then, (7) can be written as a standard form as follows

$$\begin{aligned} \min_{\mathbf{P}} \quad & \sum_n c_n P_n & (8)\\ \text{s.t.} \quad & \sum_{n=1}^{N} g_n P_n + X = I \\ & \sum_{m\neq n}^{N} h_{n,m} P_m + \sigma^2 + Y_n = h_{n,n} P_n \Omega_n, \forall n, \\ & P_n^{\min} + L_n = P_n, \forall n, \\ & P_n + U_n = P_n^{\max}, \forall n, \\ & 0 \le X, Y_n, L_n, U_n, P_n, \forall n. \end{aligned}$$

where X, Y_n, L_n, U_n, are slack variable and surplus variable. The problem (8) can be solved using two phase simplex method [11], which is used to solve the linear program problem such as: maximizing cx subject to $Ax = b$ and $x >= 0$.

Numberical Results: The system parameters are given as follows: packet traffic at $FUEs$ is assumed to be Poisson with intensity $\lambda_n = 2000pk/s$, packets' length π_n = 30bits, B_n=100, $N = 3$, $I = 10^{-9}$. Channel gains are defined using a simple path loss model. Figure 3 shows the CO_2 emission for different upper bound numerical values in the dropping probability constraints, obtaining by solving a sequence of linear programming, one for each point on the curve. As the dropping probability is relaxed, the minimized CO_2 emission decreases sharply.

IV. Maximize The Total Throughput

In this section, the objective of the femtocell network is maximizing a system-wide efficiency metric, e.g., the total system throughput. Here, we assume that $SINR_n$ is much larger than 1, thus the data rate R_n of FUE_n as a function of

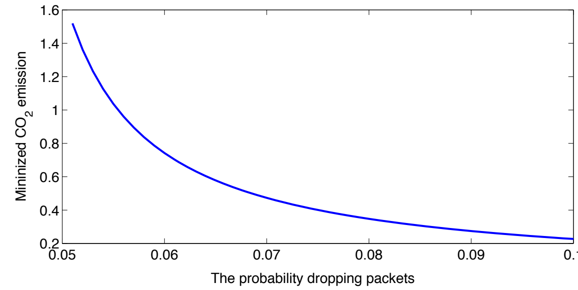

Fig. 3. The optimized CO_2 emission vs. the delay bound.

$SINR_n$: $R_n = \log(1+SINR_n)$, which can be approximated as

$$R_n = \log(SINR_n). \tag{9}$$

This approximation is reasonable when the distance between FUE_n and FAP_n is normally less than 20m, thus the sighnal level is much higher than the interference level.

Therefore, in the high SINR regime, the aggregate data rate for the femtocell network can be written as follows

$$R_{sum} = \sum_n R_n = \log\left[\prod_n (SINR_n)\right]. \tag{10}$$

Thus, the total system throughput maximization problem can be written as follows

$$\begin{aligned} \max_{\mathbf{P}} \quad & \log\left[\prod_n (SINR_n(P))\right] & (11)\\ \text{s.t.} \quad & \sum_{n=1}^{N} g_n P_n \le I \\ & \sum_{m\neq n}^{N} h_{n,m} P_m + \sigma^2 \le h_{n,n} P_n \Omega_n, \forall n, \\ & P_n^{\min} \le P_n \le P_n^{\max}, \forall n. \end{aligned}$$

The above problem is not linear problem. In order to transform the original problem (11) to a convex problem, we go through two steps as follows

Step 1: First, maximing $\log\left[\prod_n (SINR_n(P))\right]$ is equivalent to minimizing $\prod_n \frac{1}{SINR_n}$, then we obtain a equivalent problem as follows

$$\begin{aligned} \min \quad & \prod_n \frac{1}{SINR_n(P)} & (12)\\ \text{s.t.} \quad & \frac{1}{I} \sum_{n=1}^{N} g_n P_n \le 1 \\ & \frac{\sum_{m\neq n}^{N} h_{n,m} P_m + \sigma^2}{h_{n,n} P_n \Omega_n} \le 1, \forall n, \\ & \frac{P_n^{\min}}{P_n} \le 1, \forall n, \\ & \frac{P_n}{P_n^{\max}} \le 1, \forall n. \end{aligned}$$

