Energy Efficiency and Spectral Efficiency Trade-off of a Novel Interference Avoidance Approach for LTE-Femtocell Networks

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***Abstract*—The trade-off between energy efficiency and downlink spectral efficiency for LTE-femtocells can be significantly balanced by a novel interference management technique in the presence of the interference from the co-channel outdoor micro-cell and the neighbouring femtocell access points. The simulation results have been demonstrated to be meaningful in the context of considering capacity saturation of realistic modulation and coding schemes rather than theoretical Shannon's equation. The paper shows that the radio-head and operational improvement of up to 12% and 3% can be achieved. Moreover, it has been shown that the improvement does not significantly degrade the user's data rate and the proposed scheme can be implemented in unplanned self-organising networks.**

I. Introduction

Recently, a new sort of indoor base stations (BSs) called femtocell access points (FAPs) have been proposed to improve the Quality of Service (QoS) for indoor users at low cost [1]. They enable indoor connectivity through existing broadband Internet connections. Despite the huge potentials of femtocells, they still face many technical challenges relating to power control, energy consumption and interference management [2]. The strategy of interference mitigation used in a two-tier network directly influence the performance which is limited by cross-tier interference between micro-cell and femtocell networks [3].

A. Review of Existing Work

Several existing research [4], [5] has been focusing on the improvement of the spectral efficiency for femtocell network. The author in [4] outlines the cognitive radio technologies for the future mobile broadband era by proposing a cognitive femtocell solution for indoor communications in order to increase the network capacity in serving indoor users and to solve the spectrum-scarcity problems. The aggregate throughput of two-tier femtocell networks has been improved by a beamforming codebook restriction strategy and an opportunistic channel selection strategy [5]. However, the above studies did not take into account the energy consumption.

However, there also have been various approaches to investigate the power consumption and interference mitigation of the cellular networks. Much of the previous work [3], [6], [7] has focused on minimising the transmitting power of BS. The authors in [8] proposed a new automated method of simultaneously maximising coverage while minimising interference for a desired level of coverage overlap. [9] described an approach of adjusting the FAP's transmit power for fixed positions of FAPs in the enterprise offices to achieve coverage optimisation and load balance, but did not consider the evaluation of effect on user's QoS. [10] derived the downlink SINR formula for the residential femtocell but the formula had not taken the throughput into account. A theoretical framework was proposed in [11] to analyse the interference characteristics of different femtocell sub-bands for Orthogonal Frequency-Division Multiple Access (OFDMA) systems employing the Fractional Frequency Reuse scheme which can be extended to optimise power and frequency allocation, but the path loss model employed in this framework is far too simple to reflect the real characteristics of the indoor scenario.

B. Research Contribution

In this paper, a network where both the micro-cell and the LTE-femtocell use OFDMA signalling is considered. It is necessary to carefully analyse the interference to the observed FAP as the interference from the dominated source severely affects system capacity and energy consumption. From an interference management point of view, the granularity of resource allocation in OFDMA makes it possible to estimate the interference thus providing the opportunities to mitigate the interference on a sub-carrier basis. In this study, a novel interference management approach is proposed and the channel quality improvements derived from there are shown to improve the energy efficiency of the E-UTRAN.

C. Paper Outline

This paper is organised as follows. Section II briefs the LTE-feomtocell simulator and the details of the Sequential Game Coordinated Radio Resource Management (SGC/RRM) algorithm. In Section III, the energy metrics are illustrated and derived. The simulation results comparing the performance of Signal to Interference-plus-Noise Ratio (SINR), spectral efficiency and energy efficiency are presented in Section IV. Finally, Section V concludes the paper.

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II. SYSTEM MODEL

A. Introduction

An LTE system level simulator has been developed to evaluate SGC/RRM scheme for an enterprise office area. Fig. 1 illustrates the system model. Two **paired FAPs**, which will employ the SGC/RRM algorithm, are placed in the middle of and a number of users are randomly and evenly distributed within the left half of the two office rooms. FAPs in other rooms are defined as '**other FAPs**' in the rest of this paper unless otherwise specified. Rectangular rooms with light internal walls are also considered. The assumptions made are as follows:

- The micro-cell is fully loaded and persistently interfere with the FAPs.
- The paired FAPs are not fully loaded and so that do not interfere with the observed FAPs.
- The effect of FAP interference onto the micro-cell is not considered in this body of investigation as it only concerns indoor coverage.

