Downlink Femto-Macro ICIC with Blind Long-Term Power Setting

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***Abstract*—Inter-cell interference is a major issue in current wireless cellular systems, in particular with the development of femto-cells. Indeed, macro-femto inter-cell interference coordination is not an easy task and should be performed with a minimum communication between macro- and femto-base stations. We propose a blind inter-cell interference coordination approach, in which each femto base station configures its transmission power autonomously. This power setting aims at maintaining a constant macro-cell performance impact of the femto base station, whatever its location in the macro-cell, i.e., it equalises the macro-degradation. In a 3GPP-LTE context, this approach exhibits a good femto-macro performance trade-off compared to fixed femto base station transmission power.**

I. Introduction

In current mobile cellular networks, like 3GPP Long Term Evolution (LTE) networks, heterogeneous deployments mixing macro base stations (MBS) and home base stations or femto base stations (FBS) are foreseen as an effective way to ensure both mobility within a large geographical area and high data throughput, comparable to wireless LAN, at home [1][2].

Besides, due to the constant network densification resulting in cell size reduction and spectral efficiency increase in mobile cellular systems, inter-cell interference has become a main issue. In particular, fairness between cell-center and cell-edge users [3] must be sought and inter-cell interference coordination (ICIC) [3][4] appears as a proper way to mitigate the interference impact. The coordination may be adapted semi-statically or more dynamically depending on the available information and control traffic load limitation.

In heterogeneous co-channel deployments, where FBSs transmit on the same carrier frequency as MBSs, FBSs may strongly interfere with MBSs and even create coverage holes in downlink (DL). In order to secure the operator MBS traffic, priority should be put on minimizing the interference created by FBSs on MBSs. However, the FBS throughput inside home should remain reasonably high, at least at the WiFi level. Furthermore, due to the high number of FBSs under the MBS coverage, establishing a fast cooperation channel between a MBS and all FBSs under its coverage puts too much burden on the core network. Thus, blind macro-femto ICIC is desirable in a heterogeneous deployment.

In DL, the impact of the interference generated by a FBS on Mobile Terminals served by a MBS (MMTs) depends in particular on the power received by each MMT around the FBS from its serving MBS. In a theoretical deployment with a single MBS, the lower the average path-gain between MBS and MMTs close to a FBS, the higher the area in which MMTs are strongly interfered by the FBS as depicted in Fig. 1 for the *No ICIC* case without shadowing. However, with strong interference from other MBSs or strong additive white Gaussian noise (AWGN) level, the impact of FBS interference on MMTs becomes small. Thus, the degradation of MMT performance due to a FBS is also linked to the interfence plus AWGN level.

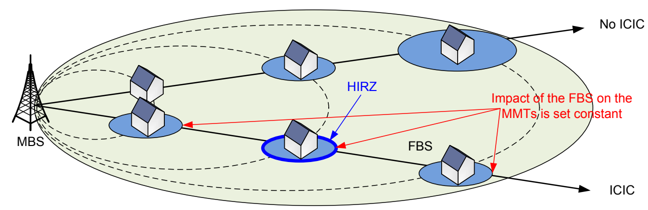

Fig. 1. ICIC providing macro-degradation equalization (single cell, no shadowing).

In the DL macro-femto ICIC approach presented in this paper, the FBS independently sets its transmit power [5], [6] according to its knowledge of the AWGN level and the received power from the closest MBS but also from neighbouring MBSs. For instance, received powers may be obtained through measurements on MBS DL signals. This power setting is not linked to the actual proximity of a MMT around the FBS but is rather a long-term setting for potential MMT positions around the FBS. Since there are more FBSs located at the MBS cell-edge, it is crucial to control their impact on the macro performance while keeping a good macro-femto performance trade-off. Furthermore, from an operator point-of-view, it is desirable that the impact of a FBS on surrounding MMTs is independent of its location in the MBS coverage. The proposed power setting achieves this property, which we call here macro-degradation equalization.

After defining some variables related to the inter-cell interference issue in Section II, we describe several key concepts and the long-term blind power setting in Section III. Finally, Section IV presents evaluation results for a 3GPP-LTE system.

