Hybrid Cognitive Approach for Femtocell Interference Mitigation

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***Abstract*—In this paper, we introduce new concept for femtocells with the purpose to minimize cross-tier interference to the macrocell users (MUEs). The cross-tier interference is mitigated by the power control algorithm minimizing the power level and, thus, ensuring that all currently active femto users (FUEs) can attach to the femto access points (FAPs). To guarantee quality of service to the FUEs even at heavy load, despite low transmitting power, the FAPs can opportunistically utilize also SU bands. To that end, we denote our scheme as a hybrid cognitive approach, which is distinguished by the fact that the FAPs can access bandwidth as a primary users (PU) and secondary users (SU) at the same time. In order to generate less overhead introduced by sensing for the purpose of determining available spectrum, we also propose an algorithm that adaptively changes a sensing period. The results show that our proposal is able to significantly reduce cross-tier interference nearly to the same level as achieved by algorithms focusing on maximization of the MUEs' performance. At the same time, our proposal ensures that the performance of the FUEs is kept at satisfactory level similarly as in the case of the algorithms focusing solely on the performance of the FUEs.**

Keywords-interference mitigation; femtocell; cognitive capabilities; sensing; power control.

I. INTRODUCTION

The Femto Access Points (FAPs) are small base stations deployed mostly indoor to cover locations with weak signal from a Macro Base Station (MBS) and to enhance performance of indoor users. The FAP can be classified depending on its access strategy into three types [1]: i) open access - the users have no restriction in accessing the FAPs, ii) closed access - only small group of users can connect to the FAPs, and iii) hybrid access a combination of both previous strategies. The FAPs can use either different frequency bands than the MBS (i.e., dedicated channel deployment) or share (fully/partly) the same bandwidth as the MBS (i.e., co-channel deployment) [2].

As pointed out by Hobby and Claussen [3], the main concern regarding the implementation of the FAPs is to guarantee that the macrocell users (MUEs) are not negatively affected by the FAPs, if closed access is considered and co-channel deployment is used. At the same time, the challenge is to achieve high performance of femtocell users (FUEs) to enable high data transmission within the coverage of the FAP. This is not a trivial problem, especially if a lot of FAPs are supposed to be deployed.

One feasible option to reduce interference is to use various power control approaches. Claussen et al. [4] propose three self-optimization schemes aimed to minimize interference to outdoor MUEs and to minimize number of generated handovers. Although the proposed power control can significantly mitigate the amount of handovers, the MUEs close to the FAP experience low SINR (Signal to Interference plus Noise Ratio). In addition, the self-optimization schemes do not always guarantee sufficient house coverage. Jo et al. [5] aim to minimize interference caused by the FAPs to passersby users, while providing sufficient indoor coverage. Yun and Cho [6] propose to adapt the FAPs power depending on the queue length at the FAP. If the queue length is low, the FAP decreases its transmitting power. In the opposite case, the FAPs power is increased in order to serve all generated data. In [7], we have designed Quality of Service guaranteed power control (QPC) algorithm. The transmitting power of the FAP is adapted not only according to current traffic load like in [6] but also according to the signal quality among the FUEs and the FAP in order to fully utilize data frame at physical layer. Still, schemes based on [6][7] are highly effective only for lower traffic loads. At heavy traffic loads, the power of the FAP has to be increased to satisfy all FUEs requirements and cross-tier interference rises as well.

Other eligible option for interference avoidance is to exploit cognitive radio and dynamic spectrum management [8]. Yu et al. [9] consider that the FAPs are able autonomously sense the radio frequencies used by the MBS and, thus, to schedule their transmission at unoccupied frequency spectrum. In addition, the optimal period for sensing of free radio resources is derived. Dynamic spectrum reuse in network with closed access FAPs is proposed by Demirdogen et al. in [10]. If the MUE is close to the FAP, the FAP equipped with cognitive radio decides whether to occupy the same frequencies or not (perfect sensing is assumed). Li and Sousa [11] view the FAP as a secondary system, which autonomously allocates orthogonal channels to avoid disturbing the MBS and its users. The objective to minimize interference among the FAPs is addressed by Li et al. in [12]. The FAPs cognitively recognize unoccupied frequencies and schedule their transmission accordingly. All above mentioned papers assume that the FAPs use only resources not currently utilized by the MBSs.

Rubaye et al. [13] exploit wider bandwidth by the FAPs than the MBS to support high demanding services in indoor environment. This work is further elaborated by Xie et al. in [14], where the idea is to use wider bandwidth by leasing available spectrum from other PSs. The authors consider leasing available spectrum among the MBSs only. Then, the leased spectrum is dynamically assigned to the FAPs to support high demanding services in indoor environment. Both [13] and [14] are solely focused on performance of indoor users and the negative impact of the FAPs on the MUEs is not addressed.