The path loss models implemented in the simulator are adopted from WINNER A1 and B4 [12]. The indoor line-of-sight (LOS) and non-line-of-sight (NLOS) path loss model $\mathrm{PL}_{\mathrm{in}}^{\mathrm{LOS}}$ and $\mathrm{PL}_{\mathrm{in}}^{\mathrm{NLOS}}$ (between the FAP and the mobile user) and the outdoor-to-indoor $\mathrm{PL}_{\text{out-to-in}}$ (between the micro-cell base station and the mobile user) are defined as follows, respectively:

$$\mathrm{PL}_{\mathrm{in}}^{\mathrm{LOS}} = 18.7\log_{10}(d_{\mathrm{FAP}}) + 46.4 + 20\log_{10}\left(\frac{f}{5}\right), \tag{1}$$

$$\mathrm{PL}_{\mathrm{in}}^{\mathrm{NLOS}} = 20\log_{10}\left(\frac{d_{\mathrm{FAP}} f}{5}\right) + 46.8 + 5n_{\mathrm{wall}}^{\mathrm{FAP}}, \tag{2}$$

$$\begin{aligned}\mathrm{PL}_{\text{out-to-in}} =& 36.7\log_{10}(d_{\mathrm{micro}}) + 22.7 + 26\log_{10}\left(\frac{f}{5}\right)\\ &+ \mathrm{PL}_{\mathrm{wall}} + 0.5d_{\mathrm{in}},\end{aligned} \tag{3}$$

where f is frequency of transmission in GHz. d_{FAP}, d_{micro} and d_{in} are FAP-to-user, micro-cell-to-user and outdoor wall-to-user distance in metres. $\mathrm{PL}_{\mathrm{wall}}$ is the wall loss penetration factor in dBs. $n_{\mathrm{wall}}^{\mathrm{FAP}}$ is the number of internal walls. The received Signal to Interference-plus-Noise Ratio (SINR) is calculated as below:

$$\gamma = \frac{|h_i|^2 P_i}{\sum_{k=1,k\neq i}^{K} |h_k|^2 P_k + |h_{\mathrm{micro}}|^2 P_{\mathrm{micro}} + \sigma^2}, \tag{4}$$

where h_i, h_k and $h_{\mathrm{micro}} \sim \mathcal{CN}(0,\ 1)$ are the multi-path coefficient of the observed FAP, interfering FAPs and micro-cell base station, respectively. They are modelled as independent and identically distributed (i.i.d.) circularly symmetric complex Gaussian random variables with zero mean and a variance of one. P_i is the received power of one sub-carrier from the observed FAP, P_k and P_{micro} are the received power of the same sub-carrier from the interfering FAPs and micro-cell base station and σ^2 is the noise power. Without considering radio resource management techniques, the paper considers a round-robin scheduler, which evenly partitions the resource blocks between users.