II. Inter-cell interference definition

We consider a planned macro-cellular system, serving MMTs, and FBSs with closed-subscriber group (CSG), e.g., private home base stations, serving femto mobile terminals

(FMTs). We denote $P_{t,F}$ the transmit power of the most interfering FBS for a given MMT, G_F the path gain from this FBS to the MMT or a FMT, P_M the received power at the MMT or a FMT from the MBS serving the MMT, N the constant AWGN power level at a MMT or a FMT, and I_O the interference power level received from other MBSs and FBSs. We consider middle-scale values for these variables, i.e., fast fading is averaged as well as the interference realizations. In order to appropriately set the FBS power, we define a performance metric for evaluating the inter-cell interference impact. The available performance metrics strongly depend on the above variables and in particular on the signal to interference plus noise ratio (SINR) for a MMT,

$$\mathit{SINR}_M\left(P_{t,F}\right) = \frac{P_M}{N + I_O + P_{t,F}G_F} \quad , \tag{1}$$

and for a FMT,

$$\mathit{SINR}_F\left(P_{t,F}\right) = \frac{P_{t,F}G_F}{N + I_O + P_M} \quad . \tag{2}$$

The performance metric is defined as an increasing function of SINR. Simple examples of performance metrics are the SINR itself, the Shannon capacity and the actual throughput or spectral efficiency.

We see from (1) and (2) that there is a trade-off between femto and macro performance driven by the FBS transmit power $P_{t,F}$. The higher the macro degradation, the higher the femto performance. Long-term FBS power setting must ensure controlled macro-femto performance trade-off for a high number of MMT and FMT SINR realizations.

III. Blind power setting principles

A. Macro-degadation equalization

For the sake of macro-degradation equalization, we introduce a *high interference reference zone* (HIRZ), as depicted in Fig. 1, which is a given area in which the level of MMT performance degradation is controlled. When the same HIRZ and the same MMT performance degadation definition and level are considered for all FBSs, all FBSs are expected to have the same impact on the MMTs. Thus, macro-degration equalization is achieved.

The HIRZ denoted Z_{MMT} is for instance a circle or a ring around the FBS, usually located outside the FBS building. The macro performance degradation is represented by a function $g(\cdot)$, decreasing with the level of performance degradation, which has the following properties:

- Being constant with or increasing with P_M,
- Being constant with or increasing with $I = I_O + N$,
- Decreasing with $P_{t,F}G_F$.

The macro degradation is defined as the ratio of the MMT performance metric (e.g., SINR) with and without FBS transmission. Thus, the range of function $g(\cdot)$ is from 0 for full degradation up to 1 for no degradation. As the path gain properties are not the same for all positions in Z_{MMT}, we consider the outage probability of the degradation function $g(\cdot)$. The FBS transmit power is set to $P_{t,F}^{sol}$ such that, in Z_{MMT}, the probability that $g\left(P_M, I, G_F P_{t,F}^{sol}\right)$ is lower than or equal to a threshold g_{th} equals P_{OUT}:

$$\Pr\left(g\left(P_M, I, G_F P_{t,F}^{sol}\right) \leq g_{th} | Z_{\mathit{MMT}}\right) = P_{OUT}. \tag{3}$$

It is equivalent to find the FBS transmit power $P_{t,F}^{sol}$ such that,

$$\Pr\left(P_{t,F}^{sol} \leq P_{t,F}^{th}\left(P_M, I, G_F, g_{th}\right) | Z_{\mathit{MMT}}\right) = P_{OUT}, \tag{4}$$

where $P_{t,F}^{th}\left(P_M, I, G_F, g_{th}\right) = g^{-1}\left(P_M, I, g_{th}\right)/G_F$ is the appropriate power setting value for a given realization of P_M, G_F and I. Function $g^{-1}(\cdot)$ denotes the inverse function of $g(\cdot)$. Thus, the solution $P_{t,F}^{sol}$ for femto transmit power setting can be expressed as a quantile function:

$$P_{t,F}^{sol} = Q_{\frac{1}{G_F}g^{-1}(P_M, I, g_{th})|Z_{\mathit{MMT}}}\left(P_{OUT}\right), \tag{5}$$

where the quantile $Q_{u|Z_{\mathit{MMT}}}(P)$ denotes the value such that the cumulative distribution function (CDF) of the function $u(\cdot)$ evaluated on the area Z_{MMT} equals P. Thus, the long-term power setting is defined by a choice of the function $g(\cdot)$, of the HIRZ Z_{MMT} and of the parameters g_{th} and P_{OUT}.

