Uplink Femto-Macro ICIC with Semi-Centralized Power Control

Julien Guillet, Loïc Brunel and Nicolas Gresset
Mitsubishi Electric R&D Centre Europe
1 Allée de Beaulieu, CS 10806, 35708 Rennes Cedex, France
Email: {j.guillet, l.brunel, n.gresset}@fr.merce.mee.com

***Abstract*—Inter-cell interference is a major issue in current wireless cellular systems, in particular with the development of femto-cells. We propose a semi-centralized uplink femto-macro ICIC approach with low network signalling in which a coordinator defines a power control function for all femto base stations in a given area based on long-term statistics they build. The power control function takes path gains as arguments and the transmit power of each femto mobile terminal is set according to the short-term path gains it reports. The proposed power control function achieves good results in terms of femto-macro performance trade-off and mobile terminal transmit power.**

I. Introduction

In current mobile cellular networks, like 3GPP Long Term Evolution (LTE) networks, heterogeneous deployments mixing macro base stations (MBS) and home 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 use the same carrier frequency as MBSs, Mobile Terminals served by FBSs (FMTs) may strongly interfere signals transmitted by Mobile Terminals served by MBSs (MMTs) in uplink (UL). In order to secure the operator MBS traffic, priority should be put on minimizing the interference created by FMTs on MMTs. 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, semi-centralized UL ICIC is desirable in a heterogeneous deployment.

In UL, the interference from all FMTs served by all FBSs is added to the useful signal from MMTs served by the MBS at the MBS receiver. Thus, each FMT transmission impacts all MMTs whatever their location. With MMT power control, making the received power of all MMTs similar, the performance impact on all MMTs is the same. Without MMT power control, cell-center MMTs are less impacted. Furthermore, the higher the average path-gain between FMTs served by a given FBS and the MBS, the higher their interference contribution. It is proposed in [5][6] to equalize this contribution, i.e., to ensure that the received power at the MBS from FMTs of a given FBS is the same for all FBSs. Thus, the FMT transmit power must be inversely proportionnal to the FMT-to-MBS path gain, up to the maximum FMT transmit power. However, the useful path gain between a FMT and its serving FBS is also an important input for UL power control since it drives the FMT performance. In [7], distributed solutions based on utility and game theory exploit the ratio of the FMT-to-FBS useful path gain over the FMT-to-MBS interfering path gain. Other approaches involving these two path gains can also be found in [6].

In this paper, we propose a promising uplink ICIC power control function which non-linearly combines these two path gains. The power control is performed in two phases. In a first phase, a semi-centralized protocol chooses appropriate parameters for the power control function, considering the statistics of the interference created by MMTs (resp. FMTs) on FMT (resp. MMT) signals, reported by MBSs (resp. FBSs) with low signalling payload. In a second phase, the MBS and each FBS apply the power control function with actual interfering and useful path gains as arguments. Thus, the power control is specific to each mobile terminal at low signalling cost.

After defining some variables related to the inter-cell interference issue in Section II, we describe the semi-centralized protocol and introduce several possible power control functions in Section III. Finally, Section IV presents evaluation results for a 3GPP-LTE system, comparing the new power control function with functions from the literature.

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 FMTs. There are N_f FBSs per MBS cell. For a FMT served by FBS i, the useful path gain $G_{F,i}$ is the path gain from the FMT to FBS i and the interfering path gain $G_{M,i}$ is the path gain from the FMT to the MBS serving MMTs at the FMT position. For a MMT,

