Simultaneous Uplink and Downlink Transmission Scheme for Flexible Duplexing

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Abstract. The idea of adaptive usage of uplink frequency resources for other purposes, such as downlink data transmission, has attracted researchers for many years. This paper discusses the concept of applying a simultaneous uplink and downlink transmission scheme for flexible duplexing, where the middle part of the so-called uplink component carrier is used for downlink data delivery. The realization of such an idea is based on the adaptive change of the transmit/reception mask at the base stations and/or mobile devices. Beside a theoretical analysis, this paper provides the calculation results of the interference rise in the system.

Keywords: Flexible duplexing · Non-contiguous transmission · Interference · LTE/LTE-A · 5G systems

1 Introduction

The problem of asymmetric traffic, typical for modern wireless networks, can be solved in various ways depending on the applied duplexing schemes between uplink (UL) and downlink (DL) data delivery. In time division duplexing (TDD), a fragment of the frequency spectrum is utilized in both directions of data transmission (i.e., from base station (BS) to mobile terminal (MT), and from MT to BS), and the split between UL and DL is done in the time domain. As the wireless standards typically provide a very detailed time hierarchy (i.e., transmitted bits are organized into frames, bursts, chunks, etc.), it can be foreseen that asymmetric traffic can be easily managed by the application of adaptive allocation of more time slots to that direction which needs to serve higher traffic. Such an approach has been discussed in, e.g., [1–4]

Contrarily, in the classical frequency division duplexing mode (FDD), the data between BS and MT can be delivered continuously in the time domain in both directions if needed, but the split between UL and DL is realized in the spectrum domain, i.e., dedicated fragments of the frequency spectrum are assigned to each transmission direction. In such a case, the problem of asymmetric traffic can be solved by allowing data transmission in a selected direction in both bands. In other words, UL band can be utilized for DL transmission and vice-versa. Some interesting discussion can be found in, e.g., [5,6]. It is also

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worth noticing here that the frequency bands dedicated for UL and DL transmission are separated by a dedicated frequency gap guaranteeing enough isolation between the transmit and receive signals. This isolation is required, as the problem of efficient canceling of strong interference at the reception interface from the transmit one is not mature enough today, although much progress has been achieved in the area of wireless full-duplex transmission [7,8]. These observations have to be considered while realizing the concept of adaptive utilization of both frequency bands for data delivery only in one direction.

In our work we concentrate on FDD solutions with particular attention given to LTE/LTE-A systems. Our motivation behind such a selection is to provide new technological solutions, while keeping the backward compatibility with current standards. In other words, one may notice that many of the existing wireless standards (including practical deployments of LTE) are based on FDD solutions. Thus, it is highly expected that the existing infrastructure be utilized as effectively as possible, and flexible usage of frequency bands in such a scenario can be one of the interesting solutions. Moreover, we assume that the amount of traffic in the DL direction is much higher than in the opposite direction, as this represents a typical situation in crowded areas where the role of the dominating service is played by mobile video streaming [9]. Clearly, an opposite situation is also possible (one can consider mass events where many persons decide to upload the photos or videos), but it is not as popular as the previous one. Finally, in such a context, the selection of LTE-based systems is natural, as this is the technology that permanently supersedes 3G systems in many places in the world. However, the application of flexible duplexing in FDD-LTE is not straight-forward, due to the continuous transmission of control signals in PUCCH in the UL band (PUCCH stands for physical uplink control channel). It means that (potentially) every time there is a useful signal present in the uplink band and it is not possible to allocate the whole UL band for downlink transmission without interfering to the base station.

One of the possible solutions in such a case is to apply the TDD mode in the uplink band [1]. In other words, the whole DL band is utilized for delivering data from BS to MT only (so the classic FDD transmission scheme is kept in the DL band), but the UL band is split in time into equal time slots which can be adaptively assigned to UL or DL depending on the current traffic in both directions. In this context, it is worth to mention further developments in this topic, known as the TDD Enhanced Interference Management and Traffic Adaptation (eIMTA) [10,11], also standardized in Release 12 of LTE [12]. Here, the split between the uplink and downlink data is considered to be flexible and modified adaptively to the observed traffic.

