# On TDD Cross-Tier In-Band Interference Mitigation: A Practical Example

Michal Čierny*, Risto Wichman*, Jyri Hämäläinen*, Cássio Ribeiro†, Zhi Ding‡ and Xin Liu‡
*Aalto University School of Electrical Engineering P.O. Box 13000 FI-00076 Aalto, Finland
†Nokia Research Center, P.O. Box 407, FI-00045 Nokia Group, Finland
‡University of California, Davis, California 95616

***Abstract*—This work considers in-band interference that appears in two-tier macro/femto cellular networks when macrocells and femtocells operate on the same frequency band. We focus on the time division duplex (TDD) mode where uplink-downlink interference occurs if time sharing between uplink and downlink are different in the overlaying macrocell and underlying femtocells. We derive an optimal power control based solution for a simple example scenario and then propose an extension for general multicell/multilink network. Finally, we show through simulations that the proposed solution can be used to mitigate the outage in the femtocell uplink without harming the macrocell layer.**

## I. Introduction

The standardization process of femtocells launched in August 2007 via the 3rd Generation Partnership Project (3GPP) is still under way [1]. Already from the beginning it has been clear that strong interference may occur between macro and femtocells as well as between individual femtocells [2]. Most of the studies this far has been considering the cross-tier interference between macro and femto layers when Frequency Division Duplex (FDD) mode is applied, see e.g. [3] for DL work, [4] for UL work and [5] for up-to-date practical issues. However, TDD scenario where femtocells and macrocells operate in the same frequency band also generates new type of interference scenarios between base stations (BSs) and between user terminals (UTs). Yet, this topic has not been examined in major scale.

Two available contributions [6] and [7] that do assume UL-DL interference propose to take advantage of the femto BS-macro BS link and apply interference cancellation. Such approach may fall into problems because of delay constraints. In this work we consider the suppression of in-band cross-layer interference that occurs when overlaying macro BS DL transmission is interfering the femtocell UL reception. We address the problem by augmenting UL power control. The femto UT usually operates relatively close to femto BS. Under acceptable interference it therefore requires low transmit power, which means there is room to increase it. Power control for interference management has been studied within heterogeneous and other wireless networks. Novelty of this work lies within applying it to the specific problem of cross-tier TDD interference in 3GPP context. We show that the median throughput in vulnerable femtocell UL can be increased by approximately 30%, while the interference to macro DL is lower than in case of femtocell DL.

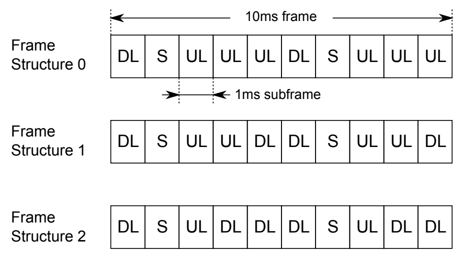


Figure 1: Three of seven possible TDD frame structures from 3GPP specification [8]. DL stands for downlink subframe, UL stands for uplink subframe and S stands for special subframe.

Our paper is organized as follows: In Section II we describe the system, focusing on TDD operation and explaining where cross-direction interference can turn up. In Section III we derive an optimal femto UT transmission power for two links: femto BS with one femto UT in UL mode and interfering macro BS with one macro UE in DL mode. In Section IV we move on to propose a viable solution for a realistic scenario with multiple links and demonstrate its performance by simulations. Finally, Section V draws conclusions of the work.

## II. System description

An up-to-date 3GPP compliant system working in TDD mode is allowed to work with one of seven frame structures, as given in [8]. Each frame is 10ms long and consists of ten 1ms subframes. There are three types of subframes: downlink, uplink, and a special subframe that itself contains a DL part, an UL part and a guard period. In Figure 1 we depict three of the seven possible frame structures. Frame structure 0 has a majority of UL subframes, frame structure 1 has the same number of UL and DL subframes and frame structure 2 has a majority of DL subframes.

Macrocells typically serve larger amount of users, and therefore it is reasonable to assume that the best subframe configuration would be stable over time. On the other hand, closed access femtocell typically serves a very low number of users, which means they may benefit from chosing the frame structure based on traffic characteristics. For example, with the three options in Figure 1, a femto BS with a lot of DL traffic in buffer can choose frame structure 2, a femto BS with a lot of UL traffic can choose frame structure 0 and in case of balanced traffic it can choose frame structure 1.