$G_{F,i}^{MMT}$ is the path gain from the MMT to FBS i and G_M^{MMT} is the path gain from the MMT to its serving MBS. We consider middle-scale values for these variables, i.e., fast fading is averaged as well as the interference realizations. $P_{F,i}$ and P_M denote the FMT transmit power in FBS i and the MMT transmit power, respectively. Note that transmit power and path gain variables are not mobile terminal specific and represent random variables in the sequel. $N_{F,i}$ and N_M denote the power level of AWGN plus interference received at FBS i and MBS from neighbouring macro-cells, respectively. We define a performance metric for evaluating the inter-cell interference impact. The available performance metrics depend on the above variables and in particular on the signal to interference plus noise ratio (SINR) for the MMT,

$$\mathit{SINR}_M \left(P_{F,1}, ..., P_{F,N_f}\right) = \frac{P_M G_M^{MMT}}{N_M + I_{FM}} \quad , \tag{1}$$

where the interference from FMTs I_{FM} is,

$$I_{FM} = \sum_{i=1}^{N_f} a_i P_{F,i} G_{M,i} \quad , \tag{2}$$

and for a FMT in FBS i,

$$\mathit{SINR}_{F,i} \left(P_{F,i}\right) = \frac{P_{F,i} G_{F,i}}{N_{F,i} + P_M G_{F,i}^{MMT}} \quad . \tag{3}$$

The FMT activity a_i of a given FBS i equals 1 if a resource is used, 0 otherwise. The FBS-to-FBS interference is neglected in the latter formula. 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) to (3) that there is a trade-off between MMT and FMT performances driven by the MMT and FMT transmit powers P_M and $P_{F,i}$. The higher the macro (resp. femto) degradation brought by FMT (resp. MMT) transmission, the higher the femto (resp. macro) performance. As shown by (1), each MMT is interfered by FMTs from all FBSs. Thus, some level of centralization is necessary in order to perform efficient UL ICIC.

III. Semi-centralized power control

A. General architecture

We assume that a coordinator performs the centralization for each MBS cell independently, optimizing the FMT and MMT performance for all MMT and FMT statistical path gain conditions. Since MBSs and FBSs do not have fast connection, demanding centralization with high MBS-to-FBS signalling cost is not allowed. The interactions between the MBS, the FBSs and the coordinator are depicted in Fig. 1. In a first step, MMTs (resp. FMTs) report path gains from their serving MBS (resp. FBS) and interfering FBSs (resp. MBS). In a second step, the MBS (resp. each FBS) builds long-term statistics of the interfering and useful path gains from MMT (resp. FMT) reports. Statistics may also be built for AWGN plus interference power level and cell load. These statistics are sent from the MBS and FBSs to the coordinator and the

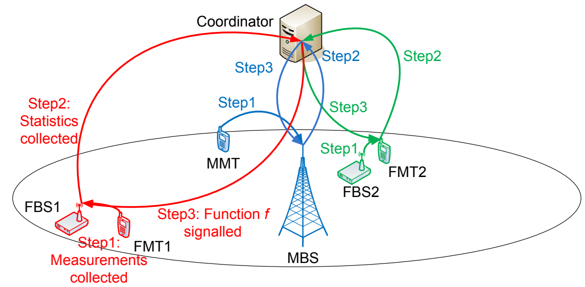

Fig. 1. Interactions in the semi-centralized UL ICIC.

coordinator optimises the power control rule for the MBS and FBSs. The power control rule is a long-term function $f(\cdot)$ of the measurement pair (interfering path gain, useful path gain). In a third step, the MBS and each FBS receive the power control information, i.e., the function $f(\cdot)$. Finally, they apply a short-term mobile-terminal-specific power control according to the function $f(\cdot)$ taking as arguments the measurement pair corresponding to the mobile terminal.

B. Power control rule

We assume that the MMT power control is already settled and we focus on defining a global FBS power control rule, i.e., a function $f(\cdot)$ common to all FBSs. We first define a structure for the power control function $f(\cdot)$, involving some parameters. Given this structure, the coordinator determines the values of the parameters based on the statistics reported by MMTs and FMTs.