In summary, the power control alone is not always able to mitigate cross-tier interference to the MUEs while satisfying QoS for the FUEs. At the same time, disadvantage of conventional cognitive approaches is that the amount of radio resources available to the secondary users (SUs) is highly dependent on activity of primary users (PUs). In this paper, the minimization of cross-tier interference is accomplished by power control, which sets transmission power of the FAPs only to such level that all active FUEs are able to connect to the FAP. In order to compensate for low transmitting power, we further introduce new concept, where the FAPs could access radio resources as a PU and SU simultaneously. Hence, if the PU bandwidth is not sufficient, the FAP can opportunistically use SU bands. The main advantage of this approach is that the FAPs are not fully dependent on other PU(s) and have always some radio resources at disposition. Since the FAPs are not able to transmit or receive any data when sensing is being performed [9], we try to maximize the profit obtained from the opportunistic usage of SU bands. To this end, we propose new algorithm minimizing the sensing time and sensing overhead, where the sensing period is adaptively changed depending on the loads of the FAP and other PUs.

The rest of the paper is structured as follows. The next section describes the system model together with problem formulation. Section III describes proposed power control algorithm and algorithm for dynamic change of sensing period. The simulation methodology and simulation results are addressed in Section IV and Section V, respectively. The discussion regarding simulation results are tackled in Section VI. The last section gives our conclusions and future work plans.

II. SYSTEM MODEL AND PROBLEM FORMULATION

The system model considers three cellular operators (denoted as Operator A, Operator B, and Operator C) covering the same geographic area. The same frequency bandwidth is assigned to each operator. In order not to interfere with each other, allocated frequency bandwidths are not overlapping (i.e., each operator has dedicated its own bandwidth). We assume that the FAPs deployed in the area use primarily frequency bandwidth allocated to Operator A, i.e., the FAPs use this bandwidth as a PUs and this frequency band is referred to as a Primary Frequency (PF). Further, we assume that all FAPs have cognitive sensing capabilities and can utilize frequency bands of other two operators. Consequently, the FAPs use frequencies of Operator B and Operator C as SUs. In this paper, these bands are referred to as a Secondary Frequency (SF). Note that the SF band can be composed from more than one secondary system. In addition the FAPs could, in general, access not just frequency bands assigned to other operators but also other available free spectrum can be utilized for our purpose.

Our study is narrowed down, without loss of generality, to area covered by one MBS of every operator as indicated

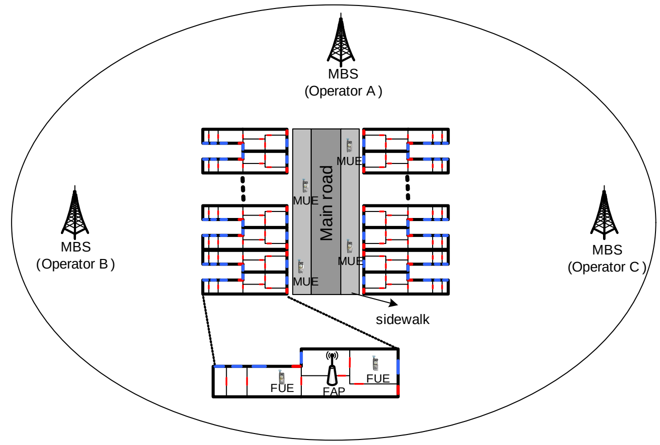

Figure 1. System model.

in Fig. 1. In this area, K femtocells are deployed transmitting with power $p_{t,1}, p_{t,2}, ..., p_{t,K}$. The FAPs are located close to the sidewalk and in the proximity of the MUEs. This scenario is very challenging in mitigating cross-tier interference, since the MUEs can experience low SINR. Note that SINR of the m-th MUEs (SINRm) is derived as

$$SINR_m = \frac{|h_{mk}|^2 \times P_t}{N + \sum_i^K |h_{mi}|^2 \times p_{t,i}}, \tag{1}$$

where $|h_{mk}|^2$ is a channel gain between the MUE and its serving MBS, $|h_{mi}|^2$ represents a channel gain between the MUE and the *i*-th FAP, P_t corresponds to the transmitting power of the MBS and N stands for the thermal noise. Similarly, SINR of the *f*-th FUE ($SINR_f$) is calculated as

$$SINR_f = \frac{|h_{ii}|^2 \times p_{t,i}}{N + \sum_{f \neq i} |h_{ft}|^2 \times p_{t,i} + |h_{fk}|^2 \times P_t}, \tag{2}$$

where $|h_{ii}|^2$ is a channel gain between the FUE and its serving FAP, $|h_{ft}|^2$ represents a channel model between the FUE and interfering FAPs and $|h_{fk}|^2$ corresponds to channel gain between the FUE and the MBS.

The maximum number of FUEs connected to one FAP is supposed to be up to four [15]. Since the access to the FAP is closed, only those FUEs belonging to FAP's Close Subscriber Group (CSG) can connect to it.

