Interference Analysis and Performance Evaluation on the Coexistence of Macro and Micro/Pico Cells in LTE Networks

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***Abstract*—3GPP Long Term Evolution (LTE) is the next generation network technology for beyond 3G. In the LTE system deployment, there may not be much separation between the frequency bands assigned to operators. Therefore, adjacent channel interference analysis between two coexisting LTE systems is a potentially important research field. In this paper, we investigate the coexistence problem between a macrocell and small cells, i.e., microcells and picocells, in LTE networks. We focus on analyzing the adjacent channel interference (ACI) between two coexisting systems with different duplex modes, i.e., frequency division multiplexing and time division multiplexing, deployed in adjacent frequency bands. Main contribution of this paper is to present the coexistence results of two systems by evaluating the macrocell performance degradation caused by ACI when it operates with microcell/picocell on adjacent channel in some typical interference scenarios. Based on comparison and analysis of simulation results, we find that in some scenarios two LTE systems could not coexist well under current LTE radio frequency requirements. We also present some suggestions and mitigation technologies to avoid large throughput loss due to ACI.**

Keywords-Coexistence, Macrocell, Microcell, Picocell, LTE

I. INTRODUCTION

To evolve the universal mobile telecommunication systems (UMTS) to cope with future requirements, the 3rd Generation Partnership Project (3GPP) started standardization of 3G Long Term Evolution (LTE) in December 2004, which is also referred as the Evolved-Universal Terrestrial Radio Access Network (E-UTRAN)[1]. Although LTE offers two to three times capacity improvement over current 3G networks, it will be insufficient to address future expected capacity demands [2]. Though acquiring more spectrums would help operators provide more capacities, additional spectrum is costly and in most cases unavailable. The latest enhancement to LTE, LTE-Advanced, will improve spectral efficiency as well as offering promise of higher network capacities in both uplink and downlink. However, due to the vast amount of mobile data demand it is still insufficient to resolve the capacity shortfall. Therefore, in order to increase capacity and improve coverage, small cell network architectures based on the low-transmission power base stations (i.e., micro BS, pico BS) have been considered.

Micro BSs are used to improve coverage of the macrocell-based network with a low power output (e.g. 38 dBm or less [3]). They provide a mid-sized coverage with the radius of less than a mile in diameter. Their antennas are mounted on external walls of existing structures, such as street lights, billboards, bridges, tunnels and so on. Compared to micro BSs, pico BSs are even smaller and have a lower power output (e.g. 24 dBm or less [3]). Normally, they are installed inside buildings to extend coverage to indoor areas, where it is difficult to reach by macrocell, such as airport terminals, train stations or shopping centres [4]. Introduction of these low-transmission power base stations transforms the flat macro mobile network into a multi-level, hierarchical radio access network, which is also useful in seamless handovers.

Although small cells offer many benefits, the interference problem in conjunction with spectrum band allocation is still a challenge. The 2.6 GHz band (from 2500 to 2690 MHz) is identified as the IMT-2000 extension band by International Telecommunication Union (ITU) and it is expected to be available for LTE systems operating in frequency division duplex (FDD) or time division duplex (TDD). In 3GPP, band 7 (2500-2570 MHz in the uplink, and 2620-2690 MHz in the downlink) for FDD and band 38 (2570-2620 MHz) for TDD are specified. In some countries, two operators might deploy LTE systems on the same geographical area using FDD and TDD, respectively. In such case, assigned frequency bands of two systems might not be far away from each other. Therefore, due to lack of radio frequency (RF) isolation, the power leakage caused by transmitters as well as imperfect rejection of receivers, the adjacent channel coexistence of networks will lead to inter-system interference (ISI) also called adjacent channel interference (ACI), which will result in the capacity degradation of both systems. Consequently, in this article, we give an overview of the coexistence studies between two LTE systems based on the same approach in the studies involving E-UTRAN deployments in [5]. This paper focuses on macrocell and microcell/picocell coexistence. Although we may know ACI will degrade the system capacity, the question is which case is sensitive to the ACI and how severe the impact is. Therefore, in order to figure out these questions, we highlight the ACI analysis as well as evaluation results. In the published literature, we can find some similar studies on the coexistence issue involving two systems, such as E-UTRA and UTRA in [6][7], WiMAX and GSM in [8], Macrocell WCDMA and Macrocell WiMAX [9] and WCDMA and Microcell-HSUPA in [10]. However, to the best of our knowledge, no existing papers have presented the coexistence results of macro and micro/pico cells in LTE networks.