In practice, the quantile may be obtained in different ways depending on how the random variable $g^{-1}\left(P_M, I, g_{th}\right)/G_F$ is described. For instance, it can be described by an analytical model, such as a normal or log-normal distribution, or by an empirical data set obtained through measurements. The statistical information on the variables P_M, I and G_F may be obtained by measurements at FMTs or FBS or by analytical models.

B. SINR-degradation-based power setting

In the sequel, we adopt the SINR as the performance metric. The macro performance degradation becomes

$$g\left(P_M, I, P_{t,F}^{sol}\right) = \mathit{SINR}_M\left(P_{t,F}\right)/\mathit{SINR}_M\left(0\right). \tag{6}$$

Using (1) in (6), we obtain,

$$P_{t,F} = \frac{g^{-1}\left(P_M, I, g_{th}\right)}{G_F} = \frac{\left(1/g_{th} - 1\right)I}{G_F}. \tag{7}$$

Instead of considering the interference plus noise level I, we correct it into $\max\left(I, P_M/\mathit{SINR}_{max}\right)$ in order to take into account the system performance saturation beyond a maximum value SINR_{max}, e.g, due to practical limitations like the maximum modulation spectrum efficiency or coding rate.

We consider a circular HIRZ Z_{MMT} encompassing the femto building and power measurements P_M^{meas} and I^{meas} at FBS of P_M and I, respectively. These measurements are assumed to be on average equal to the actual received power in Z_{MMT} divided by the wall penetration loss A_w. This assumption is satisfied if the size of Z_{MMT} is much smaller than the FBS-to-MBS distance. In log-scale, the variance of the difference between these values and the actual received power values in Z_{MMT} is assumed to be much smaller than the variance of the path gain G_F in Z_{MMT}. This assumption is true if the macro shadowing correlation distance is larger than the Z_{MMT} size.

The path gain G_F is modeled with a log-normal distribution and the exact distribution is obtained with FMT measurements

TABLE I
SIMULATED PROPAGATION MODEL FOR MBS.

Total MBS transmit power	43 dBm
Distance dependent mean path loss (dB)	$128.1 + 37.6 \log_{10}(d)$, d in km
MBS antenna type	directional (for 3-sectorized sites) with vertical selectivity
MBS Antenna gain	14 dB
Shadowing standard deviation for MBS	8 dB
Shadowing correlation for two MBSs	0.5
Shadowing correlation distance	50 m
Wall penetration loss A_w	10 or 20 dB
Small-scale channel	Rayleigh ITU-TU6

TABLE II
SIMULATED PROPAGATION MODEL FOR FBS.

Distance dependent mean path loss for indoor (dB)	$37 + 30 \log_{10}(d)$, d in m
Distance dependent mean path loss for outdoor (dB)	$37 - 6.7 \log_{10}(r) + A_w$ $-36.7 \log_{10}(d)$, d in m
FBS antenna type	Omni-directional
FBS antenna gain	5 dB
Shadowing standard deviation for MBS	10 dB
Shadowing correlation distance	Uncorrelated
Wall penetration loss A_w	10 or 20 dB
Small-scale channel	Rayleigh ITU-InH NLOS

TABLE III
SIMULATED 3GPP-LTE PHYSICAL LAYER.