Both the MBS and the FAPs adopt OFDMA (Orthogonal Frequency Division Multiple Access) system based on LTE-A (Long Term Evolution-Advanced). The smallest amount of radio resources allocated for one user corresponds to a radio Resource Block (RB) occupying n_{SC} consecutive subcarriers in a frequency domain, and n_{SMB} OFDM (Orthogonal Frequency Division Multiplexing) symbols in a time domain. The RB is further decomposed to Resource Elements (REs) encompassing one subcarrier over one OFDM symbol. The amount of data transmitted in one RB for user j is derived as

$$n_{RB}^j = \Gamma \times \left(n_{SC} \times n_{SMB} - n_{OH}^{RE}\right), \tag{3}$$

 ISBN: 978-1-61208-318-6

where Γ is a transmission efficiency and n_{OH}^{RE} represents the number of REs in one RB dedicated for signaling overhead (e.g., reference signals or control information). The parameter Γ indicates the quantity of bits sent per RE and it depends on selected modulation and coding scheme (MCS) assigned according to the measured SINR. The amount of RBs per frame necessary for data transmission of m active FUEs is calculated as

$$n_{RB,r} = \sum_{j=0}^{m} ceil\left(\frac{\eta^j}{\eta_{RB}^j}\right), \quad (4)$$

where η^j is the amount of data sent in downlink (DL) for user j. The data is transmitted in a physical layer frame consisting of twenty RBs (m_{RB}) in time domain. In frequency domain, quantity of RBs per one frame (χ) depends on selected bandwidth (χ varies between 6 and 110). As a consequence, the amount of RBs available for a FAP during one frame within PF band is

$$n_{RB}^p = \chi \times m_{RB}. \quad (5)$$

Similarly, the amount of radio resources available in SF bands can be expressed as

$$n_{RB}^s = \left(\chi \times m_{RB} - n_{RB}^{B,u}\right) + \left(\chi \times m_{RB} - n_{RB}^{C,u}\right), \quad (6)$$

where $n_{RB}^{B,u}$ and $n_{RB}^{C,u}$ represent the quantity of RBs currently used by the MBSs of Operator B and Operator C. To decide, which radio resources at SF bands are not occupied, the FAPs are equipped with sensing functionality. The physical frames are sorted into sensing and data frames. The FAPs perform sensing solely during the sensing frames while the data frames are dedicated only for data transmission (including signaling). The overhead caused by the sensing of the i-th FAP is indirectly proportional to sensing period, T_s, and it is calculated as

$$\sigma^i = n_{RB}^p \times \frac{T_f}{T_s^i}, \quad (7)$$

where T_f represents length of one frame.

In general, the paper aims at addressing two problems. The first problem is to minimize FAPs transmitting power to avoid cross-tier interference to the MUEs. Thus, if we define P_{min} and P_{max} as the minimal and maximal transmitting power of the FAPs and $S_j = \{s_1^i, s_2^i, ..., s_g^i\}$ as a set of experienced SINR of q active FUEs connected to FAP i, our goal is to

$$min \sum_{i=1}^{K} p_{t,i} \quad (8)$$

$$s.t.\ s_i > SINR_{min} + \delta | \forall s_i \in S_i, \quad (9)$$

where $P_{min} \leq p_{t,i} \leq P_{max}$, $SINR_{min}$ represents the minimal value of SINR guaranteeing that the FUE is able to connect to the FAP and parameter δ stands for fading margin to have certain reserve to protect FUEs again fading effects.

The second problem is to minimize the sensing overhead and, thus, to maximize throughput for FUEs despite low transmitting power of the FAPs. Sensing overhead is a function of the current FUEs requirements ($n_{RB,r}$), the amount of radio resources in PF band (n_{RB}^p) and in SF bands (n_{RB}^s). Hence, the second objective is formulated as

$$min \sum_{i=1}^{K} n_{RB}^p \times \frac{T_f}{T_s^i} \quad (10)$$

$$s.t.\ T_{min} \leq T_s^i \leq T_{max}\ and\ T_s^i = f\left(n_{RB,r}, n_{RB}^p, n_{RB}^s\right). \quad (11)$$

III. PROPOSED SCHEME

The basic principle of the proposed scheme is depicted in Fig. 2. The FAP accesses the frequency band of Operator A as a PU. Note that the whole bandwidth of Operator A can be used by the FAP when compared, e.g., to [9] or [10], where only fraction of bandwidth, not occupied by the MBS, is available to the FAPs. To guarantee minimal cross-tier interference to MUEs of Operator A, the power of the FAP is set only to such level to maintain reliable connection between the FAP and its worst FUE (i.e., the FUE with the lowest SINR). Thus, the worst FUE has to utilize a more robust MCS (in Fig. 2, the FUE2 is the worst FUE and hence it uses 1/3 QPSK [16]). On the other hand, the radio channel between the FAP and the FUE1 is of a better quality. As a result, more efficient MCS is applied (in Fig. 2, 2/3 16QAM is shown as an example). The QoS of the FUEs would be degraded if only PF band is used by the FAP and if FUE's requirements exceed the number of available RBs at PF. An increase of power of the FAP can result in high cross-tier interference to the MUEs. Therefore, we rather suggest utilizing additional RBs of the Operator B and Operator C that are not currently used.