The rest of the paper is organized as follows. System model and interference analysis are briefly introduced in Section II and III, respectively. Evaluation results are presented in Section IV. Finally, Section VI concludes the paper.

II. SYSTEM MODEL

In this section, we firstly illustrate the coexistence scenarios, and then propagation model used in the evaluation is given.

Finally, power control and link level performance model are presented.

A. Coexistence scenarios

For single macrocell system, base stations with 3 sectors per site are placed on a hexagonal grid with distance of 3×*R*, where *R* is the cell radius, with wrap around. For macrocell layout, the inter-site distance (between two macro BSs), i.e., 3×R is 1000 meter. For coexistence case, define *D* as the distance offset between macro base station (BS) and the centre of microcell/picocell grid, which are shown in Fig.1. For uncoordinated case, i.e. offset $D = \sqrt{3} \times R$, microcell/picocell grid are located at the macrocell network's cell edge. For coordinated, co-location of sites is assumed, i.e. offset $D = 0$.

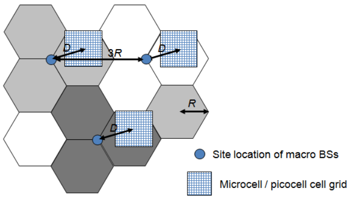

Fig. 1: Cell layout

A.1 Macrocell and Microcell deployment

The microcell grid is based on the Manhattan deployment model[11], which has 72 BSs in every second street junction with block size 75 meters and road width 15 meters as shown in Fig.2 (left-hand). This layout is selected in order to have large enough macrocells and low amount number of microcells so that computation times remain reasonable. Further, macro BSs' positions are selected so that as many conditions as possible can be studied (i.e. border conditions etc.).

A.2Macrocell and Picocell deployment

The picocell grid using the indoor office model [11] as shown in Fig.2 (right-hand) has been mapped on to the macrocell network. Here, it is assumed that pico BS is operating inside the building hence the signals entering and exiting the building are attenuated because of the wall losses.

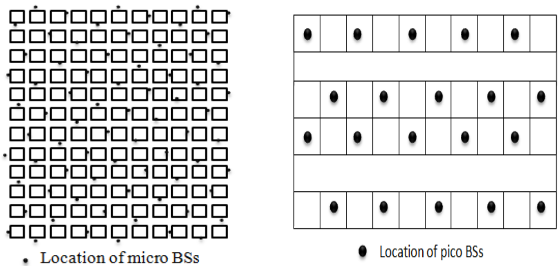

Fig. 2: Microcell /picocell grid model

B. Propagation model

Table 1 and Table 2 summarize pathloss models [11] for macrocell/microcell coexistence, and macrocell/picocell coexistence, respectively.