The macro degradation is controlled in such a way that the mean interference from FMTs on MBS I_{FM} is kept proportional to the mean AWGN plus interference level $\mathbb{E}\left[N_M\right]$ without FMT transmission. With (2) and

$$P_{F,i} = f\left(G_{M,i}, G_{F,i}\right) = C \times g\left(G_{M,i}, G_{F,i}\right), \tag{4}$$

we obtain,

$$\mathbb{E}\left[I_{FM}\right] = C\mathbb{E}\left[\sum_{i=1}^{N_f} a_i g\left(G_{M,i}, G_{F,i}\right) G_{M,i}\right] = \alpha\mathbb{E}\left[N_M\right] \tag{5}$$

where α is a proportion factor corresponding to the tolerated macro degradation and C is a constant controlling this degradation and optimized by the coordinator. For a given function $g(\cdot)$, the mean interference level $\mathbb{E}\left[I_{FM}\right]$, driven by C, is directly linked to the macro degradation. The structure of function $g(\cdot)$ impacts the shape of the interference level distribution. From (5), considering statistical independence of the activity and the path gains,

$$C = \frac{\alpha\mathbb{E}\left[N_M\right]}{\sum_{i=1}^{N_f} \rho_i X_i}, \tag{6}$$

where $X_i = \mathbb{E}\left[g\left(G_{M,i}, G_{F,i}\right) G_{M,i}\right]$ and $\rho_i = \mathbb{E}\left[a_i\right]$ is the load of FBS i, i.e., the probability for a resource to be used. Thus, the MBS has to send the mean AWGN plus interference level $\mathbb{E}[N_M]$ to the coordinator and each FBS has to send its load ρ_i and the statictics involved in X_i. The value of X_i may directly be sent when the $g(\cdot)$ function is known by each FBS. We introduce below five different ways to define the function $g(\cdot)$.

Method 1 - Constant FMT transmit power: The same transmit power is fixed for all FMTs.

$$g(G_{M,i}, G_{F,i}) = 1 \quad \text{then} \quad X_i = \mathbb{E}[G_{M,i}]. \tag{7}$$

For a high number of FBSs, it is possible to avoid transfering X_i by instead using the MMT-to-MBS path gain G_M^{MMT} with a possible wall penetration loss correction c. In addition, an *effective* number of FBSs $N'_f = \sum_{i=1}^{N_f} \rho_i$ may be assumed and may replace the FBS load information. A worst-case FBS load $\rho_i = 1$ may also be assumed for each FBS. Finally,

$$C = \frac{\alpha \mathbb{E}[N_M]}{N'_f c \mathbb{E}[G_M^{MMT}]} \tag{8}$$

and FBSs may not have to transfer any information. Subsequently, the coordinator may compare the level of interference experienced by the MBS with the expected value and adapt C.

Method 2 - Interfering path gain based FMT power control: UL ICIC is performed by equalizing the FMT impact on the MBS whatever the FMT location [5][6]. Thus, the FMT transmit power is set in order to compensate the interfering FMT-to-MBS path gain:

$$g(G_{M,i}, G_{F,i}) = 1/G_{M,i} \quad \text{then} \quad X_i = 1. \tag{9}$$

Among all methods, Method 2 results in a minimum variance of $\log(I_{FM})$, i.e., in a maximum MBS performance. The coordinator only requires the *effective* number of FBSs N'_f.

Method 3 - Useful path gain based FMT power control: When ICIC is not directly taken into account at the FMT level and the FMT performance is equalized, the FMT transmit power is set in order to compensate the useful path gain between the FMT and its serving FBS:

$$g(G_{M,i}, G_{F,i}) = 1/G_{F,i} \quad \text{then} \quad X_i = \mathbb{E}[G_{M,i}/G_{F,i}]. \tag{10}$$

Assuming independence between the path gains $G_{M,i}$ and $G_{F,i}$, X_i can be computed from $\mathbb{E}[G_{M,i}]$ and the harmonic mean $1/\mathbb{E}[1/G_{F,i}]$.