CROWNCOM 2012, June 18-20, Stockholm, Sweden

DOI 10.4108/icst.crowncom.2012.248599

We assume here that the macro BSs and femto BSs are time synchronized, which is a default assumption in Time Division Duplexing (TDD) based deployments. For Frequency Division Duplexing (FDD) deployments there is also motivation for time synchronization in order to support Time Domain enhanced Inter-Cell Interference Coordination (TDM eICIC), where either the macrocell or the femtocell does not transmit data in some of the subframes. One application of such technique is the avoidance of macro coverage holes, e.g. allowing DL transmissions for macro UTs that are located too close to the femtocell. It is then straightforward to comtemplate a situation where the femto BS has frame structure 0 and the overlay macro BS has frame structure 1, which means that in the 5th and 10th subframe femtocell UL transmission is interfered by macrocell DL transmission.

According to [9] the total transmit power of a UT in dB is given by

$$P_{\text{UT,dB}} = \min\left[10\log_{10}(M) + P_0 + \alpha PL + \varepsilon\ ;\ P_{\text{max,dB}}\right], \quad (1)$$

where $M$ is the number of active resource blocks (RBs), $P_0$ is the power control constant, $\alpha \in \langle 0; 1\rangle$ is the path loss compensation factor, $PL$ is path loss from BS to corresponding UT in dB, $\varepsilon$ is a correction factor and $P_{\text{max,dB}}$ is the maximum allowed power. Parameters $P_0$ and $\alpha$ represent the open-loop basis of the power control, while $\varepsilon$ includes corrections from the closed-loop mechanism.

Our goal in this work is to augment the power control mechanism so that femtocell UL transmission does not suffer extensive interference from macrocell DL transmission. Current 3GPP specification does not allow abrupt changes in transmit power, which limits the capability to handle large changes of interference level on a subframe basis. However, this is a potential issue raising from traffic-oriented frame structure setting, which motivates the power *boost* introduced in the subsequent sessions.

## III. Two-link scenario

Let us consider a small part of an OFDMA cellular network consisting of two links: macro BS with macro UT in DL mode and femto BS with femto UT in UL mode. Because macrocell typically serves multiple UTs, our macro UT represents the one which is most vulnerable to femto UL interference. As a base point, at femto BS we expect the interference from macro BS transmission to be stronger than from macro UT transmission. In this section we therefore look for a power boost that will augment the open-loop power control (1). We denote the power boost value per subcarrier as $P^+_{\text{F},n}$.

### A. System model

Our channel model is given by a combination of distance dependent path loss and fast Rayleigh fading. The path loss between macro BS and macro UT, femto UT and femto BS, macro BS and femto BS, femto UT and macro UT is denoted by $H_{\text{MM}}$, $H_{\text{FF}}$, $H_{\text{MF}}$ and $H_{\text{FM}}$, respectively. The fast fading power (in the same order) is denoted as $h_{\text{MM}}$, $h_{\text{FF}}$, $h_{\text{MF}}$ and $h_{\text{FM}}$. The situation is depicted in Figure 2.

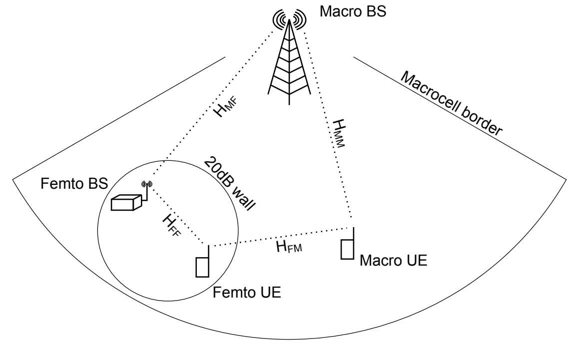


Figure 2: Two-link scenario with one femtocell link and one macrocell link. The macro UT represents the UT that is most vulnerable to interference from femtocell UL transmission.