Step 2: The problem (12) is now in standard form of the geometric convex programming problem and not a convex optimization problem. However, by using a logarithmic change of the variables and a logarithmic operation to the function, we can turn it into the following equivalent problem as

$$\begin{aligned}
\min \quad & \sum_{n=1}^{N} \log\left(\frac{e^{-y_n}}{h_{n,n}}(e^{Z_n}+\sigma^2)\right) \qquad (13)\\
\text{s.t.} \quad & \sum_{n=1}^{N} g_n e^{y_n} - I \leq 0\\
& \log\left(\frac{e^{-y_n}}{h_{n,n}}(e^{Z_n}+\sigma^2)\right) - \log\Omega_n \leq 0, \forall n,\\
& y_n - \log P_n^{\max} \leq 0, \forall n,\\
& -y_n + \log P_n^{\min} \leq 0, \forall n,\\
& \sum_{m\neq n}^{N} h_{n,m} e^{y_m} - e^{Z_n} = 0, \forall n,
\end{aligned}$$

where $y_n = \log P_n$ thus $P_n = e^{y_n}$. Here, we introduce an auxiliary variable $\{Z_n\}$ that every FUE_n has the capability to estimate the interference $e^{Z_n} = \sum_{m\neq n}^{N} h_{n,m}P_m$. The problem (13) is a convex problem [12] and could be solved by using its dual problem.

The Lagrange function of (13) is given as follows

$$\begin{aligned}
& L(\{y_n\},\{Z_n\},\lambda,\mu,\nu,\kappa,\varsigma)\\
&= \sum_{n=1}^{N} \log\left(\frac{e^{-y_n}}{h_{n,n}}(e^{Z_n}+\sigma^2)\right)\\
&+ \lambda\left(\sum_{n=1}^{N} g_n e^{y_n} - I\right)\\
&+ \sum_{n=1}^{N} \mu_n\left(\log\left(\frac{e^{-y_n}}{h_{n,n}}(e^{Z_n}+\sigma^2)\right) - \log\Omega_n\right)\\
&+ \sum_{n=1}^{N} \nu_n\left(y_n - \log P_n^{\max}\right)\\
&+ \sum_{n=1}^{N} \kappa_n\left(-y_n + \log P_n^{\min}\right)\\
&+ \sum_{n=1}^{N} \varsigma_n\left(\sum_{m\neq n}^{N} h_{n,m}e^{y_m} - e^{Z_n}\right), \qquad (14)
\end{aligned}$$

where $\lambda, \mu, \nu, \kappa$ are Lagrange multipliers and $\{\varsigma_n\}$ are consistency prices.

We can apply the decomposition method of Lagrange relaxation of the coupling constraint which is proposed in [13]-[20]. Due to the decomposability of the Lagrange function, it can separate into N subproblems, each of which is given as follows

$$\begin{aligned}
& L_n(y_n, Z_n, \lambda, \mu_n, \nu_n, \kappa_n, \varsigma_n)\\
&= \log\left(\frac{e^{-y_n}}{h_{n,n}}(e^{Z_n}+\sigma^2)\right)\\
&+ \lambda g_n e^{y_n} + \mu_n \log\left(\frac{e^{-y_n}}{h_{n,n}}(e^{Z_n}+\sigma^2)\right)\\
&+ \nu_n y_n - \kappa_n y_n + \sum_{m\neq n}^{N} \varsigma_n h_{m,n} e^{y_n} - \varsigma_n e^{Z_n}. \qquad (15)
\end{aligned}$$

Then, (13) can be solved by each FUE_n, respectively. The dual problem is given as

$$\begin{aligned}
\max \quad & D(\lambda,\mu,\nu,\kappa,\varsigma) \qquad (16)\\
\text{s.t.} \quad & \lambda,\mu,\nu,\kappa \geq 0,
\end{aligned}$$

where $D(\lambda,\mu,\nu,\kappa,\varsigma) = \min_{y_n, Z_n} L(\{y_n\},\{Z_n\},\lambda,\mu,\nu,\kappa,\varsigma)$ is the dual function.