Method 4 - First interfering and useful path gain based FMT power control: By combining the interfering path gain and useful path gain informations, both the FMT performance and its interference on the MBS are considered in order to achieve a good MMT-FMT performance trade-off. Method 4 is a first combination of Methods 2 and 3 [6]:

$$g(G_{M,i}, G_{F,i}) = \frac{1}{G_{F,i} G_{M,i}} \text{ then } X_i = \mathbb{E}[1/G_{F,i}]. \tag{11}$$

Method 5 - Second interfering and useful path gain based power control: More flexibility in combining Method 2 and 3 may further improve the MMT-FMT trade-off by appropriately balancing them through a parameter B:

$$g(G_{M,i}, G_{F,i}) = \min\left(\frac{1}{G_{M,i}}, \frac{B}{G_{F,i}}\right) \tag{12}$$

The underlying idea is to consider a usual useful path gain based power control within certain limits imposed by tolerable macro degradation. Parameter B strongly depends on relative statistics $G_{M,i}$ and $G_{F,i}$ over all FBSs. Thus, we re-write (12) into

$$g(G_{M,i}, G_{F,i}) = \frac{1}{G_{M,i}} \min(1, C_s z_i) \tag{13}$$

where the normalized path gain ratio z_i is

$$z_i = \frac{G_{M,i}}{G_{F,i}} \left(\frac{1}{N_f} \sum_{i=1}^{N_f} \mathbb{E}\left[\frac{G_{M,i}}{G_{F,i}}\right] \right)^{-1} \tag{14}$$

and the parameter C_s is a shape constant impacting the shape of the I_{FM} probability density function (pdf). C_s is more stable than B for different $G_{M,i}$ and $G_{F,i}$ statistics and can be optimized by the operator for many deployments. From (13), a given value of C_s corresponds to a given probability P_2 of using Method 3, ranging from 0 to 1:

$$P_2 = \int_0^{1/C_s} p(z_i)\, \mathrm{d}z_i, \tag{15}$$

where p is the pdf of z_i. The coordinator numerically optimises C and C_s. For instance, it maximizes the 5%-ile FMT performance, which is a function of $f(G_{M,i}, G_{F,i})$, the useful path gain $G_{F,i}$ and the AWGN plus interference level $\mathbb{E}[N_{F,i}]$, with the constraint in (5). A log-normal distribution can be assumed for random variables $G_{M,i}$, $G_{F,i}$ and $N_{F,i}$. Thus, assuming independence of the interfering path gain and the useful path gain, the coordinator only needs the mean and variance of the variables $G_{M,i}$, $G_{F,i}$ and $N_{F,i}$ and the FBS load ρ_i for each FBS i. From (13), (14) and (6), for a given C_s,

$$X_i = 1 - \int_0^{1/C_s} p(z_i)\, \mathrm{d}z_i + C_s \int_0^{1/C_s} z_i p(z_i)\, \mathrm{d}z_i. \tag{16}$$

IV. Performance results

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 [8]. 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 [8]. 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.

TABLE I
SIMULATED PROPAGATION MODEL FOR MBS.

Distance dependent mean path loss (dB)	$128.1 + 37.6 \log_{10}(d)$, d in km
MBS Antenna type	directive tri-sector with vertical selectivity
MBS Antenna gain (dB)	14
Shadowing standard deviation for MBS	8 dB
Shadowing correlation between BS	0.5
Shadowing correlation distance	50 m
Wall penetration loss A_w	10 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	Omnidirectional
FBS Antenna gain (dB)	5 dB
Shadowing	Uncorrelated
Shadowing standard deviation for MBS	10 dB
Wall penetration loss A_w	10 dB
Small-scale channel	Rayleigh ITU-InH NLOS

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 $r = 6$ m are assumed. We consider two FBS densities, namely 23 and 230 FBSs per km^2, i.e., 20 and 200 FBSs per MBS cell, respectively. All FBSs and MBSs have full load. We simulate 20 realizations of FBS positions and shadowing for each FBS density. For Method 5, C_s is set equal to 14 dB. Several values of α are tested, resulting in different MMT-FMT performance trade-offs.

TABLE III
SIMULATED 3GPP-LTE PHYSICAL LAYER.