Using this notation, the subcarrier signal-to-interference-plus-noise power ratio (SINR) at the macro UT is given by

$$\gamma_{\text{M},n} = \frac{P_{\text{M},n} H_{\text{MM}} h_{\text{MM}}}{P_{\text{F},n} H_{\text{FM}} h_{\text{FM}} + P_{\text{N}}}, \quad (2)$$

where $P_{\text{M},n}$ is transmit power per subcarrier at the macro BS, $P_{\text{F},n}$ is transmit power per subcarrier at the femto UT and $P_{\text{N}}$ is noise power per subcarrier. The noise is modeled as a thermal noise floor with the dB value $P_{\text{N,dB}}$ given by $10\log_{10}(kTB_n) + NF_{\text{dB}}$, where $k$ is Boltzmann constant, $T$ is ambient temperature, $B_n$ is subcarrier bandwidth and $NF_{\text{dB}}$ is noise figure of the receiver. A similar system model has been used e.g. in [10].

When increasing the transmit power of the femto UT, we must keep in mind two things: not to exceed the power budget and not to cause too much interference to the macrocell DL. This can be formulated into an optimization problem as

$$\underset{\{P^+_{\text{F},n}\}}{\text{maximize}} \quad \sum_{n=1}^{N} C_{\text{F},n}(P^+_{\text{F},n}) \quad (3)$$

$$\text{subject to} \quad \sum_{n=1}^{N} C_{\text{M},n}(P^+_{\text{F},n}) \geq C_{\text{M,min}}, \quad (4)$$

$$P_{\text{F}} \leq P_{\text{max}}, \quad (5)$$

where $N$ is the number of subcarriers, $C_{\text{F},n}$ is subcarrier throughput at the femto BS, $C_{\text{M},n}$ is subcarrier bit rate at the macro UT, $C_{\text{M,min}}$ is minimum accepted throughput at the macro UT (parameter of choice) and $P_{\text{F}}$ is the total transmit power of the femto UT.

It is assumed that the SINR maps to throughput via Shannon's equation $C = \log_2(1+\gamma)$. This means that the femtocell UL throughput $C_{\text{F},n}$ is an increasing function of boost $P^+_{\text{F},n}$, while the macrocell DL throughput $C_{\text{M},n}$ is a decreasing function of boost $P^+_{\text{F},n}$.

In order to make the analysis tractable we assume ideal interleaving among subcarriers. Because of correlated fading accross subcarriers it is generally difficult to derive closed form results for groups of subcarriers (e.g. resource blocks, RBs). Assuming ideally interleaved data on subcarriers, the statistics becomes i.i.d. and it is possible to find tractable distributions on subcarrier basis.

It is also important to note that while the femto UT can theoretically have knowledge of $H_{\text{FM}}$, it cannot know the powers of individual subcarriers. We will therefore consider a single power boost value $P_{\text{F}}^{+}$ for each subcarrier, leading to a simplified optimization problem

$$\text{maximize} \quad P_{\text{F}}^{+} \tag{6}$$

$$\text{subject to} \quad \sum_{n=1}^{N} C_{\text{M},n}(P_{\text{F}}^{+}) \geq C_{\text{M,min}}, \tag{7}$$

$$P_{\text{F},n} \leq \frac{P_{\text{max}}}{N}. \tag{8}$$

*B. Scenario analysis*

The PDF of the received signal power at the macro UT is based on the pdf of exponential random variable (RV). Transforming into dB scale we get

$$p_{\text{S}}(x) = \frac{\lambda \log(10)}{10 P_{\text{M},n} H_{\text{MM}}} 10^{\frac{x}{10}} e^{-\frac{\lambda}{P_{\text{M},n} H_{\text{MM}}} 10^{\frac{x}{10}}}, \tag{9}$$

where $\lambda$ is parameter of the exponential RV. Similarly, the pdf of -(interference+noise) per subcarrier is given by

$$p_{\text{-IN}}(x) = \begin{cases} \frac{\lambda \log(10)}{10 P_{\text{F},n} H_{\text{FM}}} 10^{\frac{-x}{10}} e^{\frac{-\lambda}{P_{\text{F}.n} H_{\text{FM}}}\left(10^{\frac{-x}{10}} - P_{\text{N}}\right)}, & x < -P_{\text{N,dB}} \\ 0 & \text{otherwise.} \end{cases} \tag{10}$$