Our proposal is composed of two algorithms: power control algorithm and algorithm for dynamic adaptation of sensing period. These are described in detail in the next subsections.

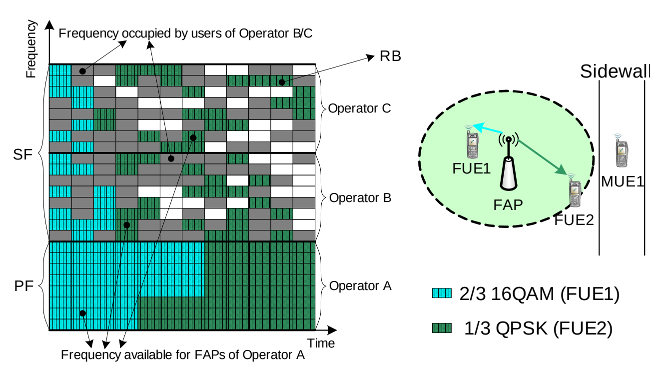

Figure 2. The example of proposed principle.

A. Power control algorithm

The flow chart of the power control algorithm is depicted in Fig. 3. First, the FAP discovers whether there is at least one active FUE. This is continuously determined after expiration of adaptation interval Δt. If no data are transmitted, the power of the FAP is set to its minimal value (P_{min}) to decrease a probability of interference to the close MUEs. In the opposite case, the transmitting power of the FAP is adjusted according to channel quality between the FAP and active FUEs. The transmitting power of the FAP is decreased by power adaptation step ΔP if

$$\forall s_j \in S_j |\ s_j > (SINR_{min} + \delta + \Delta P)\,. \tag{12}$$

The transmitting power after each iteration cannot exceed its minimal allowed value (P_{min}). Note that parameter ΔP serves as a kind of hysteresis to guarantee that the power is not decreased if the power was increased in the previous Δt. The transmitting power of the FAP is incremented by ΔP if

$$\exists s_j \in S_j |\ s_j < (SINR_{min} + \delta)\,. \tag{13}$$

Similarly as in previous case, the FAP can increase its transmitting power only to P_{max}.

The example of power adaptation according to the observed SINR is depicted in Fig. 4 where we assume, for the sake of clarity, that just one active FUE is attached to the FAP. At the beginning of the process, the transmitting power is set to P_{max} and subsequently is decreased until $s_j = SINR_{min} + \delta + \kappa$, where κ varies between 0 and ΔP (see Fig. 4). As long as the SINR is within allowed limits (i.e., $SINR_{min} + \delta < s^j < SINR_{min} + \delta + \Delta P$), the power remains the same. Note that slow fluctuation of SINR in Fig. 4 can be caused by slow movement of indoor users, not by different transmitting power of the FAP. The FUEs SINR can be temporarily not within allowed limits due to fading effects (in Fig. 4 indicated by variable η). If the SINR is suddenly increased, there is no harm for the FUE and transmitting power of the FAP is subsequently decreased. In the opposite case when the SINR is abruptly decreased, the outage can occur. This phenomenon is illustrated in Fig. 4 by sudden drop of SINR below $SINR_{min}$ during Δ_{out}. As a consequence, the transmission power of the FAP is increased step by step as long as all active FUEs experience sufficient SINR. The time when the FUE is in the outage needs to be minimized. This could be accomplished by proper setting of the power control parameters such as Δt, ΔP and δ. Due to space limitations and since the paper is rather focused on introduction of hybrid cognitive approach, the optimization setting of individual parameters is left for future research.

B. Algorithm for dynamic adaptation of sensing period

If radio resources at the PF band are not sufficient for the FUEs, the FAP can access also SF bands, if available. In order not to interfere with the MUEs of Operator B and Operator C, the FAP has to be aware of which RBs are currently utilized at SF bands. This is accomplished by sensing

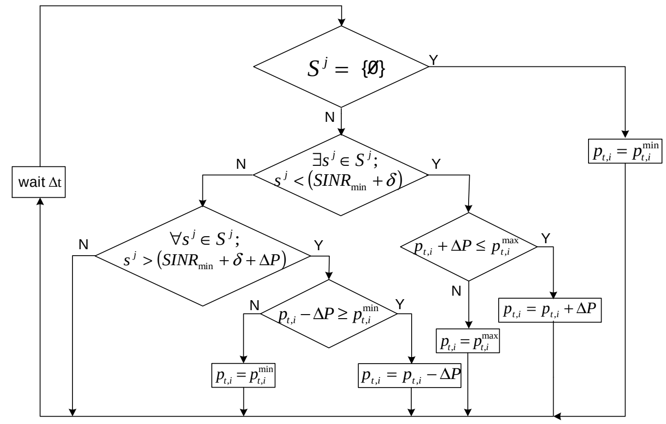

Figure 3. Flow chart of proposed power control algorithm.