In the approach discussed in this paper, we propose to use the uplink bands in a highly flexible way, so that the split between uplink and downlink traffic depends mainly on the current user demands and assumed priorities. We consider simultaneous data transmission in both uplink and downlink directions, implementing advanced adaptive transmission/reception filtering for out-of-band attenuation. In general, this technique allows us to utilize the middle part of the uplink component carrier for DL transmission. Clearly, such a transmission scheme results in an interference rise observed inside the serving and all surrounding cells. Thus, in order to evaluate the proposed scheme, we have analyzed its impact on the interference boost observed by other users (mobile terminals or base stations). Based on that analysis, we propose to apply simple localization techniques for further enhancements in the proposed scheme, as well as we discuss the backward compatibility of that study. The key idea of the paper is to check the possibility of utilizing a fragment of all uplink resources for downlink transmission, even if the rest of these uplink resources are occupied. This approach is highly flexible, and can be used as a solution for advanced spectrum utilization in 5G networks. Moreover, the proposed technique can also guarantee backward compatibility with 4G systems. Thus, in order to check the correctness of the proposed approach (i.e., simultaneous uplink and downlink transmission) and its backward compatibility, we intentionally modeled a 4G-like scenario where uplink control data are transmitted at the edges of the uplink band. Nevertheless, this scenario can easily be generalized.

The paper is structured as follows. In the next section, we briefly remind selected techniques proposed for flexible duplexing, and present a few potential application scenarios including the key limiting factors of the LTE/LTE-A systems. We also discuss the main idea of simultaneous data transmission and the method of pre-calculating the transmit/reception masks. The analysis is followed by a presentation of the obtained numerical results.

2 Flexible Duplexing for 4G and 5G

2.1 TDD Mode Applied in Uplink Band

The concept of flexible utilization of unused frequency resources in FDD-based wireless communication systems is one of the immediate solutions that appeared during the discussion on the effective management of asymmetric traffic in current and future networks. As introduced in the previous section, various schemes have been considered so far (please see the discussion in, e.g. [1]), but the most focus has been put on TDD-based solutions. In such a case, the UL band is utilized following the time division duplex mode, where for certain time slots, the UL channel is used for downlink data transmission. Clearly, such a scheme results in an interference increase observed by other system users (for example, by those located in the surrounding cells). In order to minimize the impact of this phenomenon, quite often, (almost) ideal synchronization between cells is considered. This issue is illustrated in Fig. 1, where a frame consisting of 10 subframes is shown. In the upper part, the classic case is shown, where the whole UL band is used only for UL transmission. In such a case, one can ideally assume the lack of interference between the neighboring cells (in the figure, we used the names Cell A and Cell B). In the middle part of the figure, some arbitrarily selected subframes are used for DL data transmission, causing interference to the adjacent cells. The problem is more severe if there are some synchronization problems between the cells, as shown in the bottom part of the figure.

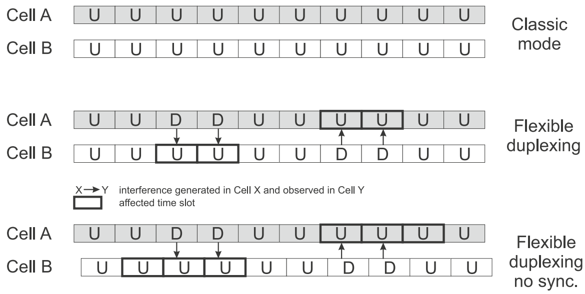

Fig. 1. Examples of flexible duplexing schemes in TDD mode

2.2 Considered Use Cases

There are various practical use cases considered in the context of flexible duplexing that can be found in the literature. In order to illustrate the idea we show two of them below. First, as discussed in the previous subsection, one can apply flexible duplexing at the macro-cell level. Thus, it is the macro base station that decides to assign some of the slots for downlink transmission, and such a transmission scheme is unique within the whole cell. The interference is then observed in the neighboring cells - please see Fig. 2. Another case includes the presence of small cells, i.e., there is more flexibility in assigning the subframes for UL or DL transmission, as this decision can be made either at the macro, or small-cell level. In the latter case, interference is induced into both serving and neighboring sites, as shown in Fig. 3. Without a loss of generality, we concentrate on the two macro-cell scenario, having in mind that the scheme proposed in this paper can be immediately applied to other cases with few or even no modifications.