By calculating a convolution integral of (9) and (10) we get a pdf of signal to interference plus noise ratio (SINR) in dB domain per subcarrier:

$$\begin{aligned} p_{\text{SINR}}(x) &= \int_{-\infty}^{\infty} p_{\text{S}}(x-y) p_{\text{-IN}}(y) dy = \\ &= \int_{-\infty}^{-P_{\text{N,dB}}} p_{\text{S}}(x-y) p_{\text{-IN}}(y) dy = \\ &= \Bigg[ \frac{\log(10)}{(P_{\text{F},n} H_{\text{FM}} 10^{\frac{x}{10}} + P_{\text{M},n} H_{\text{MM}})^2} 10^{\frac{x-y-10}{10}} \times \\ &\times e^{\frac{-\lambda}{P_{\text{F}} H_{\text{FM}}}\left(10^{\frac{-y}{10}} - P_{\text{N}}\right)} e^{\frac{-\lambda}{P_{\text{M}} H_{\text{MM}}} 10^{\frac{x-y}{10}}} \Bigg( \lambda P_{\text{M},n} H_{\text{MM}} + \\ &+ P_{\text{F},n} H_{\text{FM}} \left( \lambda 10^{\frac{x}{10}} + P_{\text{M},n} H_{\text{MM}} 10^{\frac{y}{10}} \right) \Bigg) \Bigg]_{y=-\infty}^{-P_{\text{N,dB}}} = \\ &= \frac{\log(10)}{(P_{\text{F},n} H_{\text{FM}} 10^{\frac{x}{10}} + P_{\text{M},n} H_{\text{MM}})^2} 10^{\frac{x+P_{\text{N,dB}}-10}{10}} \times \\ &\times e^{\frac{-\lambda}{P_{\text{M},n} H_{\text{MM}}} 10^{\frac{x+P_{\text{N,dB}}}{10}}} \Bigg( \lambda P_{\text{M},n} H_{\text{MM}} + \\ &+ P_{\text{F},n} H_{\text{FM}} \left( \lambda 10^{\frac{x}{10}} + P_{\text{M}.n} H_{\text{MM}} 10^{\frac{-P_{\text{N,dB}}}{10}} \right) \Bigg) \end{aligned} \tag{11}$$

A typical modern cellular system has a set of modulation and coding schemes (MCSs), which in case of the latest 3GPP specification ranges from low coding rate QPSK to high coding rate 64QAM. In order to achieve the minimum throughput in macro DL $C_{\text{M,min}}$ with a chosen MCS with $C_{\text{M},n}$ bits per subcarrier, a correct detection of at least $L_{\text{min}} = \lceil C_{\text{M,min}} / C_{\text{M},n} \rceil$ subcarriers is needed. For that, the $L_{\text{min}}$ or more subcarriers need to have a bit error rate (BER) lower than the system maximum $\text{BER}_{\text{max}}$. In other words, the SINR on $L_{\text{min}}$ or more subcarriers needs to be higher than a minimum value $\rho_{\text{min,dB}}$, where $\rho_{\text{min,dB}}$ is given by $\text{BER}_{\text{max}}$ and the given MCS of choice.

The probability that SINR on a single subcarrier is higher than $\rho_{\text{min,dB}}$ is given by

$$\begin{aligned} p_{\rho}^{(1)}(P_{\text{F},n}) &= \int_{\rho_{\text{min,dB}}}^{\infty} p_{\text{SINR}}(x) dx = \\ &= \frac{P_{\text{M},n} H_{\text{MM}}}{P_{\text{F},n} H_{\text{FM}} 10^{\frac{\rho_{\text{min,dB}}}{10}} + P_{\text{M},n} H_{\text{MM}}} e^{\frac{-\lambda}{P_{\text{M},n} H_{\text{MM}}} 10^{\frac{\rho_{\text{min,dB}} + P_{\text{N,dB}}}{10}}}. \end{aligned} \tag{12}$$

With i.i.d. Rayleigh fading the number of successful subcarriers $L_{\rho}$ with SINR higher than $\rho_{\text{min,dB}}$ has a Bernoulli distribution and we can write

$$\begin{aligned} \Pr\{L_{\rho} > L_{\text{min}}\} &= 1 - \Pr\{L_{\rho} \leq L_{\text{min}}\} \\ &= 1 - I_{1 - p_{\rho}^{(1)}(P_{\text{F},n})}(N - L_{\text{min}}, L_{\text{min}} + 1) \\ &= I_{p_{\rho}^{(1)}(P_{\text{F},n})}(L_{\text{min}} + 1, N - L_{\text{min}}), \end{aligned} \tag{13}$$

where $I_p(a, b)$ is a regularized incomplete beta function, a CDF of Bernoulli distribution. By choosing an arbitrarily high $C_{\text{M,min}}$ success probability $p_{C_{\text{M,min}}}$ so that