The dual problem can be solved by using the sub-gradient method which updates the Lagrange multipliers and consistency prices as follows

$$\lambda(t) = \left[\lambda(t-1) + \theta(t)\left(\sum_{n=1}^{N} g_n e^{y_n(t)} - I\right)\right]^+, \qquad (17)$$

$$\begin{aligned}
\mu_n(t) &= \max\{0, \mu_n(t-1)\\
&+ \eta(t)\left(\log\left(\frac{e^{-y_n(t)}}{h_{n,n}}(e^{Z_n(t)}+\sigma^2)\right) - \log\Omega_n\right)\}
\end{aligned} \qquad (18)$$

$$\nu_n(t) = \left[\nu_n(t-1) + \alpha(t)\left(y_n(t) - \log P_n^{\max}\right)\right]^+, \qquad (19)$$

$$\kappa_n(t) = \left[\kappa_n(t-1) + \beta(t)\left(-y_n(t) + \log P_n^{\min}\right)\right]^+, \qquad (20)$$

$$\varsigma_n(t) = \varsigma_n(t-1) + \varphi(t)\left(\sum_{m\neq n}^{N} h_{n,m}e^{y_m(t)} - e^{Z_n(t)}\right), \qquad (21)$$

where $\theta(t), \eta(t), \alpha(t), \beta(t), \varphi(t)$ are step sizes which must be positive. $[X]^+ = \max\{X, 0\}$ and t is the iterative time. Based on the KKT necessary condition, the optimal transmit power $\{P_n\}$ of each FUE_n can be obtained individually through the following equation:

$$\frac{\partial L_n(y_n, Z_n, \lambda, \mu_n, \nu_n, \kappa_n, \varsigma_n)}{\partial y_n} = 0, \qquad (22)$$

thus the power solution is given as follows

$$P_n^* = e^{y_n^*} = \left[\frac{1+\mu_n-\nu_n+\kappa_n}{\lambda g_n + \sum_{m\neq n}^{N} \varsigma_n h_{n,m}}\right]^+, \forall n. \qquad (23)$$

The auxiliary variable Z_n can be achieved according to KKT necessary condition as follows

$$\frac{\partial L_n(y_n, Z_n, \lambda, \mu_n, \nu_n, \kappa_n, \varsigma_n)}{\partial Z_n} = 0, \qquad (24)$$

then we obtain the solution as follows

$$e^{Z_n^*} = \left[\frac{1+\mu_n}{\varsigma_n} - \sigma^2\right]^+, \forall n. \quad (25)$$

We then have the Distributed pOwer cOntrol foR Total rAte maximizatioN (DOORTAN).

Algorithm 1 DOORTAN

- Initializing $t = 0$; and $\lambda(0) > 0$, $\mu(0) > 0$, $\nu(0) > 0$, $\kappa(0) > 0$, $\varsigma(0)$, $P_n^{\min} \leq P_n(0) \leq P_n^{\max}$, $\forall n$.
- Algorithms at FAP_n.