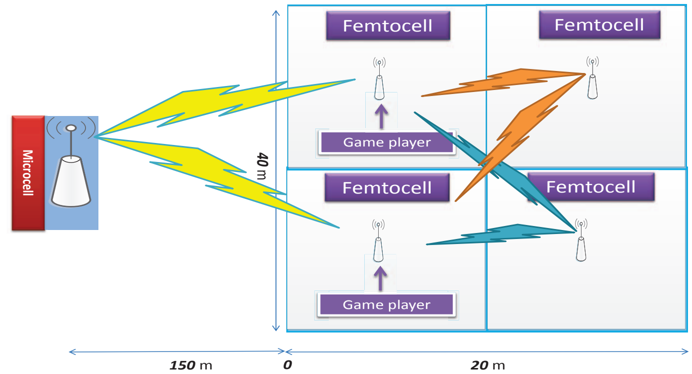

Fig. 1. Simulation model

B. Sequential Game Coordinated Radio Resource Management (SGC/RRM) Algorithm

The motivation of the SGC/RRM algorithm is to exploit the communication between the FAPs, via the X2 interface, with a vision of exchanging instantaneous offered load information with the objective of reducing the neighbouring FAP interference thus reducing the required transmit power thereby reducing the energy consumption. In this study, the SGC/RRM algorithm is defined as a dynamic radio resource allocation functionality modelled as a two player sequential game in which both players are independent FAPs. A two player sequential game generally involves the first player choosing a strategy and then the second player deciding what strategy to adopt based on the strategy of the first player. In this study the sequential game was played out between the two FAPs closer to the micro-cell as shown in Fig. 1.

1) Player Status Assignment (PSA): PSA determines the principal player FAP and the agent player FAP. PSA is formulated as follows:

$$\begin{aligned}&\text{maximise} && \sum_{k\in\{0,1\}} L_k(1-\beta_k)\\ &\text{subject to} && \sum_{k\in\{0,1\}} \beta_k \leqslant 1.\end{aligned} \tag{5}$$

where k is the FAP index, L_k is the offered load (Mbit/s) of FAP k. β_k are binary values, $\beta_k \in \{0,1\}$, which represent the PSA. The value of β_k is 1 if cell k is the agent player and 0 if cell k is the principal player.

2) Game Strategy Definition: The game strategy of each player (principal or agent) defines the choice of transmission frequency bands. The transmission frequency band strategy set S_t for both the principal player and the agent player was carefully chosen to adhere to the possible LTE bandwidth utilisation specifications i.e. 1.4, 3, 5, 10, 15 and 20 MHz. S_t is defined as:

$$\begin{aligned}S_t = \{&Idle, VLow, Low, MediumL,\\ &MediumH, High, VHigh\}.\end{aligned} \tag{6}$$

Considering a maximum LTE transmission bandwidth of 20MHz, Fig. 2 presents the SGC/RRM algorithm definition

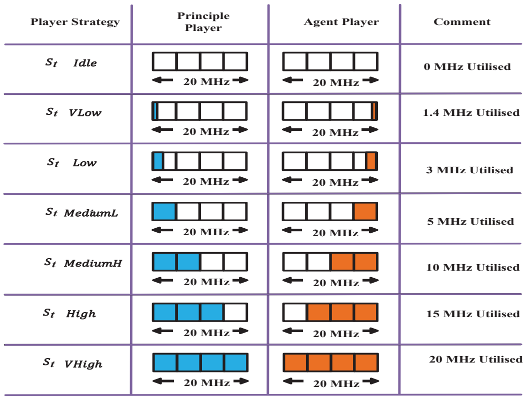

Fig. 2. SGC/RRM algorithm player strategy definition

of the individual FAP strategies. Furthermore the individual strategies of the principal player and the agent player were designed to avoid interference between the players.

3) Player Interference Rank Measurement: The FAP interference rank measurement R_k is a classification of the amount of interference to FAP k due to the paired FAP participating in the SGC/RRM algorithm. The FAP interference rank measurement of each player is a function of the transmission frequency strategies adopted by both the principal (S_t^P) and agent (S_t^A) players.

$$R_k = f(S_t^P, S_t^A), k \in \{\text{Principal, Agent}\}, \tag{7}$$

where S_t^P and S_t^A are the transmission frequency strategies of principal and agent players respectively, defined in Eq. (6). Higher FAP interference rank values represent greater interference between the players Thus the FAP interference rank R_k is proportional to the number of interfering frequency bands. In this study the constant of proportionality was chosen as unity, however any positive constant may be utilised.

$$R_k = F, k \in \{\text{Principal, Agent}\}, \tag{8}$$

where F is the number of interfering frequency bands in MHz.