$$\Pr\{L_{\rho} > L_{\text{min}}\} \geq p_{C_{\text{M,min}}}, \tag{14}$$

we can derive the femto BS transmit power per subcarrier to be

$$P_{\text{F},n} \leq \frac{P_{\text{M},n} H_{\text{MM}} \left(1 - \frac{I_{\text{inv}}}{EXP}\right)}{H_{\text{FM}} 10^{\frac{\rho_{\text{min,dB}}}{10}} \frac{I_{\text{inv}}}{EXP}}, \tag{15}$$

where $I_{\text{inv}} = I^{-1}(p_{C_{\text{M,min}}}, L_{\text{min}} + 1, N - L_{\text{min}})$ is the inverse of regularized incomplete beta function and

$$EXP = e^{\frac{-\lambda}{P_{\text{M},n} H_{\text{MM}}} 10^{\frac{\rho_{\text{min,dB}} + P_{\text{N,dB}}}{10}}}. \tag{16}$$

The value of $I_{\text{inv}}$ can either be found numerically, or one can apply well-known upper bounds for Bernoulli distribution. Taking into account the maximum femto UT transmit power we get a result

$$P_{\text{F},n}^{(\text{opt})} = \min \left[ \frac{P_{\text{M},n} H_{\text{MM}} \left(1 - \frac{I_{\text{inv}}}{EXP}\right)}{H_{\text{FM}} 10^{\frac{\rho_{\text{min,dB}}}{10}} \frac{I_{\text{inv}}}{EXP}} \;\; ; \;\; \frac{P_{\text{max}}}{N} \right], \tag{17}$$

from which the power boost per subcarrier can be directly obtained.

*C. Results*

The results are demonstrated by simulating the two-link scenario. The macro BS serves a single 120° sector with 334m radius, in which the macro UT and femto BS are dropped randomly. Femto UT is then dropped within 10m distance from the femto BS. The path loss models, transmit powers, UL power control and other parameters are taken from 3GPP specifications [12]. The scenario of choice is Urban macro, the fading parameter $\lambda = 0.5$, the number of subcarriers $N = 72$ (corresponding to 1.4MHz system bandwidth), the ambient temperature is 300K and the noise figure is 9dB. At the macro DL we require with $p_{C_{\text{M,min}}} = 0.99$ probability at least $L_{\text{min}} = 36$ subcarriers to have SINR higher than $\rho_{\text{min,dB}} = 0$dB. The value

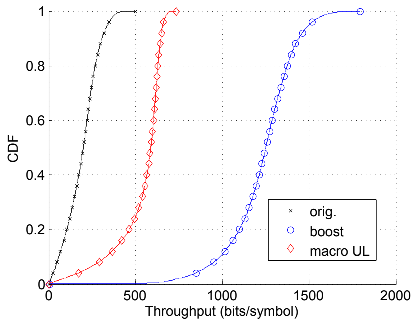


Figure 3: Throughput (in bits per OFDMA symbol) of the femto UL in the two link scenario. Original results for basic open loop power control, results with boosted transmit power based on (17) and results under macro UL interference for comparison.

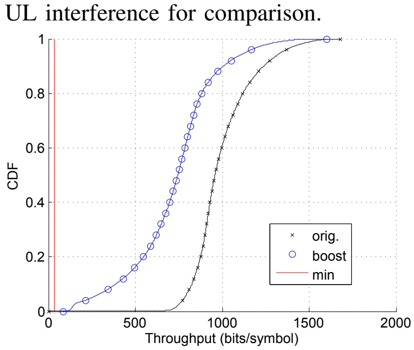


Figure 4: Throughput of macro DL in the two link scenario and the effect of boosted transmit power at the femto UT. The red line represents minimum required throughput.

of throughput per subcarrier is evaluated based on Shannon's capacity formula.

In Figure 3 we compare the CDF of throughput at the femto link in three cases: throughput with the original open loop power control as given in 3GPP specifications, throughput with the proposed transmit power as given in (17), and throughput with the original power control, but under macro UL interference. The throughput with the original power control under macro DL interference is on all percentiles at least 50% lower than under macro UL interference. With our boosted transmit power, the median throughput is increased approximately six-fold.