Table 1: Pathloss model for macrocell and microcell coexistence

Scenario	Model
Micro BS to Micro UE	$L = 20\cdot\log_{10}(\frac{4\pi d_n}{\lambda}\cdot D(\sum_{j=1}^{n} s_{j-1}))$ $D(x) = \begin{cases} x/x_{br}, x > x_{br} \\ 1, x \le x_{br} \end{cases}$ $k_n=k_{n-1}+d_{n-1}c$ and $d_n=k_n s_{n-1}+d_{n-1}$, where λ denotes wavelength, *c* is a function of the angle of the street crossing. For a 90 degree street crossing the value *c* should be set to 0.5. Further, s_{n-1} is the length in meters of the last segment. A segment is a straight path. d_n is the "illusory" distance. The initial values are set according to: k_0 is set to 1 and d_0 is set to 0.
Macro BS to Micro BS	$L = 40(1\text{-}4\times10^{-3}h_b)\log10(R) - 18\log10(h_b) + 21\log10(f) + 80$ dB where *f* is the carrier frequency, h_b is the base station antenna height, in metres, measured from the average rooftop level, and *R* is the separation between base station and UE in kilometres.
Macro BS to Micro UE	$L = 40(1\text{-}4\times10^{-3}h_b)\log10(R) - 18\log10(h_b) + 21\log10(f) + 80$ dB
Macro UE to Micro BS	For the case that the macro UE is inside the street, the model is the same with that of the micro UE to micro BS; $L = -10\log_{10}(\frac{\lambda}{2\sqrt{2}\pi R})^2 - 10\log_{10}\left[\frac{\lambda}{2\pi^2 r}(\frac{1}{\theta}-\frac{1}{2\pi+\theta})^2\right]$ $-10Log_{10}(\frac{d}{R})^2 \quad \theta = \tan^{-1}\left(\frac{\lvert\Delta h_m\rvert}{x}\right), r = \sqrt{(\Delta h_m)^2 + x^2}$ where Δh_m is the difference between the mean building height and the mobile antenna height (set 10.5m as typical value), *x* is the horizontal distance between the mobile and the diffracting edges (set 15m as typical value).
Macro UE to Macro BS	$L = 15.3 + 37.6\log10\ (R)$

Table 2: Pathloss model for macrocell and picocell coexistence

Scenario	Model
Pico BS to Pico UE	$L_1 = 37 + 30\log10(r) + 18.3n^{((n+2)/(n+1)-0.46)}$ where *r* is the transmitter-receiver separation given in metres and *n* is the number of floors in the path (We assume the 3-floor model. Therefore, the max value of *n* is 3).
Pico UE to Macro BS	The pathloss of macro UE to macro BS + wall loss attenuation (For each wall, loss attenuation is assumed as 10dB).
Macro UE to Pico BS	The same with macro UE to Pico UE
Pico BS to Macro BS	L_2 + wall loss attenuation

C. Power control and Link Level Performance Model

The power control schemes for downlink and uplink are followed the suggestion in [5]. Similarly, the link level performance model considering link adaptation and hybrid automatic repeat request (HARQ) can also be found in Annex A.1 [5].

III. INTERFERENCE ANALYSIS

Because of non-linearity of power amplifier, when transmitting in its own channel, a part of transmitted power is leaked to adjacent channels. On the other hand, the non-ideal filter in receiver is unable to receive only the desired signal alone. All these factors cause ACI, which can lead to significant reduction in its neighbor system capacity. The level of ACI depends on the spectral 'leakage' of the interferer's transmitter and the adjacent channel blocking performance of the receiver. For the transmitter, the spectral leakage is characterized by the adjacent channel leakage ratio (ACLR), which is defined as the ratio of the transmitted power to the power measured in the adjacent RF channel at the output of a receiver filter. Similarly, the adjacent channel performance of the receiver is characterized by the adjacent channel selectivity (ACS), which is the ratio of the receiver filter attenuation on the assigned channel frequency to the receiver filter attenuation on the adjacent channel frequency. In order to determine the composite effect of the transmitter and receiver imperfections, the ACLR and ACS values are combined to give a single ACIR value using the following equation

$$\frac{1}{ACIR} = \frac{1}{ACLR} + \frac{1}{ACS} \tag{2}$$

Uplink interference is measured at base stations and the total interference includes co-channel interference (CCI), which is mainly caused by frequency reuse, and ACI. Define I_{CCI}^{U} as the uplink CCI power and I_{ACI}^{U} as the uplink ACI power. The total uplink interference power is given by

$$I^{U} = I_{CCI}^{U} + I_{ACI}^{U} \tag{3}$$

Define $P_{k,i}$ as the transmission power of the user i to the base station k, $G_{k,i}$ the antenna gain sum of transmitter and receiver for the user i to the base station k, $PL_{k,i}$ the path loss between the user i to the base station k. Therefore, the desired signal power is $P_{k,i}G_{k,i}PL_{k,i}$. $G_{m,i,k}$ denotes the antenna gain sum for the user i in the intra-system sector m to the base station k, $PL_{m,i,k}^{\text{intra}}$ the path loss between the user i in the sector m to the base station k. Therefore, we have

$$I_{CCI}^{U} = \sum_{m \neq k} P_{m,i} G_{m,i,k} PL_{m,i,k}^{\text{intra}} \tag{4}$$