C. Player Strategy Selection

First the principal player decides what strategy to adopt based on the offered load presented, and then the agent player decides what strategy to adopt given the strategy of the principal player. The SISO capacities of the LTE Physical Downlink Shared Channel (PDSCCH) for 1.4, 3, 5, 10, 15 and 20 MHz are 4.26, 10.65 17.75, 35.51, 53.26, 71.01 Mbit/s, respectively using the highest modulation and coding scheme (MCS). In order to achieve these capacity values, SINR values greater than 35.94 dB are required. Since the users on average experience SINR values of 30 dB, this paper utilised a reduction factor of $\frac{10^3}{10^{3.594}} = 0.25$ from the capacity values in order to characterise the instantaneous offered load, e.g. offered loads between 0 Mbit/s and 1.1 Mbit/s (4.26 × 0.25) are characterised as low loads. The agent player chooses a transmission strategy from the set of transmission frequency strategies that minimises its FAP interference with the principal player given the transmission frequency strategy adopted by the principal player, Eq. (9).

$$S_t^A = \min_{s \in S_t} (R_A | S_t^P). \tag{9}$$

The best response strategies are the strategies that result in a FAP interference rank measurement of zero. From the player FAP interference rank payoff matrix (Table. I), it is observed that there are multiple best responses (roll back equilibriums) that the agent player can adopt given the strategy of the principal player. In situations where the agent player has multiple best response strategies to the strategy adopted by the principal player, the agent's best response strategy that utilises more of the transmission band is chosen as the agent players strategy. It is worth noting that the principal player will only play the idle strategy if and only if the offered load presented is 0 Mbit/s; by definition this implies that the agent player also has an offered load of 0 Mbit/s. The SGC/RRM algorithm is repeated periodically to capture the dynamic characteristics of the instantaneous offered load and ensure that no single players (FAPs) dominate the principal player status.

III. Energy Metrics

For a given amount of data demanded, the higher the femtocell capacity, the lower the transmission time $T_{\text{FAP}}^{\text{RH}}$. This can also be translated to an radio-head (RH) energy reduction, which can be extended to the operational (OP) energy reduction by considering a fixed over-head (OH) power consumption. The energy consumption can be reduced to a lower-bound of the ratio between the OH power and the OP power, which is about 80%. In order to compare the energy consumption of the same system operating in different conditions, the concept of transmission duration and operational duration are defined. Consider a FAP with indoor users that demand a traffic load of M bits of data over a finite time duration of $T_{\text{FAP}}^{\text{OH}}$. Two systems are considered: a reference and a test system, both of which have a capacity that exceed the offered traffic load. Due to the fact that the reference and the test system might have different capacities and scheduling mechanisms, the duration which the radio-head spends in transmitting the same M bits is different. In order to compare two systems, useful metric is the Energy Reduction Gain (ERG), which is the reduction in energy consumption when a test system is compared with a reference system:

$$\text{ERG}_{\text{RAN}}^{\text{OP}} = 1 - \frac{E_{\text{FAP,test}}^{\text{OP}}}{E_{\text{FAP,ref.}}^{\text{OP}}} = 1 - \frac{P_{\text{test}}^{\text{RH}} L_{\text{test}} + P_{\text{test}}^{\text{OH}}}{P_{\text{ref.}}^{\text{RH}} L_{\text{ref.}} + P_{\text{ref.}}^{\text{OH}}}, \tag{10}$$

where $P_i^{\text{RH}} = P_i^{\text{RF}}/\mu_\Sigma$, P^{RF} is the radio-head power, P^{OH} is the FAP over-head power and μ_Σ is the radio-head efficiency [13]. The throughput of the system is defined as $R_{\text{FAP},i} = M/T_{\text{FAP}}^{\text{RH},i}$, which is greater or equal to the offered load, $R_{\text{traffic}} = M/T_{\text{FAP}}^{\text{OH}}$, and $L_i = \frac{R_{\text{traffic}}}{R_{\text{FAP,i}}}$ is the ratio of the offer load to the throughput. The term $\frac{P_i^{\text{RH}}}{R_{\text{FAP},i}}$ in (10) is an indication of the average radio transmission efficiency, which