In Figure 4 we can observe the effect of (17) on the macro DL. The throughput gets considerably lower, but this is expected, and it is partly caused by using Shannon's formula without upper limit. Looking at the minimum required macro DL throughput, it seems that (17) is very robust and conservative limitation on femto UT transmit power. However, the simulations reveal that (15) is active in less than 5% of the cases. Most of the time the limiting factor is $P_{\mathrm{UT,max}}$. Even by such a simplified model, this is a valuable observation, hinting that macro DL is not limited by interference from femto UT.

## IV. Multi-cell scenario study

In this section we describe the macro/femto heterogeneous network (HetNet) scenario which is studied in 3GPP, discuss the practical restrictions for the deployment of results from Section III, propose a realistic transmit power setting for femto UT under macro DL interference and present simulations of the proposed scheme.

### A. Realistic power setting

Here we explain how the transmission power boost is selected in our simulated scenario. We base the proposal on the following three principles.

*a) Feasibility of knowing the presence of macro UT:* Even rough knowledge of channel conditions from femto UT to the closest macro UT is difficult to obtain. Several strategies can be used to detect if the transmission from femto UTs is creating interference to macro UTs. For example, the macro BS can infer the interference from unexpected performance degradation of macro UT in a subframe with UL femto transmission. Alternatively, assuming that the cell area covered by the femto BS is small compared to the distance between the femto BS and the macro UT, the macro UT can infer the interference caused by the femto UL based on DL measurements from the femto BS. Correspondingly, the femto BS may be able to measure the power of macro UT transmissions directly. The different schemes require different type of information to be shared in the network, for example using the X2 interface [11] or directly over-the-air. In this paper we assume that the only information available for the femto BS is whether or not there is a macro UT affected by femto UT transmissions, but no further information on the radio link between the devices.

*b) Realistic knowledge of fading:* In Section III we assumed that the fading statistics does not change throughout the network, and that the parameters of the statistics are known. For the multi-cell scenario study, these assumptions do not hold. We therefore assume that a femto BS can only have information it can measure, e.g. channel quality information and received signal power from an associated femto UT, and that this information cannot be relayed to other BS.

*c) Femto-to-femto interference:* Compared with the two-link scenario from Section III, the multi-cell scenario has more interference from both macrocells and femtocells. From the point of view of our problem, multiple macro BSs do not make much difference – the limiting factor is still the closest macro UT. On the other hand, femto-to-femto interference is important, as increasing femto UT transmission power may cause unbearable interference e.g. in neighbours' apartments.

Based on these three principles (or limitations), we propose the following algorithm of setting the transmit power of femto UT in subframes under macro DL interference. The overlay macro BS informs the femto BS whether it is causing interference to some macro UT (recall the one-bit information from the first principle). Such presence is detected by a macro UT measuring reference signal received power (RSRP) from the femto BS larger than a threshold $\Gamma$. In case there is a *vulnerable* macro UT close by, the femto BS sets a low target SINR level $\rho_{\mathrm{low}}$ for its associated UT, corresponding to low MCS. This is the only thing the femto BS can do without knowing the channel condition to the vulnerable macro UT. To meet the $\rho_{\mathrm{low}}$ target, the femto BS is collecting samples for CDF of own-channel-power-to-interference-plus-noise ratio $\Phi_{\text{ChINR}}(x)$ and then sets the femto UT transmit power according to

$$P_{\text{F,n}} = \min\left[\frac{\rho_{\text{low}}}{\Phi^{-1}_{\text{ChINR}}(1-p_{\rho_{\text{low}}})}\ ;\ \frac{P_{\max}}{N}\right], \qquad (18)$$

where $p_{\rho_{\text{low}}}$ (parameter of choice) is the probability of meeting the target $\rho_{\text{low}}$.

In case there is no vulnerable macro UT close to the femto BS, the femto BS will set the femto UT transmit power so that it does not cause excessive interference at the closest neighbour femtocell. The femto BS will collect samples for CDF of received signal power from its associated femto UT $\Phi_{\text{R}}(x)$ and assume that the neighbour femtocell has a similar one. It will also measure RSRP from the closest neighbour femtocell and, based on the channel reciprocity in TDD, calculate the corresponding channel attenuation $H_{\text{I}}$. Based on these two pieces of information it will set the femto UT transmit power so that the signal-to-interference ratio (SIR) at the neighbour femto BS is higher than $\varphi_{\text{NB}}$ given by

$$P_{\text{F,n}} = \min\left[\frac{\Phi^{-1}_{\text{R}}(1-p_{\varphi_{\text{NB}}})}{\varphi_{\text{NB}} H_{\text{I}}}\ ;\ \frac{P_{\max}}{N}\right], \qquad (19)$$

where $p_{\varphi_{\text{NB}}}$ (parameter of choice) is the probability of meeting the target $\varphi_{\text{NB}}$. Note that this takes into account an effect of single interferer, whereas the statistics $\Phi_{\text{ChINR}}(x)$ from previous paragraph includes aggregate interference at the receiver.