Define $G_{n,i,k}$ as the antenna gain sum of transmitter and receiver for the user i in the sector n to the base station k, $PL_{n,j,k}^{\text{inter}}$ the path loss between the user j in the sector n to the base station k. the Therefore, the uplink ACI is presented by

$$I_{ACI}^{U} = \frac{1}{ACIR} \sum_{n} \sum_{j} P_{n,i} G_{n,j,k} PL_{n,j,k}^{\text{inter}} \tag{5}$$

The SINR of the i^{th} user is given by

$$\begin{aligned} SINR_i &= \frac{P_{k,i}G_{k,i}PL_{k,i}}{I_{CCI}^{U} + I_{ACI}^{U} + N_0} \\ &= \frac{P_{k,i}G_{k,i}PL_{k,i}}{\sum\limits_{\substack{m \neq k \\ m=1}}^{N} P_{m,i}G_{m,i,k}PL_{m,i,k}^{\text{intra}} + \frac{1}{ACIR}\sum\limits_{n=1}^{N}\sum\limits_{j=1}^{N_u} P_{n,j}G_{n,j,k}PL_{n,j,k}^{\text{inter}} + N_0} \end{aligned} \tag{6}$$

where N denotes the total number of sector, N_u represents the number of active user per sector and N_0 is the additive white Gaussian noise power.

Downlink interference is measured at UE sides, where CCI and ACI are measured from all base stations. Define I_{CCI}^{D} as the downlink CCI and I_{ACI}^{D} as the downlink ACI. The total downlink interference is given by

$$I^{D} = I_{CCI}^{D} + I_{ACI}^{D} \tag{7}$$

where $I_{CCI}^{D} = \sum_{m=1, m \neq k}^{N} P_{m,i} G_{m,i} PL_{m,i}^{intra}$, and $G_{m,i}$ denotes the antenna gain sum of transmitter and receiver for the user i from the base station m, $PL_{m,i}$ represents the path loss between the user i from the base station m and $PL_{m,i}^{intra}$ means the path loss between the user i from the base station m.

$$I_{ACI}^{D} = \frac{1}{ACIR} \sum_{n=1}^{N} P_{n,i} G_{n,i} PL_{n,i}^{inter} \tag{8}$$

where $G_{n,i}$ denotes the antenna gain sum of transmitter and receiver for the user i from the base station n, and $PL_{n,i}^{inter}$ represents the path loss between the user i to the base station n.

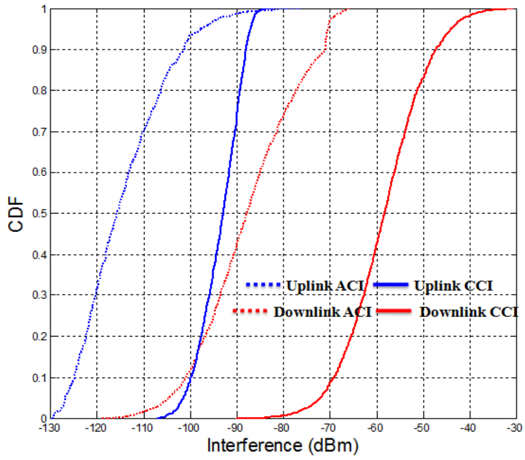

Fig.3 Downlink and uplink interference

Therefore, the SINR of the i^{th} user is given by

$$\begin{aligned} SINR_i &= \frac{P_{k,i}G_{k,i}PL_{k,i}}{I_{CCI}^{D} + I_{ACI}^{D} + N_0} \\ &= \frac{P_{k,i}G_{k,i}PL_{k,i}}{\sum\limits_{\substack{m \neq k \\ m=1}}^{N} P_{m,i}G_{m,i}PL_{m,i}^{intra} + \frac{1}{ACIR}\sum\limits_{n=1}^{N} P_{n,i}G_{n,i}PL_{n,i}^{inter} + N_0} \end{aligned} \tag{9}$$