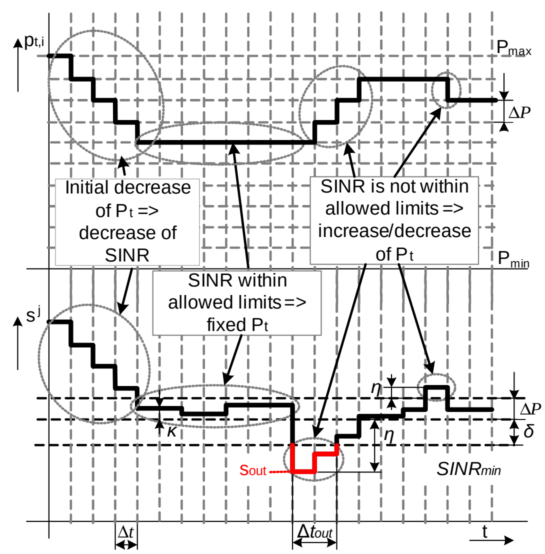

Figure 4. The example of power adaptation and its impact on observed SINR for *j*-th user.

the transmissions at SF to avoid interference. Contrary to [9], where fixed T_s is assumed we propose to set T_s dynamically depending on current traffic load of both the FAP and SF bands. The objective is to minimize the overhead generated by the sensing algorithm, i.e., to perform sensing only if it is profitable for the FAP.

The proposed algorithm for dynamic change of the T_s is depicted in Fig. 5. The sensing procedure is initiated after the power control is performed and once the required amount of RBs for DL transmission is derived. After the sensing is complete, it is evaluated if the amount of radio resources available for the FAP at the PF band is sufficient with respect to users requirements (i.e., if $n_{RB}^{p} > n_{RB,r}$). If this is the case, the T_s is set to its maximal value to minimize the sensing overhead. In this situation, the sensing is redundant, since the FAP uses only PF band. Nevertheless, it is still profitable to perform sensing occasionally to have overview regarding utilization of radio resources in SF bands. In this case, the algorithm sets Secondary Spectrum Usage Indicator (SSUI) to "0". The SSUI distinguishes whether the FAP allocates data only at PF or at both PF and SF.

 ISBN: 978-1-61208-318-6

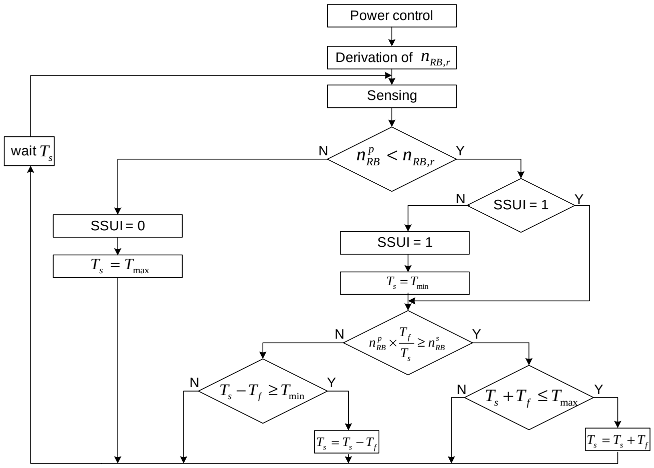

Figure 5. Flow chart of proposed sensing algorithm.

As soon as the amount of RBs available for the FAP at PF band is not sufficient (i.e., if $n^p_{RB} < n_{RB,r}$), the SSUI is switched to 1. After that, Ts is decreased to Tmin. This ensures that the FAP has up to date knowledge on utilization of the SF. Hence, the possibility of the FAP's interference to other PSs is minimized. On the contrary, the amount of generated overhead is increased. As long as the FAP requires additional radio resources to transmit all data, the length of Ts is dynamically changed depending on utilization of SF band by its PUs. Note that the sensing decreases the performance of the FAP if

$$n^p_{RB} \times \frac{T_f}{T_s} > n^s_{RB}, \tag{14}$$

since the sensing overhead is higher than available RBs at SF bands.

If the SF bands are currently overloaded and most of their radio resources are used, the proposed algorithm increases the length of sensing and, thus, decreases sensing overhead. The T_s is continuously increased until it is equal to T_{max} or until the load in SF band is decreased sufficiently. Contrary, T_s can be shortened when the amount of RBs at SF band is sufficient and, hence, more up to date knowledge of SF utilization minimize the probability of interference to other PSs.

The important aspect in sensing procedure is to estimate if RBs are utilized by other PSs or not. In this paper, we assume perfect sensing when the estimation whether RB is occupied or not is without errors similarly as in [10]. The reason is that the main purpose of this paper is not to propose new sensing techniques but we just exploit the ability of the FAP to perform the sensing.