1) Measure the interference $\sum_{m \neq n}^{N} h_{n,m} P_m(t)$ generated by other $FUEs$ and the noise σ^2; Estimate the channel gains $h_{n,m}$.
2) Calculate $e^{Z_n(t+1)} = \left[\frac{1+\mu_n(t)}{\varsigma_n(t)} - \sigma^2\right]^+$
3) Update the Lagrange multiplier $\mu_n(t+1)$ and the consistency price $\varsigma_n(t+1)$ according to (18) and (21) respectively
4) Transmit $\mu_n(t+1)$, $\varsigma_n(t+1)$ to FUE_n and broradcast $h_{n,m}$

- Algorithms at FUE_n.

1) Estimate the channel gain g_n and receive $\{P_m\}_{m \neq n}$ to calculate the total interference at the MBS; Receive the Lagrange multiplier $\mu_n(t+1)$ and the consistency price $\varsigma_n(t+1)$, the channel gain $\{h_{m,n}\}_{m \neq n}$
2) Update the Lagrange multipliers according to (17), (19) and (20) respectively
3) Calculate the power value
$$P_n(t+1) = \left[\frac{1+\mu_n(t)-\nu_n(t)+\kappa_n(t)}{\lambda(t) g_n + \sum_{m \neq n}^{N} \varsigma_n(t) h_{n,m}}\right]^+$$
4) Broadcast g_n and $P_n(t+1)$

Numberical Results: We present numerial resutls for the proposed power control algorithms. We consider a femtocell network with a MBS and 3 femtocells distributed randomly inside. The system parameter are defined as follow: $P_{max} = 1mW$, $I = 10^{-9}$. Channel gains are defined using a simple path loss model. Figure 4 illustrates the power convergence properties of each FUE in the DOORTAN algorithm separately. We can see that each FUE's power level can converge to its optimal power solution. Figure 5 shows the total throughput of all $FUEs$. As can be seen, at the first time the total throughput is hight due to high power control, however it violates the interference constraint to the MBS. Thus, the total throughput decreases and converges to the optimal point in order to protect the MBS and satisfy the delay constraint.

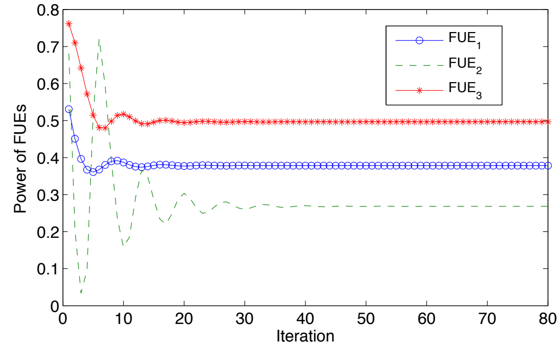

Fig. 4. The optimized power of FUEs.

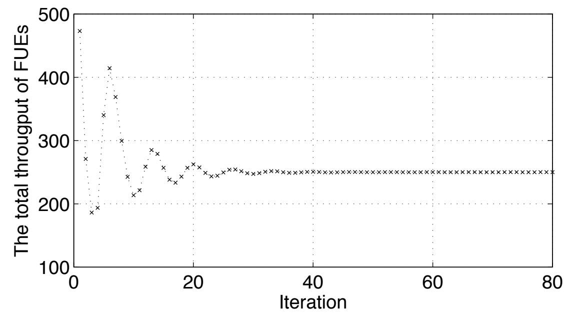

Fig. 5. The optimized total throughput of FUEs.

V. Conclusion

In this paper, we study the power control problem in Cognitive Femtocell networks aiming to minimize the total CO_2 emissions and maximize the total throughput under both the interference and the probability of dropping a packet due to buffer overflow constraints. Based on linear programming, the minimize the total CO_2 emissions problem can be solved in a centralized manner without any messages exchange between $FUEs$. On the other hand, due to nonlinear object function of the total throughput maximization problem, we use convex optimization theory to design a distributed algorithm to solve the dual problem since the duality gap of a convex problem is zero. The algorithm proposed in this paper could be carried out at each $FUEs$ with some exchanged messages and have fast convergence performances.

VI. Acknowledgement

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