Modulation waveform	OFDM
Bandwidth	5 Mhz
FFT size	512
Useful sub-carriers	300
Sub-carrier spacing	15 kHz
MMT/FMT allocation size	12 sub-carriers
Maximum spectral efficiency	6 b/s/Hz (SIMO, 64-QAM, coderate 1)

or through a predefined path loss model. In the latter case, the variance is the shadowing variance and the mean is for instance obtained from a log-distance path loss model, using the Z_{MMT} radius. With log-normal distribution, the solution for femto transmit power setting is in log scale,

$$P_{t,F}^{sol}|_{dB} = C + A_w|_{dB} + \max\left(I^{meas}|_{dB}, P_M^{meas}|_{dB} - SINR_{max}|_{dB}\right) \quad (8)$$

with,

$$C = 10 \log_{10}\left(1/g_{th} - 1\right) - \overline{G}_F|_{dB} - \sigma_{G_F|_{dB}} Q_{\mathcal{N}}\left(P_{OUT}\right), \quad (9)$$

where $Q_{\mathcal{N}}$ is the quantile function of the standard normal distribution, i.e., the probit function, and $x|_{dB}$ denotes the expression of x in dB. $\overline{G}_F$ and $\sigma^2_{G_F}$ are the mean and variance of G_F in area Z_{MMT}, respectively.

IV. PERFORMANCE RESULTS

A. Simulation scenario

We simulate an LTE system with 2 GHz carrier frequency, using a static multi-cell system-level simulator. MBSs are deployed with 1732 m inter-site distance according to the 3GPP case 3 [7]. Nineteen tri-sectorized sites (3 cells per site) are simulated with wrap-around. The indoor femto propagation model is the 3GPP LTE-A femto-cell model and the indoor-to-outdoor model uses the attenuation coefficient of the 3GPP Urban Microcell NLOS model [7]. The small-scale Rayleigh channels are the ITU 6-path Typical Urban channel model for MBS and the ITU-InH NLOS channel model for FBS. Model details are gathered in Tables I and II. In all simulations, ideal path gain measurements and perfect knowledge of propagation models are assumed. Furthermore, the 50 m shadowing correlation distance makes power measurements at FBS well representative of power levels at MMTs in Z_{MMT}.

Mono-stream 1x2 single-input multiple-output (SIMO) transmission with independent channel realizations between receive antennas is performed on a 5 MHz system bandwidth as described in Table III. In order to simply model small-scale channel effects and link-level system characteristics, the outage spectral efficiency with perfect scheduling is used as link level to system level interface. The link level to system level interface associates a performance level to the middle-scale SINR. In perfect scheduling, each FMT or MMT is scheduled as if it were the only FMT or MMT in the system, i.e., without any FMT or MMT allocation collision constraint. The outage spectral efficiency is a good indicator of the maximum achievable data rate and is limited here to the maximum LTE mono-stream spectral efficiency, i.e., 6 bits/s/Hz.

Circular FBS buildings with radius r are assumed. All base stations have full load.

B. Equalization properties: Geographical representation

Figure 2 shows the spectral efficiency for each MMT position without shadowing in order to ease interpretation. We consider here 10 m radius for femto buildings and 30 m radius for HIRZ. 10 dB wall penetration loss is used. There are 100 FBSs deployed in the 57 macro-cells. As reference, the case without ICIC is illustrated here with fixed FBS transmit power equal to 10 dBm, which leads to near-maximum FBS performance. Figure 3 shows the ratio between the SINR with FBS 10 dBm transmission and the SINR without FBS transmission. In both figures, we observe that the size of MBS coverage holes strongly depends on the FBS position.

Figure 4 shows the SINR ratio when FBS transmit powers are set according to (9) with $g_{th} = 0.5$ and P_{OUT} adjusted to have the same global cell-edge FMT performance as without ICIC, i.e., the same 5%-ile performance over all FMTs. We observe the macro-degradation equalization property of the simulated power setting. As targeted, the MMT SINR ratio equals 0.5 around each FBS, i.e., at 30 m from the FBS.