The cumulative distribution functions (CDF) of both co-channel and adjacent channel interference with 30 dB ACIR for both uplink and downlink are given in Fig.3. We can observe CCI is much stronger than ACI, which means CCI dominates the system performance. Meanwhile, we can see the downlink interference level is stronger than that of the uplink due to the higher transmission power. Therefore, it can be foreseen that aggressor BSs would have much larger impact on the victim system than aggressor UEs, which can be confirmed by the simulation results given next section.

IV. EVALUATION

In this section, we present the coexistence results of two systems by evaluating the macrocell performance degradation caused by ACI when it operates with microcell/picocell on adjacent channel in some typical interference scenarios. In our simulation, we focus on the 2.6 GHz band (2500-2690 MHz). In some countries, there will be at least two operators that deploy LTE systems on the same geographical area, possibly with FDD and TDD respectively.

One of our motivations is to see if the small cells with low-transmission power BSs can coexist with macrocell network in the adjacent frequency band. If there is some possibilities, it will provide operators one possible choice of using dedicated frequency band to small cells instead of wasting the spectrum resource to guard band. Therefore, we assume evaluation scenario where macrocell network employing FDD and microcell/picocell TDD network are operating in adjacent each other as shown in Fig.4. Firstly, we investigate impacts of ACI from BSs and UEs of TDD micro/pico system on the uplink capacity of FDD macrocell network (left-hand of Fig.4). Secondly, we also inivestigates impact of ACI from BSs of TDD micro/pico system on the downlink capacity of FDD macrocell network (right-hand of Fig.4). The simulation results are provided in terms of throughput loss in percent relative to the single system throughput without ACI. Both the average throughput loss and 5% CDF throughput loss (cell edge) are compared and analyzed. Different system offsets and power control parameter settings are aslo considered in our simulations. Other simulation pareameters are summarized in Table 3.

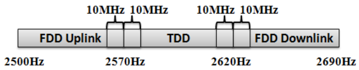

Fig. 4. Spectrum allocation scenario

Table 3: Simulation parameters

Parameters	Uplink	Downlink
Cell layout	Macro: Hexagonal 19 cell sites grid, 3 sectors per cell; Micro: Manhattan deployment model [11]; Pico: Indoor office model [11]	
Carrier frequency	2600 MHz	
Bandwidth	10 MHz	
Inter-site distance	1000 m	
Resource Block (RB) size	180 kHz	
Number of active UEs per sector	5	50
BS antenna height, h_b	30 m	
UE antenna height	1.5m	
Receive antenna gain (include feeder loss)	Macro: 15 dBi Micro: 6 dBi Pico: 3 dBi	0 dBi
Transmission antenna gain (include feeder loss)	0 dBi	Macro: 15 dBi Micro: 6 dBi Pico: 3 dBi
log-normal fade shadow	10 dB	
Shadowing correlation	Between cells: 0.5, Between sectors: 1.0	
BS max Tx power	Macro: 46 dBm; Micro: 38 dBm; Pico: 24 dBm	
UE max/min Tx power	24 dBm / -30 dBm	
white noise power density	-174 dBm/Hz	
BS noise figure	5 dB	
UE noise figure	9 dB	

In Fig.5 and Fig.6, we observe that the downlink ACIs caused by both TDD microcell and picocell have the significant impact on the FDD macrocell uplink throughput performance. To guarantee the throughput loss smaller than 5%, at least about 77 dB and 50 dB ACIR are needed for macrocell & microcell and macrocell & picocell coexistences, respectively. On the contrary, in Fig.7 and Fig.8 which are presenting the case of the TDD uplink interfering the FDD uplink, 37 dB ACIR is required for macrocell and microcell coexistence, but only 17 dB for macrocell and picocell coexistence. Fig.9 shows the case where TDD downlink interferes the FDD downlink. The needed ACIR for macrocell and microcell coexistence is small, but 42 dB for macrocell and picocell coexistence. The main reason is FDD macro UEs indoor will suffer strong interference from TDD pico BSs. The requirements of ACLR and ACS for BS and UE defined in [12] and [13] are summarized in Table 4. ACIR based on these requirements can be calculated by (2) and the results are given in Table 5.