Modulation waveform	OFDM
FFT size	512 for 5MHz bandwidth
Useful sub-carriers	300
Sub-carrier spacing	15 kHz
MMT/FMT allocation size	12 sub-carriers (one LTE physical resource block)
Maximum spectral efficiency	6 b/s/Hz (SIMO, 64-QAM, coderate 1)

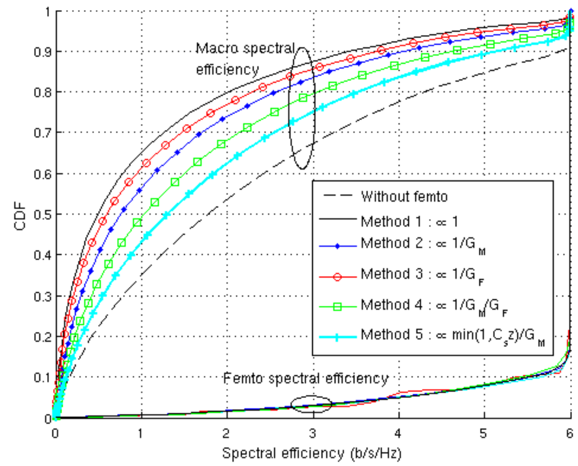

Fig. 2. MMT and FMT spectral efficiency with 230 FBSs per km^2 with target 5%-ile FMT spectral efficiency equal to 4 b/s/Hz.

In Fig. 2, the cumulative distribution functions (CDFs) of the MMT and FMT spectral efficiencies are compared for the different power control methods. For each method, a specific value of α is chosen in order to get the same FMT 5%-ile spectral efficiency. As expected, power control achieves an MMT performance improvement compared to constant FMT transmit power. The best methods are Methods 4 and 5, combining both the interfering path gain and the useful path gain. Among them Method 5, performs the best.

We show in Fig. 3 and 4, the MMT 5%-ile spectral efficiency and the mean FMT transmit power, respectively, as functions of the 5%-ile FMT spectral efficiency for the high FBS density of 230 FBS per km^2. Useful path gain based Method 3 minimizes the mean FMT transmit power among all FBSs. Compared to constant FMT transmit power, Method 3 achieves similar MMT-FMT performance trade-off with lower average transmit power. With simple ICIC using interference path gain based Method 2, the MMT-FMT performance trade-off is improved at the expense of an increased FMT average power. By performing a more advanced FMT-specific power control by Method 4 or 5, combining interfering path gain and useful path gain in order to achieve efficient ICIC, the performance trade-off is further improved while limiting the FMT average power increase compared to useful path gain based power control. Among these methods, the new Method 5 performs better on both spectral efficiency and transmit power consumption aspects. For a 5%-ile FMT spectral efficiency of 4 b/s/Hz, the 5%-ile MMT spectral efficiency with Method 5 is improved by more than 30% compared to Method 4, while the mean transmit FMT power is reduced by 5 dB. Figures 5 and 6 show results with the low FBS density of 23 FBS per km^2. The relative performances and mean FMT transmit powers of the different methods remain the same as with high density. The performance trade-off difference between Methods 2, 4 and 5 vanishes, whereas the mean FMT power difference remains of the same order. Note that with high FBS density, beyond a given mean transmit power, the 5%-ile FMT spectral efficiency

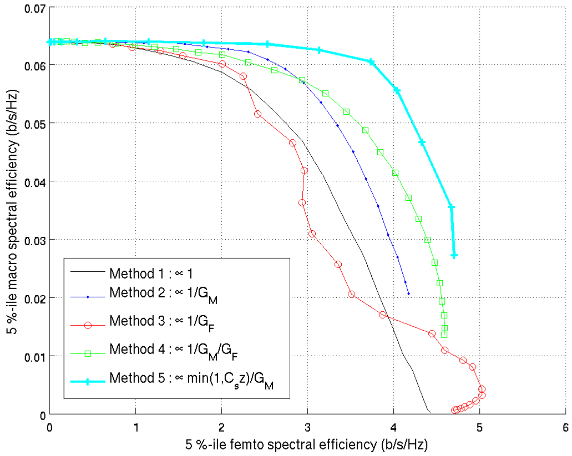

Fig. 3. MMT-FMT performance trade-off for 230 FBSs per km^2.