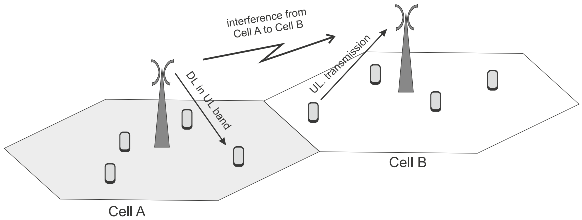

Fig. 2. Two macro cell scenario

2.3 Proposed Simultaneous Flexible Duplexing Scheme

Let us now consider an FDD-LTE-based system operating in both macro cells (hereafter denoted as Cell A and Cell B) with the frequency reuse factor close to unity; the application of the soft frequency reuse can be considered as well, but it does not influence the idea investigated here. In such a case, the uplink

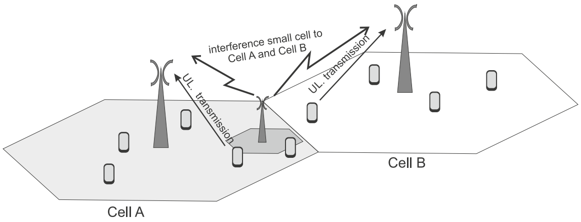

Fig. 3. Two macro cell and one small cell scenario

component carrier is used, broadly speaking, for user data delivery (realized in PUSCH, standing for physical uplink shared channel) and for uplink control information transmission (typically performed via PUCCH). It is important to notice that the PUCCH data are transmitted using small frequency segments located on the borders of the component carrier. In the considered scenario, we focus on the case when the UL channel (in Cell B) is used only for conveying control information, and there are no user data to be delivered to the base station. At the same time, Cell A is using the middle part of its own component carrier for downlink transmission, causing some interference rise. The idea is illustrated in Fig. 4, where the first seven subframes are managed in the way described above. However, we foresee that the proposed scheme can be extended to a more flexible situation where the fragment of the UL band will also be used for user data transmission (as shown in the last four subframes); this is a topic for further investigation. Please notice that we have also intentionally illustrated the presence of inference observed within the serving cell (Cell A), as the resource blocks used for PUCCH delivery in Cell A will be affected by the DL transmission in the middle of the band. The key concept proposed by us is to apply advanced, adaptive spectrum shaping algorithms originally considered to be used in non-

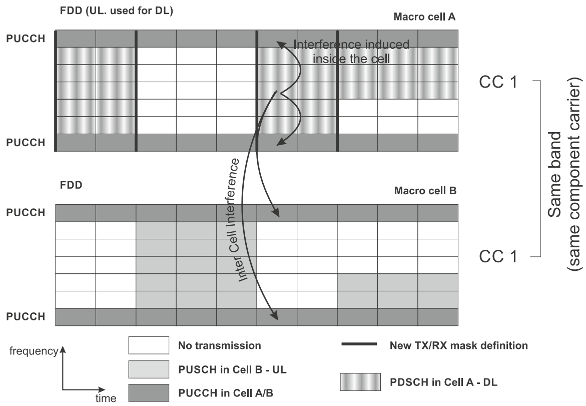

Fig. 4. Proposed scheme for simultaneous flexible duplexing

contiguous multicarrier transmission schemes [13]. These solutions can guarantee a significant reduction of unwanted out-of-band emission even in a very narrow frequency band at a reasonable complexity. Moreover, these algorithms can be applied at the beginning of a frame, allowing for a precalculation of the required spectrum masks (filter shapes). The moments when the new spectrum masks have to be changed within the cell are indicated by solid bold vertical lines in Fig. 4.

2.4 Synchronization Problems

As stated, in the considered scenario, the DL data signal in Cell A will be transmitted adjacently (in frequency) to the UL control signal in Cell B. As such, there will be some interference between UL (SC-FDMA, single-carrier frequency division multiple access) and DL (OFDMA), depending on the guaranteed synchronization level between both systems:

- full frequency and time synchronization - there is no inter-carrier interference,
- only frequency or only time synchronization - there is inter-carrier interference.