Table 4: Requirements of ACLR and ACS for BS and UE

	ACLR (dB)	ACS (dB)
10 MHz BS	45	42.3
10 MHz UE	30	33.0

Table 5: ACIRs for each scenario

Interference scenario	ACIR@10 MHz (dB)
BS→UE	32.7
UE→BS	29.8
BS→BS	40.4

Together with these simulation results, we summarize the needed extra isolation for each scenario in Table 6.

Table 6: Extra isolation requirement for each scenario

Interference scenarios	Extra isolation	Interference scenarios	Extra isolation
TDD Micro BS to FDD Macro BS	~ 38 dB	TDD Pico BS to FDD Macro BS	~10 dB
TDD Micro UE to FDD Macro BS	~1 dB	TDD Pico UE to FDD Macro BS	No need
TDD Micro BS to FDD Macro UE	No need	TDD Pico BS to FDD Macro UE	~ 9 dB

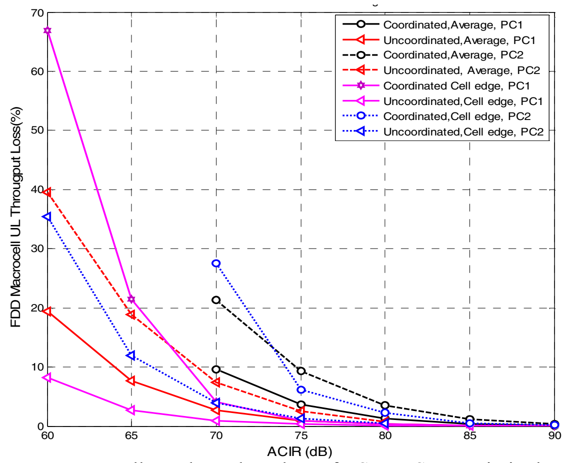

Fig. 5 FDD macrocell UL throughput loss of BS-to-BS scenario in the case of macrocell and microcell coexistence

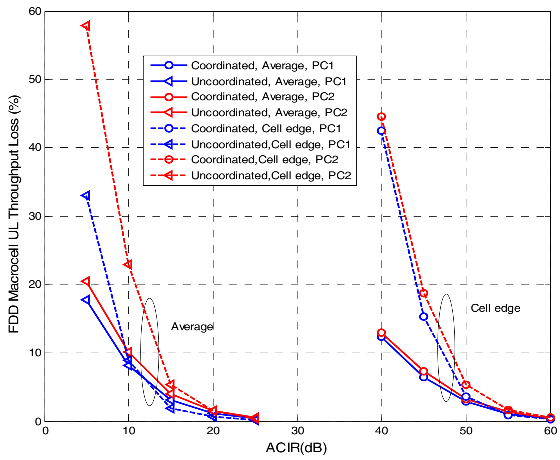

Fig. 6 FDD macrocell UL throughput loss of BS-to-BS scenario in the case of macrocell and picocell coexistence

There are a number of solutions to the additional isolations that can be taken alone or in combination to limit the interference. The interference limiting techniques include antenna techniques, guard bands, additional front-end filters, restricted channels, deployment restrictions, special site engineering and so on. All solutions are associated with an increased level of complexity, as there is always a trade off to consider. Following our research results, the required extra isolation of TDD picocell BS to FDD macrocell BS is much smaller than that of TDD micocell BS to FDD macrocell BS, which implies one could place the base station indoors to reduce the severe ACI. Meanwhile, for outdoor deployments, a useful method is to deploy the base station without line of sight to the interfered based station. Since guard band would penalize spectral efficiency, it is better to be utilized in conjunction with other solutions such as additional front-end filters and restricted channels. On the other hand, for the co-located case using vertical antenna separation is another effective way together with additional frontend filters, which gives sufficiently low interference.