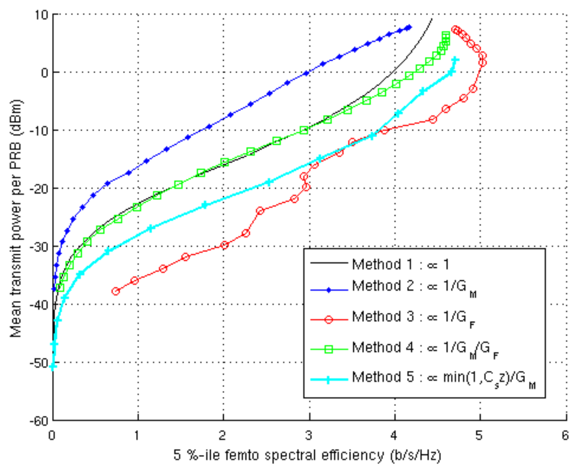

Fig. 4. FMT performance - FMT consumption for 230 FBSs per km^2.

decreases due to the inter-cell interference between FMTs of different FBSs. Indeed, some FMTs have already achieved their maximum transmit power and the inter-cell interference due to neighboring FMTs with non-saturated transmit power still increases.

V. Conclusion

For a semi-centralized uplink power control, different structures of the power control function are evaluated. The power control function, common to all FBSs, is determined in a coordinator based on low-payload signalling including long-term statistics and not directly on short-term FMT measurement reports. However, the power control function is applied separately for each FMT, based on the actual path gains it measures. Among evaluated structures, the structure proposed in Method 5, efficiently combinining the interfering path gain and useful path gain based power control, achieves the best MMT-FMT performance trade-off.

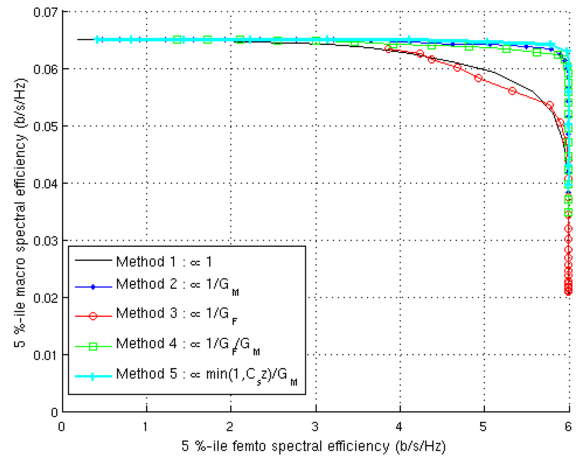

Fig. 5. MMT-FMT performance trade-off for 23 FBSs per km^2.

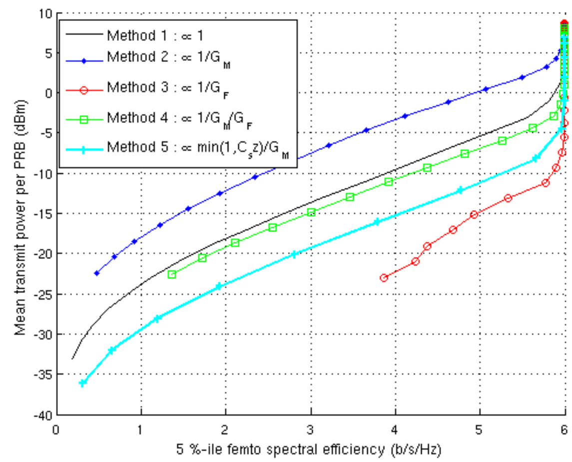

Fig. 6. FMT performance - FMT consumption for 23 FBSs per km^2.

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