We define the high interference zone (HIZ) as the area where the outdoor MMT spectral efficiency is degraded by more than 50% due to FBS transmission. Spectral efficiency CDFs are shown in Fig. 5. Only MMTs located in the union of HIZ with ICIC and HIZ without ICIC, i.e., MMTs significantly impacted by the FBS transmission, are considered. In most cases, this union HIZ is close to the HIZ without ICIC. We observe that the FMT performances with and without ICIC are

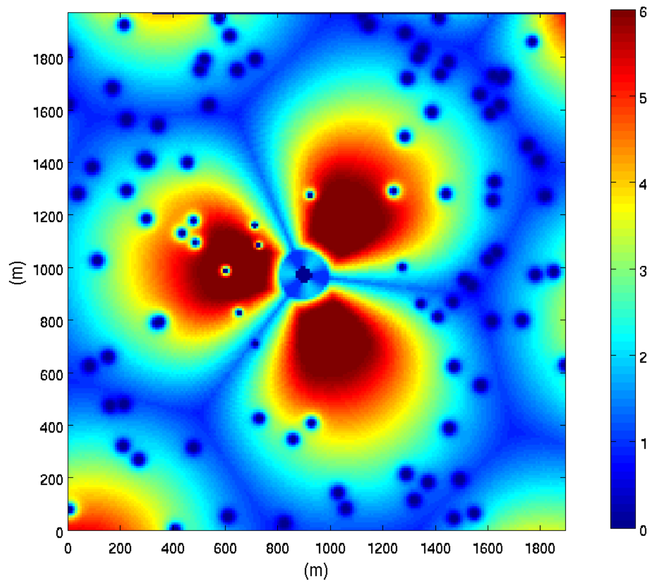

Fig. 2. MMT spectral efficiency with fixed power (b/s/Hz).

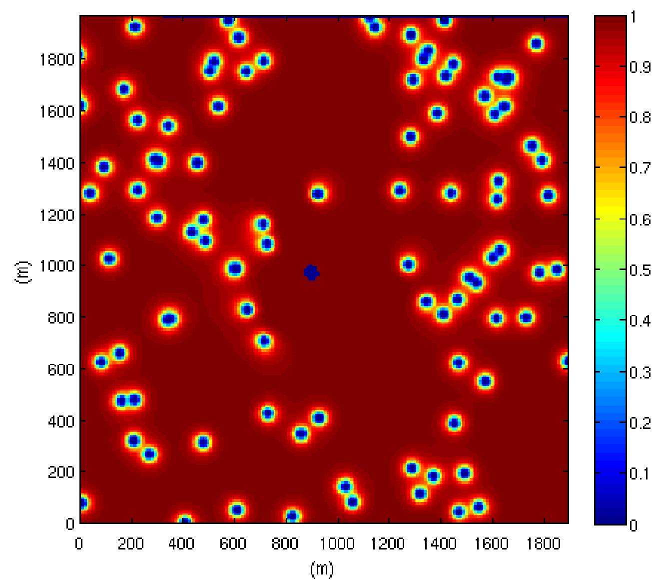

Fig. 4. MMT SINR ratio with ICIC.

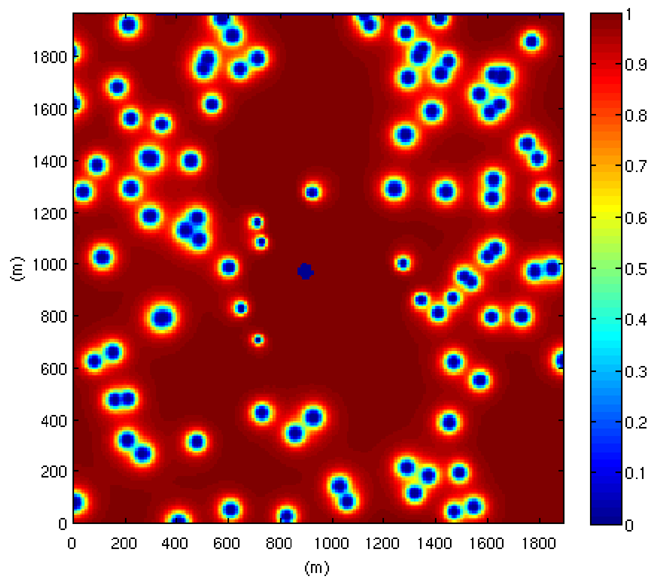

Fig. 3. MMT SINR ratio with fixed power.