### *B. Scenario description*

The employed HetNet scenario is similar to the one used in 3GPP e.g. in [12]. It consists of three tiers of hexagonal macrocells, each with three sectors, and three dual stripe apartment buildings, each randomly located in one sector of the central macrocell. The overall number of macrocell sectors (one transmission point in each) thus counts 57, although our simulations run only with two active tiers, i.e. 21 active macrocell transmission points. The statistics are collected only from the central macrocell. Each apartment building consists of two $100\text{m} \times 10\text{m}$ stripes with six floors. Each floor has 20 $10\text{m} \times 10\text{m}$ apartments. From all the apartments in the scenario, 10% have a closed access femtocell with one femto BS and one femto UT inside. In the central macrocell, there are 20 macro UTs per sector, from which $p_{\text{in}} \in \{35\%, 80\%\}$ are located inside the buildings. All macro and femto BSs have a single antenna.

Our simulation consists of snapshots, during which the UTs do not move. The scheduling algorithm is round robin and the throughput calculation is based on Shannon fitting, with the number of bits per subcarrier given by

$$C_n = B_{\text{eff}} \min\left[\log_2\left(1 + \frac{\rho_n}{\rho_{\text{fit}}}\right)\ ;\ C_{\max}\right], \qquad (20)$$

where $\rho_n$ is the SINR at given subcarrier, the effective bandwidth coefficient $B_{\text{eff}} = 0.7$, the fitting parameter $\rho_{\text{fit}} = 2\text{dB}$ and the maximum number of bits per subcarrier $C_{\max} = 4.8$. The lowest useful value of $\rho_n$ is $-7$dB. Remaining important system parameters are listed in Table I.

We assume full buffer traffic model, i.e. all users always have enough UL and DL data to fill all radio resources. The macro BSs apply the frame structure 1 of Figure 1. All femto BSs apply either frame structure 0 or frame structure 2, or 50% apply frame structure 0 and 50% apply frame structure 2. Uplink power control is based on (1) where the correcting factor $\varepsilon$ is non-zero only during the 5th and 10th subframes where we apply power boost described in Subsection IV-A.

Table I: Some simulation parameters.

| Parameter | Value |
|---|---|
| System bandwidth | 10MHz |
| Number of active subcarriers | 600 |
| Macro BS transmit power | 43dBm |
| Femto BS transmit power | 20dBm |
| Maximum UT transmit power | 23dBm |
| UL PC constant $P_0$ | -75dBm |
| UL PC compensation ceofficient $\alpha$ | 0.8 |
| DL noise figure | 7dB |
| UL noise figure | 5dB |

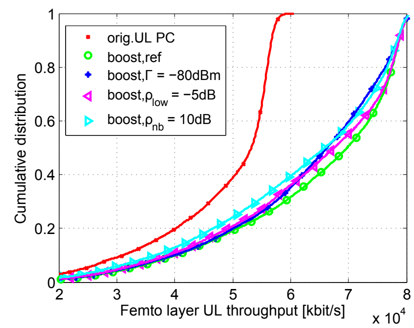


Figure 5: Throughput of femtocell UL in scenario with $p_{\text{in}} = 35\%$ and all femtocells using frame structure 0. In UL subframes under macro DL interference, the femto UT transmit power is either original power control (red), boost mechanism with reference parameter values (green), or boost mechanism with one of the key parameter values changed.

### *C. Simulation results*

Figure 5 presents the first set of results – femtocell UL throughput for scenario with $p_{\text{in}} = 35\%$ macro UTs located inside the apartment blocks and all femtocells using frame structure 0. The throughput is aggregated over all UL subframes, $2/3$ of which are under macro UL interference and use the original power control, while $1/3$ are under macro DL interference and use either the original power control (red curve) or the boost mechanism from previous subsection. The reference boost mechanism parameters (green curve) are: $\Gamma = -60\text{dB}$, $\rho_{\text{low}} = 0\text{dB}$, $p_{\rho_{\text{low}}} = 0.95$, $\varphi_{\text{NB}} = 5\text{dB}$ and $p_{\varphi_{\text{NB}}} = 0.95$. The rest of the curves in Figure 5 then present the impact of changing the values of $\Gamma$, $\rho_{\text{low}}$ and $\varphi_{\text{NB}}$ in comparison with reference values.