TABLE I
INTERFERENCE RANK PAY OFF MATRIX

	S_t^A Idle	S_t^A VLow	S_t^A Low	S_t^A MediumL	S_t^A MediumH	S_t^A High	S_t^A VHigh
S_t^P Idle	0	0	0	0	0	0	0
S_t^P VLow	0	0	0	0	0	0	1.4
S_t^P Low	0	0	0	0	0	0	3
S_t^P MediumL	0	0	0	0	0	0	5
S_t^P MediumH	0	0	0	0	0	5	10
S_t^P High	0	0	0	0	5	10	15
S_t^P VHigh	0	1.4	3	5	10	15	20

does not consider the overhead energy. This is commonly used to measure energy consumption in literature [14], and is known as the Energy-Consumption-Ratio (ECR).

IV. SIMULATION RESULTS

In this section, the paper presents the performance of the interference avoidance techniques in terms of the SINR performance, the spectral efficiency, the radio-head ECR and the operational ERG. The details of the system parameters and model assumptions are: Room size (10 m × 20 m), system bandwidth (20 MHz), carrier frequency (2130 MHz), total number of users (21), user distribution (Uniform), FAP transmit power (0.1 W), FAP radio-head efficiency (6.67%), FAP overhead power (5.2 W), micro-cell antenna gain (10 dBi), d_{micro} (150 m), outdoor wall loss (10 dB), indoor wall loss (5 dB) and interference from other FAPs (0–10 W). The SINR performance is used to quantify the expected channel quality experienced by a user measured in dBs. The spectral efficiency is used to analyse the efficiency of the FAP networks in bits/s/Hz. The radio-head ECR performance and the operational ERG are used to measure the energy efficiency of the FAP networks in Joules/bit and the operational energy comparison in percentage, respectively.

The SGC/RRM algorithm dynamically mitigates the effects of FAP interference based on the instantaneous offered load presented to the individual FAP in the E-UTRAN. Fig. 3(a) illustrates the comparison of the SINR performance of the user grids with and without using SGC/RRM algorithm. It can be found that the SGC/RRM algorithm produced a higher SINR range compared to the baseline scenario without eliminating any FAP interference. The SINR performance improvement of the SGC/RRM is a result of that a user in a particular FAP will not experience interference from one of the dominant neighbouring FAP due to the fact that the user's serving FAP is engaged in the SGC/RMM algorithm with one of the dominant interfering FAP. An improvement in SINR translates to utilisation of fewer resource blocks for a given offered load, thus reducing the required transmit power and radio-head energy.

The comparison of the spectral efficiency for the FAP network is presented in Fig. 3(b). It can be seen that the spectral efficiency decreases in both baseline and SGC/RRM algorithm scenario along with the increase of total interference from those which are not paired into this particular group. However the difference in spectral efficiency of the two scenarios reduces dramatically with the increase of the interference. Due to the fact that most of the user's SINRs are usually in the high regime as shown in Fig. 3(a), all the users can be scheduled in the first TTI. That is to say, the targeted QoS for each user is met.

The radio-head and operational energy performance of the SGC/RRM algorithm were compared with the baseline scenario as shown in Fig. 3(c) and Fig. 3(d). The SGC/RRM algorithm is more energy efficient than the baseline case. This can be explained that the SGC/RRM algorithm provides the two players a change to use only half of the total radio power in the whole network compared to the baseline scenario to produce more than half of the total RAN throughput. It can be found that the SGC/RRM algorithm works more effectively when the strength of the surrounding interference becomes stronger (i.e. larger than 15 dB). It should also be noted that this algorithm can offer 2.5%–3.5% and 1.6%–2.2% of the operational energy reduction in high load and low load scenarios.

V. CONCLUSIONS

This body of investigation has proposed a novel strategy of interference avoidance for indoor LTE-Femtocell deployment, which mitigates the effects of interference through a sequential game play between FAPs in the E-UTRAN based on the offered load presented to the individual FAP. This is done for a 2D office scenario. The comparisons of the simulation results have shown that up to 12% in radio-head energy and 3% in operational energy can be saved by consuming less than half radio-head power while maintaining the user offered load unchanged.