It is well known that both systems utilize the same subcarrier spacing and cyclic prefix (CP) length. Both systems could have the same reference oscillator frequency, synchronized using, e.g., GPS. On the other hand, according to LTE modulation specification, subcarriers in UL (after DFT processing) are moved by 0.5 subcarrier spacing in comparison to the DL signal in order to obtain minimum peak-to-average power Ratio (PAPR). As such, DL and UL subcarriers are not orthogonal to each other, i.e., inter-carrier interference occurs. One solution would be to shift 5G transmission by 0.5 subcarrier spacing to achieve subcarriers orthogonality and rely on the carrier frequency offset estimation at the receiver.

Another issue is related to the time synchronization of frames between Cells A and B. Typically, all mobile terminals attached to Cell B have different *timing advance* values (due to different propagation times) in order to synchronize their UL signal at the Cell B base station. However, in a practical case, DL transmission within Cell A is not synchronized or only partially synchronized with Cell B UL, and interference occurs. On the other hand the protection of Cell A UEs (DL) from interference caused by Cell B UEs (UL) cannot be achieved by means of synchronization (many sources of interference with different propagation delays). Other solutions have to be considered, such as the above-mentioned filtering.

2.5 Sources of Interference in Non-orthogonal OFDM/SC-OFDM Systems

The interference power in the considered scenario at the SC-OFDM receiver (Cell B base station/eNodeB) comes from two sources [14]:

- *Out-of-band (OOB) radiation of the DL/UL transmitter* - this is mostly the effect of sinc-like subcarrier spectrum. As it has been shown in [14], each subcarrier in the time domain can be represented by a complex sinusoid windowed using a rectangular window. However, there are a number of spectrum shaping methods designed in order to reduce OOB radiation power, e.g., [15,16]. The simplest one is to use so-called *guard subcarriers* [14] by modulating subcarriers closest to the currently utilized spectrum bandwidth with zeros (i.e., subcarriers close to the PUCCH band in Cell B are zeroed). Another source of OOB radiation is the high PAPR of an OFDM transmission carried using a nonlinear front-end. However, it can be effectively reduced using PAPR minimization or predistortion techniques [17].
- *Limited selectivity of OFDM/SC-OFDM receiver* - in a case when there is no user data transmission in the uplink (only the control channel is present), the middle part of the UL component carrier is empty, and only the resource blocks at the border convey useful data. However, the DFT operation is carried at the receiver on N consecutive incoming samples cut out from a stream of incoming samples. As such, time-domain windowing with N-length rectangular window is used. The reception filter characteristic of a single subcarrier has a sinc-like shape. If there is a DL signal (transmitted as stated above in the middle of the UL band) observed by the Cell B receiver, high power sidelobes of a sinc function will cause interference on the used subcarrier (conveying control information). In order to overcome this problem, time-domain windowing or filtering should be applied at the receiver.

3 Simulation Results

In order to evaluate the proposed scheme, we would like to measure the impact of the interference induced to other users due to the application of the proposed flexible duplexing scheme (i.e., when the advanced spectrum shaping proposed in [15,16] is implemented). We consider the presence of various receivers in the system, ones that are equipped with the proposed spectrum shaping algorithms, and others that can be treated as classical LTE devices (base stations or mobile terminals). The idea here is to guarantee backward compatibility with the existing devices.

3.1 Power Spectral Density Analysis

First, SC-OFDM (UL) and OFDM (DL) occupying a maximum of 20 MHz bandwidth are considered with IFFT/FFT of size $N = 2048$. Both systems transmit their signals in dedicated time slots (0.5ms duration each) composed of 7 OFDM/SC-OFDM symbols. While the first symbol in a slot utilizes 160 samples with CP, the rest are 144 samples long, each. It is assumed that there is no synchronization, neither in the time, nor in the frequency domain (as it is the most challenging scenario, as presented in the previous section). According to [19], the maximal number of Resource Blocks (RBs) in the considered scheme is