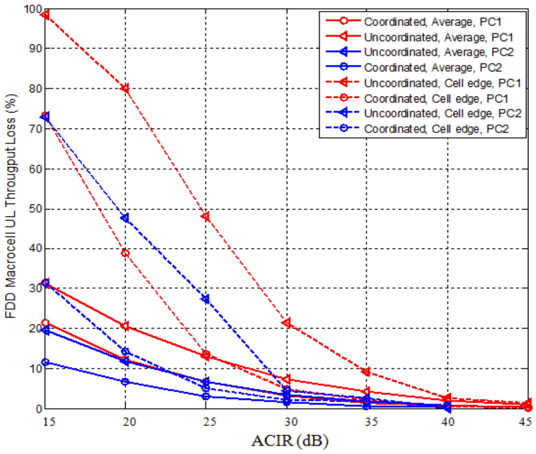

Fig.7. FDD macrocell UL throughput loss of UE-to-BS scenario in the case of macrocell and microcell coexistence

VI CONCLUSIONS

In this paper, we highlighted the coexistence problem between macrocell and microcell/picocell in LTE networks by evaluating the macrocell performance degradation caused by ACI. The detailed ACI analysis was given using evaluation methods of system coexistence. From the comparison and analysis of the simulation results, we can observe that in some scenarios due to strong ACI two LTE systems could not coexist well under current RF requirements. We suggested extra mitigations are needed to ensure successful coexistence such as antenna techniques, guard bands, additional front-end filters and so on. In our following work, the impact of FDD macrocell on the microcell/picocell will also be analyzed and the results will be given in the future.

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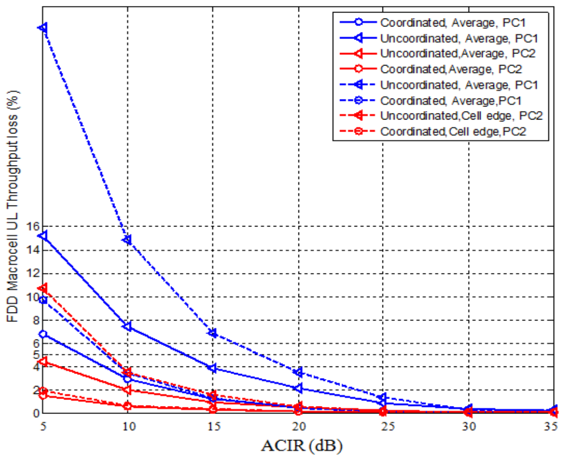

Fig. 8 FDD macrocell UL throughput loss of UE-to-BS scenario in the case of macrocell and picocell coexistence

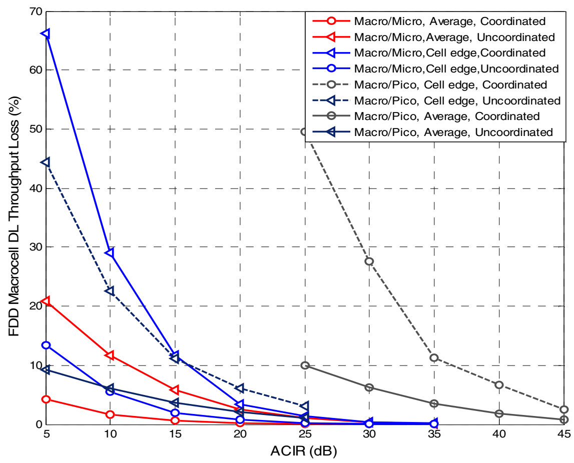

Fig. 9 FDD macrocell DL throughput loss of BS-to-UE scenario in the cases of macrocell /microcell and macrocell/picocell coexistence