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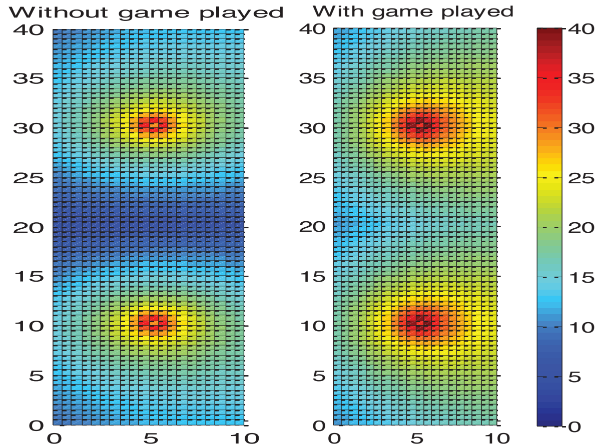
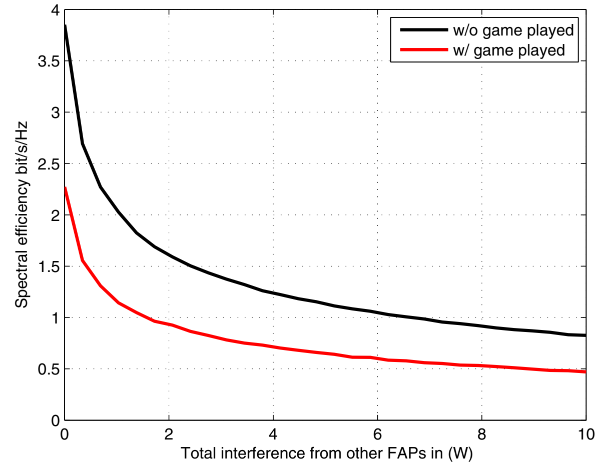
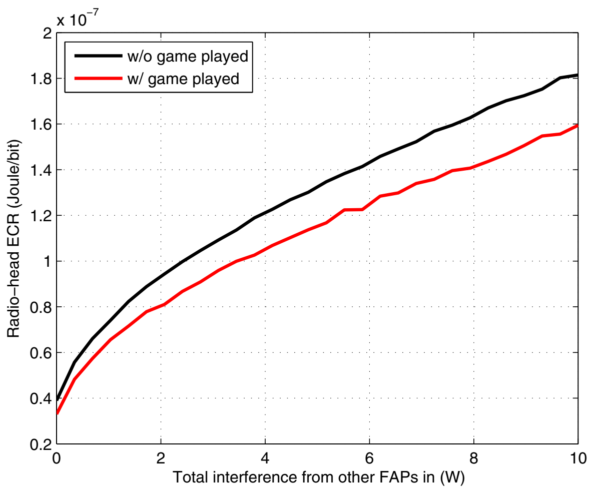


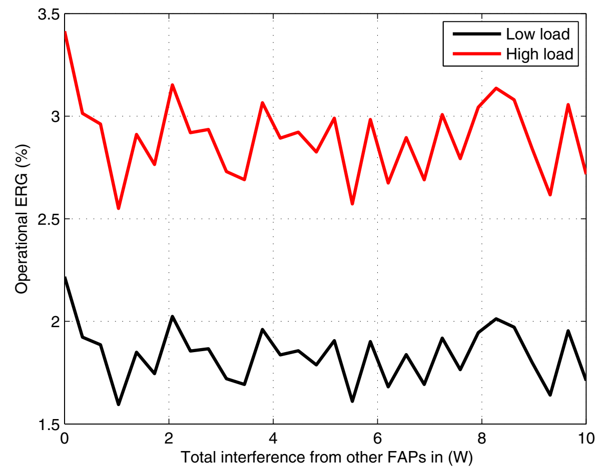
(a) User SINR distribution



(b) Spectral efficiency



(c) Radio-head ECR



(d) Operational ERG

Fig. 3. Trade-off of spectral efficiency and energy efficiency

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