By applying the boost mechanism with reference parameter values, the femtocell UL median throughput is increased by approximately 30%. This is a substantial improvement, considering the fact that changes apply to only $1/3$ of the UL subframes. Increasing $\varphi_{\text{NB}}$ decreases throughput in the highest range of percentiles, which intuitively means that majority of femtocells are limited by the femto-to-femto interference

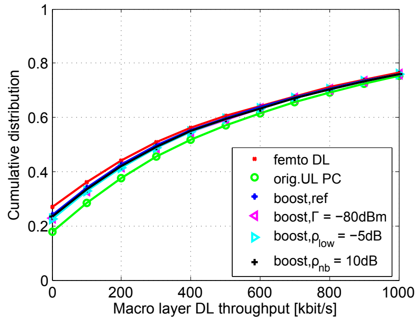


Figure 6: Throughput in macrocell DL in scenario with $p_{\text{in}} = 35\%$. Femtocells are using either frame structure 2 (red) or frame structure 0 (all other curves).

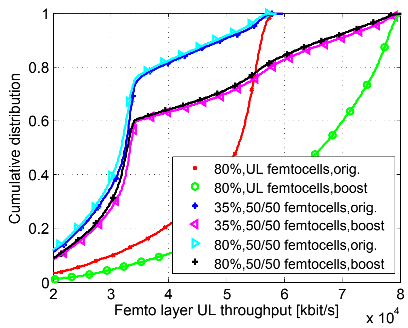


Figure 7: Throughput in femtocell UL for remaining scenario settings: different percentages of macro UTs inside and different femtocell frame structure settings.

constraint. On the other hand, decreasing $\rho_{\text{low}}$ effects only femtocells that have vulnerable macro UTs close by, which is a minority. Decreasing the $\Gamma$ threshold increases the number of such femtocells and has a visible effect in the range from approximately 20th to 90th percentile.

Figure 6 presents the impact of the boost mechanism on macrocell DL throughput. The scenario is the same as for results in Figure 5, except we also added result of a case when all femtocells use frame structure 2, i.e. the DL oriented frame structure. The plot is zoomed on the low percentages so that it shows the impact on macro DL probability of zero throughput. We can conclude that the boost mechanism (with all tested parameter values) increases the probability of zero throughput macro DL, but it never gets as seriously as in case of frame structure 2.

In Figure 7 we present the femtocell UL throughput results for the rest of the scenarios: $p_{\text{in}} = 80\%$ with all femtocells using frame structure 0 and $p_{\text{in}} \in \{30\%, 80\%\}$ with half of the femtocells using frame structure 0 and the other half using frame structure 2. In all three cases we compare results with original power control to results with boost mechanism with reference parameter values applied in 5th and 10th UL subframes. The performance improvements in femtocell UL throughput stay consistent in all the scenarios.

## V. Conclusions and Future Work

In this work we discussed femtocell uplink interfered by overlay macrocell downlink and proposed a solution. We considered the problem analytically in a simplified scenario assuming one femto link and one macro link and derived the optimal transmit power for the femto UT that ensures a minimum throughput requirement at the macro link. We observed that the interference to macrocell DL is only in a minority of cases a limiting factor, and in most cases the uplink transmit power was limited by the maximum allowed value. This was a good motivation to design a power control mechanism that is applicable to general multi-link case. This mechanism was then simulated with a HetNet scenario following 3GPP assumptions, where it showed approximately 30% median increase in femtocell UL throughput. The shortcoming due to larger transmit power was a slightly increased probability of macro UT to have zero throughput. However, this probability is still lower than in case of femtocell DL, even if UT is allowed to transmit with twice the power of femto BS.

An interesting idea for future work is to apply the concept of cognitive radio as in [13]. The macro UT is then considered as a primary user, while the femto BS is a secondary user. With such framework, the femto BS can listen to feedback information sent by macro UT (channel quality indicator) and adapt the femto UT transmission power so that the macro DL is not disturbed.

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