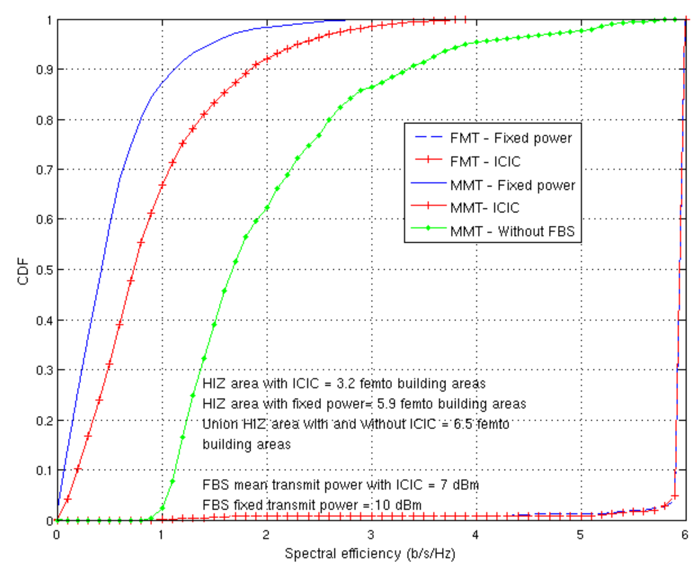

Fig. 5. MMT spectral efficiency in union HIZ and FMT spectral efficiency in FBS buildings.

similar. With ICIC, the MMT spectral efficiency is strongly improved and the average FBS transmit power is decreased from 10 dBm down to 7 dBm. Finally, the HIZ is almost divided by two when applying appropriate power setting.

C. Global statistical results

We now simulate shadowing and consider a high number of independent shadowing and FBS deployment realizations. The buildings now have 5m radius. As an ICIC performance metric, we evaluate the worst FBS performance as a function of the worst effect of FBS on MMT. To that aim, for each realization, many ICIC parameter values and fixed transmit powers are tested.

We first simulate the deployment of a single FBS, with 400 realizations of FBS position over 50 realizations of shadowing with 10 dB and 20 dB wall penetration losses. We evaluate for each FBS realization the FBS cell-edge spectral efficiency as the 5%-ile FMT spectral efficiency and the HIZ area. Figure 6 depicts the 5%-ile FBS cell-edge spectral efficiency as a function of the 95%-ile HIZ area, i.e., the worst FBS and MBS cases, respectively. We observe significantly lower worst HIZ impact with ICIC, especially with low wall penetration loss. For an HIZ of 3 buildings areas, which roughly corresponds to a ring around FBS buildings with width one building radius, and for 10 dB wall penetration loss, we obtain for 5%-ile FBS cell-edge spectral efficiency 0.5 b/s/Hz without ICIC and 2.9 b/s/Hz with ICIC, i.e., a gain of almost a factor 6. For 20 dB

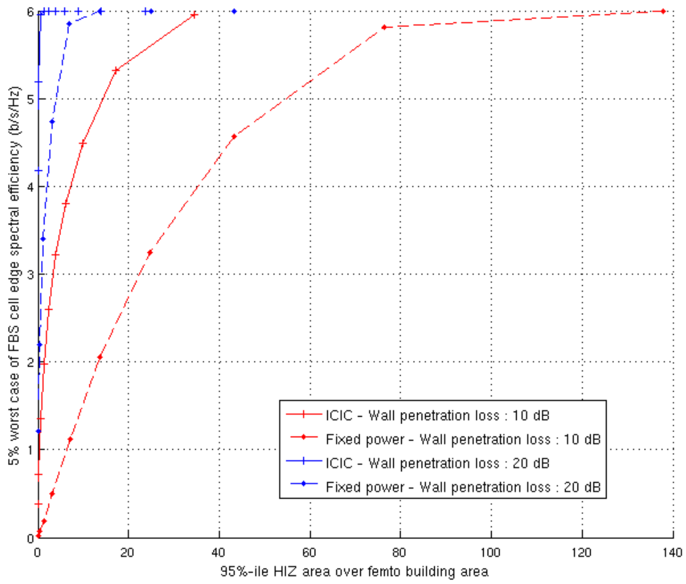

Fig. 6. 5%-ile worst case FBS performance vs. 5%-ile worst case MMT HIZ area.