IV. Simulation Setup

To evaluate the performance of the proposed scheme, simulations in MATLAB have been performed. Although the proposal is applicable to any OFDMA-based system, we use simulator based on FDD (Frequency Division Duplex) LTE-A (Release 10) with parameters set-up aligned with Small cell forum as presented in Table I. The movement of MUEs is restricted by sidewalks boundary (see Fig. 1). The MUEs are moving along straight trajectories from south to north with a speed of 1 m/s. Their distance from the house boundary is randomly generated with equal distribution between 1 and 3 meters. The intensity of MUEs arrival to the system follows Poisson distribution and it corresponds approximately to 140 passing users per hour. The movement of the FUEs within the house is based on [4]. At the beginning of the simulation, a start position for all FUEs is randomly selected at some waypoint (four FUEs are considered within each house). After that, the FUEs are moving along predefined trajectories between waypoints and points of decision as depicted in Fig. 7. The time spent by a FUE at the waypoint is described by normal distribution and differs for each room (parameters μ and σ of the distribution are also derived from [4]).

In the simulation, seven positions of the FAPs are selected in a distance varying between 1m to 7m from the house boundaries (see Fig. 6).

The path loss in indoor environment is calculated according to ITU-RP.1238 model. For evaluation of path loss in outdoor environment, COST 231 empirical model is used. Both selected path loss models are assumed, since these are widely used in the evaluation of femtocell concepts [17].

The amount of RBs available in SF band is indirectly proportional to traffic loads experienced by the MBSs of Operator B and Operator C. In the simulation, the traffic load of both MBSs varies between 50% and 100% with mean traffic load set approximately to 65%. This corresponds to the scenario when system is at heavy load state. The variation of the traffic load of the MBSs depends on activity/inactivity of MUEs of Operator B and Operator C. The MUEs change their status from active to inactive and vice versa by means of simple two state Markov model with the probability of 20%

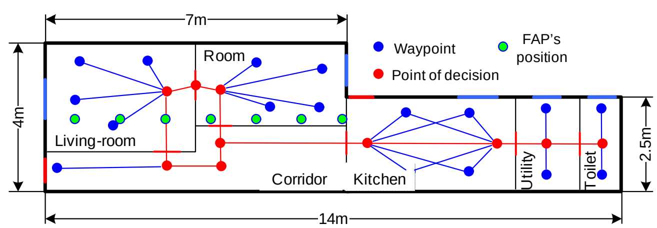

Figure 6. Indoor mobility model.

TABLE I. Parameter's setting

Parameter	Value
Carrier frequency f [GHz]	2.0
MBS/FAP channel bandwidth BW (both primary and secondary bands) [MHz]	10/10
The number of RB in frequency domain χ [-]	50
Frame duration T_f [ms]	10
Max./min. FAP transmit power P_{max} / P_{min} [dBm]	21/-20
MBS transmit power [dBm]	43
Noise [W]	$BW \times 4 \times pW/GHz$
Number of FAPs/houses [-]	50/100
Loss of internal wall, external wall, window [dB]	5, 10, 3
δ [dB]	4
ΔP [dB]	2
Δt [ms]	10
T_{min},T_{max} [s]	0.2, 10
SINRmin [dB]	- 2 [16]
Physical layer overhead [%]	25

that the status of activity is changed. In addition, the outdoor MUEs are supposed to use more voice than data and, thus, voice is applied in 60% while FTP model is applied in 40%.

In the simulations, we have considered several performance metrics. The first one reflects the performance of FUEs, which is measured by served traffic in DL. In this case, model with mean generated traffic of 8.8 Mb/s is implemented in the simulations. The model is a combination of VoIP and FTP models according to [18]. The served traffic load (TL_s) in the performed simulation can be characterized as a difference between the generated traffic load (TL_g) and lost traffic load (TL_l) due to insufficient available radio resources formulated as

$$TL_s = TL_g - TL_l. \tag{15}$$

The second performance metric expresses the performance of the MUEs and it is measured by the transmission efficiency Γ. As already mentioned in Section II, Γ represents the amount of bits that could be sent through one RE. The Γ is derived from SINR, which sets the suitable MCS for data transmission. In our simulation, Γ is derived from SINR of the MUEs according to [16]. Note that the highest MCS (64QAM, coding 4/5) enables to transmit 4.8 bits per one RE [b/RE].

The third performance metric in our simulation is the sensing overhead (see (7)). The minimal value of T_s is set to 0.2 s, i.e., 20 frames. This value is selected in accordance with [9]. On the other hand, the maximal value of T_s is set to 10 s when sensing overhead is negligible, that is, 0.1%.

V. Results

The performance of our approach (in simulation labeled as Hybrid Cognitive Approach, HCA) is compared to the QPC scheme based on [7] and Cognitive Femtocell (CF) approach based on [9]-[12]. The QPC represents the case when the performance of the FUEs is maximized (in terms of served traffic) disregarding impact on the MUEs. On the other hand, the CF corresponds to a scenario when the FAPs use only radio resources not currently occupied by the MBS. Thus, the CF offers the highest performance to the MUEs even if the QoS of the FUEs could be worsened due to insufficient amount of radio resources at the side of the FAP. Note that in case of the CF, the FAPs transmission power is set according to simple auto-configuration scheme based on [4].

Fig. 7 illustrates the performance of outdoor MUEs moving along the sidewalk. The best results are achieved by the CF scheme, where performance is not negatively influenced by the FAPs as the FAPs use different radio resources. Consequently, the transmission efficiency is equal to 2.29 b/RE disregarding the FAPs location or generated load. Note that this value of Γ would be the same for the MUEs if no FAPs were introduced, since perfect sensing is considered and no interference is introduced to the MUEs. Further, it is obvious that the FAPs utilizing the QPC scheme cause the most significant interference to the MUEs as the MUEs experience DL transmission efficiency only in range between 1.02 to 2.07 b/RE. The situation is, in particular, unfavorable if the FAPs are located close to house boundaries. The performance of the HCA is only slightly lower than the performance of the CF in case that the FAP is located between 4 m and 7 m from house boundaries. But also for other cases the results are significantly better than the QPC.

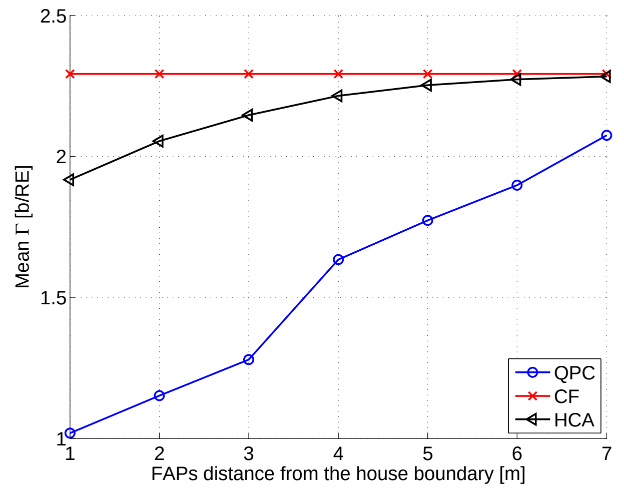

Figure 7. Mean transmission efficiency of MUEs.

Fig. 8 depicts the amount of served traffic for the FUEs. The highest amount of traffic is served in case of the QPC. This corresponds to the fact that the QPC tries, by all means, to satisfy the FUEs in terms of QoS. Consequently, approximately 97% of all generated data are successfully transmitted to the FUEs disregarding the FAPs position or generated load. On the contrary, the CF scheme is able to serve the lowest ratio of traffic varying only between 75% and 82.5%. The HCA scheme is able to ensure that up to 89% of generated traffic can be served indoor, which is substantially higher than in case of the CF.

Fig. 9 shows the influence of the amount of radio resources in SF band on traffic served by the FAPs. The simulations have been performed for all positions of the FAPs similarly as in Fig. 7 and Fig. 8 and subsequently the results were averaged out for individual loads. The performance of the QPC

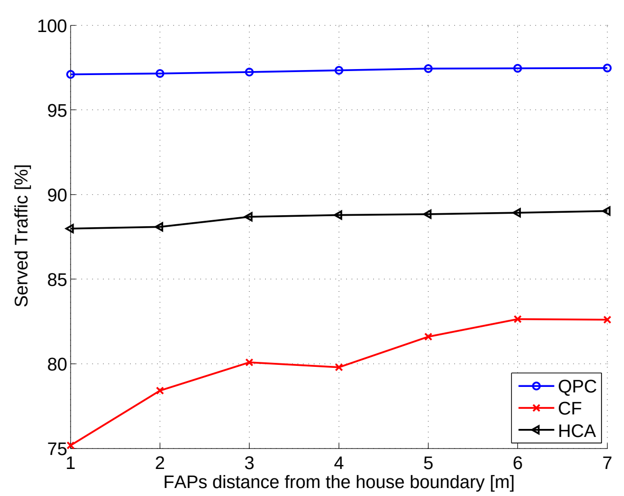

Figure 8. The amount of served traffic for FUEs.

 ISBN: 978-1-61208-318-6

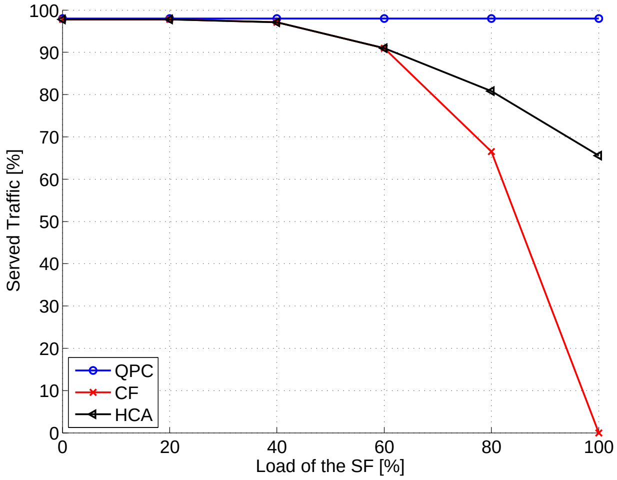

Figure 9. The amount of served traffic for FUEs depending on the load of the SF bands.

is the same as in Fig. 8, since it utilizes only PF band and no SF bands are taken into account. On the other hand, the CF performance is reliant only on the free radio resources in the SF band. As a consequence, the CF is able to serve less amount of traffic than the QPC. In the extreme case if the SF band is totally overloaded, no data can be transmitted by the CF scheme. On the other hand, the proposed HCA is not fully dependent on the utilization of SF bands by their users. Consequently, if no SF bands are available, still 65% can be served.