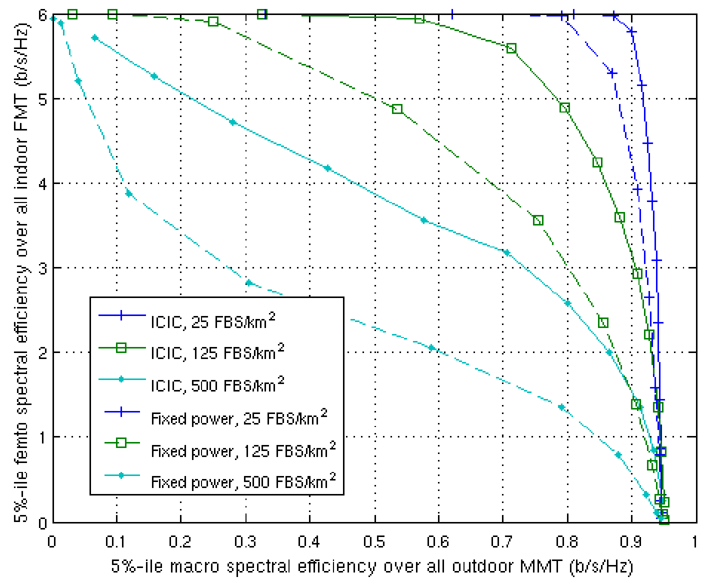

Fig. 7. Global FMT-MMT performance trade-off in term of cell-edge spectral efficiency.

wall penetration loss, the gain is around a factor 1.5. With this high wall penetration loss and with ICIC, we can obtain near maximum FBS performance without reducing MMT performance by more than 50% outside the FBS building. With 10 m building radius, ICIC gain, which is not shown here, is reduced.

We finally evaluate for a deployment with many FBSs the global FMT-MMT performance trade-off, i.e., the 5%-ile FMT spectral efficiency over all FBSs as a function of the 5%-ile MMT spectral efficiency over all outdoor MMTs. Three FBS densities are considered: 25, 125 and 500 FBSs per km^2, i.e., 22, 109 and 434 FBSs per MBS sector, respectively. We simulate 20 realizations of FBS positions and shadowing for each FBS density. In Fig. 7, showing results for 10 dB wall penetration loss, we observe better FMT-MMT performance trade-off with ICIC. With very little number of FBSs, e.g., in a rural environment, the degradation on MMTs is negligible and ICIC does not bring much global performance gain. With a higher number of FBSs, we observe a non-negligible gain of ICIC over fixed FBS power transmission. For a 5% global diminution of cell-edge MMT spectral efficiency (0.9 b/s/Hz instead of 0.95 b/s/Hz without FBS), the cell-edge FMT spectral efficiency gain of ICIC over fixed power transmission is 2.7 with 500 femto per km^2 (0.6 b/s/Hz with fixed power and 1.6 b/s/Hz with ICIC) and 1.4 with 25 femto per km^2 (4.2 b/s/Hz with fixed power and near maximum 5.8 b/s/Hz with ICIC). With higher wall penetration loss of 20 dB, results not shown here exhibit near maximum FMT performance without significant impact on MMTs. Finally, the gain brought by ICIC is better with 10 m building radius.

V. Conclusion

A new framework for ICIC based on long-term power setting is presented, using the concept of HIRZ for controlling the macro degradation due to FBS transmission. Since the power and path gain properties may vary over the HIRZ, we introduce an outage probability as a parameter for ICIC and we obtain a macro-degradation equalization through appropriate long-term power setting. In the simulated 3GPP-LTE context, this power setting improves the global FMT-MMT performance trade-off. This improvement decreases with wall penetration loss and increases with FBS density.

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