Fig. 10 presents sensing overhead generated by individual schemes. The highest sensing overhead is caused by the CF where fixed T_s is considered. In this case, 5% of FAP radio resources is required for the sensing. On the contrary, no sensing overhead is produced by the QPC since this scheme does not perform sensing at all. Regarding the HCA, the sensing overhead could be decreased approximately to 3.5%.

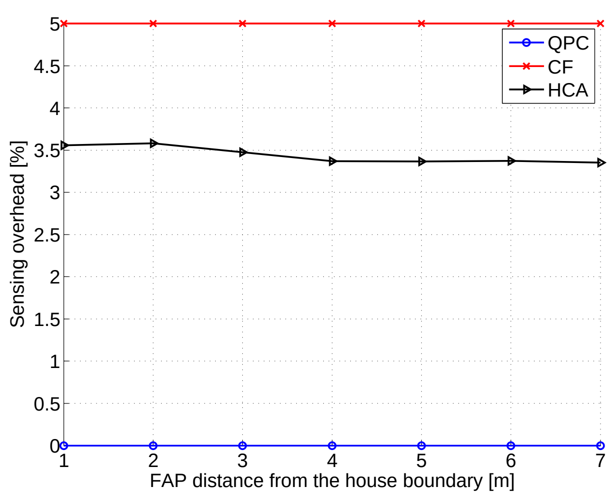

Figure 10. Comparison of overhead generated by sensing process.

VI. Discussion

The comparison of individual methods, when the results are averaged out over all FAPs location, is summarized in Table II. Regarding served traffic for the FUEs, the performance is the highest for the QPC, which serves 97.31% of traffic. Nevertheless, the main weakness of the QPC is its high interference to the MUEs as transmission efficiency is only 1.55 b/RE. Thus, applicability of the QPC is not feasible.

When the performance of MUEs is the main objective, the best results are achieved by the CF as the transmission efficiency is the highest (2.29 b/RE). On the other hand, the CF notably decreases performance of FUEs (only 80.05% is served), which is also not desirable, since the main purpose of the FAP is to enable high indoor data transmission. This problem can be further emphasized if the CF has not enough radio resources at SF. In this case, the CF fails and it is not able to serve FUEs at all (Fig. 9).

Based on above mentioned, the QPC is not suitable for the MUEs, whilst the CF is not sufficient from the FUEs point of view. The performed simulations indicate that the HCA is a convenient compromise between the QPC and the CF schemes. When compared to the CF, the transmission efficiency of MUEs is decreased only negligibly (2.16 b/RE). At the same time, the HCA ensures better performance for FUEs in comparison to the CF (88.61%). Also the sensing overhead is decreased in case of the HCA if compared to the CF.

As already suggested in Section 3A, the performance of the HCA can be further improved by optimization of several parameters such as Δt, ΔP and δ. The setting of individual parameters should be varying in dependence on the position of the FAPs. This way, the performance of the HCA in terms of transmission efficiency of the MUEs can be significantly improved to close the gap between the CF and the HCA. Similarly, the performance of the FUEs can be improved in terms of the FUEs served traffic to minimize a difference between the HCA and the QPC. The setting of optimal parameters is left to future research due to paper length limitation.

VII. Conclusion

paper has proposed a new hybrid cognitive approach where the FAPs can use both primary and secondary frequencies. Low interference to the MUEs is achieved by proposed power control algorithm. In addition, the minimization of sensing overhead is accomplished by algorithm that adaptively changes sensing period.

The results have been compared with two other competitive schemes. In overall, a disadvantage of the QPC is that the interference to the MUEs is significant while the CF degrades the performance of the FUEs, especially if the SF bands are heavily loaded. To that end, the proposed scheme offers a good

TABLE II. Comparison of individual methods

Scheme	**MUEs Γ [b/RE]**	**FUEs served traffic [%]**	**Sensing overhead [%]**
QPC	1.55	97.31	0.00
CF	2.29	80.05	5.00
HCA	2.16	88.61	3.44

trade-off between the MUEs and the FUEs performance. The results accomplished by the HCA can be further improved by optimization of power control parameters, such as adaptation interval, power adaptation step and fading margin. The optimization itself will be done in our future work.

ACKNOWLEDGMENT

This work has been supported by Grant No. 13-24932P funded by the Czech Science Foundation.

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 ISBN: 978-1-61208-318-6