100. In the case of no data transmission in UL, only PUCCH is transmitted on both ends of the available band, i.e., RBs indexed 50 and -50. In the proposed scheme, unused resource blocks in the middle can be utilized by Cell A for its DL transmission. In Fig. 5, normalized PSDs of UL and DL signals are shown using solid lines. Cell A transmission utilizes RBs with indexes $\{-48, ..., -1, 1, ..., 48\}$, i.e., a contiguous band around the DC subcarrier (0th RB is not used). Signals are normalized to have equal received power per utilized RB. It can be observed that the OOB radiation of DL transmission in-band of UL transmission equals about -25 dB (solid, blue line). However, as presented previously, OOB radiation can be decreased by the application of advanced spectrum shaping methods (like Optimized Cancellation Carriers Selection, OCCS, discussed in [15]). In the presented plot, 20 OCCS subcarriers have been used, i.e., about 1.8 % out of all used subcarriers are devoted to OOB reduction. It is visible that a significant OOB radiation reduction can be obtained (solid, black line).

On the other hand, the values of the effective signal and interference power observed at the SC-OFDM receiver (i.e. after passing the FFT block) are shown with dashed lines. It can be noticed that the application of the proposed flexible duplexing scheme with no dedicated filtering, i.e., where standard receivers (std. RX) at the Cell B and standard transmitters (std. TX) at Cell A are used, results in the highest effective interference power, i.e., about -22 dB. The modification of only one side of the system (either the transmitter using the OCCS method, or the receiver by applying 256-samples-long Hanning windowing before FFT operation) does not significantly decrease the interference power. However, if both methods are combined (dashed, black line) the interference power is decreased significantly giving about -45 dB.

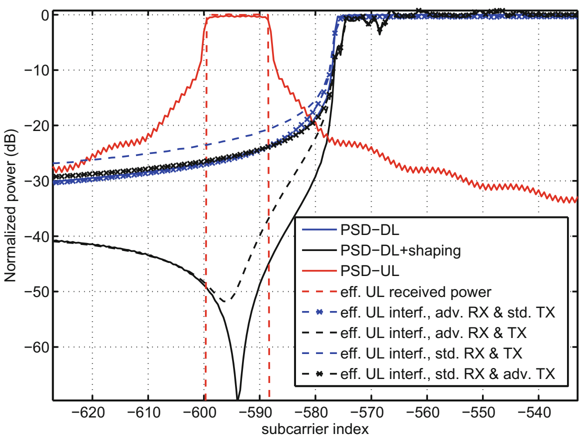

Fig. 5. Normalized PSDs of UL and DL transmitted signals, effective interference/useful signal power at Cell B base station (receiver). Only lower frequency edge is shown

3.2 Adjacent Channel Interference Ratio Analysis

In this section we analyze the adjacent channel interference ratio (ACIR) as a good metric used for the assessment of the ratio of wanted power to the interference power from the other bands. Mathematically, ACIR is the function of the adjacent channel leakage ratio (ACLR, used to characterize the transmitter) and the adjacent channel selectivity (ACS, used to characterize the receiver), i.e., $\mathrm{ACIR} = \frac{1}{\mathrm{ACLR}^{-1}+\mathrm{ACS}^{-1}}$. As it has been mentioned, another possibility to decrease interference power at the Cell B receiver is to use Guard Subcarriers (GSs) [14]. Turning off DL subcarriers closest to the utilized UL band increases both ACLR and ACS. Let us note that such an approach is compliant with the existing LTE TX/RX technology, although it decreases the achievable rate (as some subcarriers are not utilized). The efficiency of this approach is considered here. In Fig. 6, ACIR values of the standard and advanced TX/RX technologies are shown as the functions of frequency separation between the UL and DL signals. ACIR is defined as the ratio of Cell-A-originated transmitted power observed at the antenna of Cell B base station to the power of effective interference at Cell B RX, i.e., power observed at the utilized subcarriers after the FFT block (in resource blocks used for PUCCH transmission). It is shown that when the PDSCH and PUCCH overlaps (frequency separation equal 0), ACIR equals about 20 dB. The situation changes rapidly when guard subcarriers are used. Even in the case of a standard transmitter and receiver, the introduction of a single empty resource block between the UL and DL bands (frequency separation equal to 2) increases ACIR to 42 dB. In the case of advanced TX and RX utilization (with the spectrum shaping algorithms discussed previously), the frequency

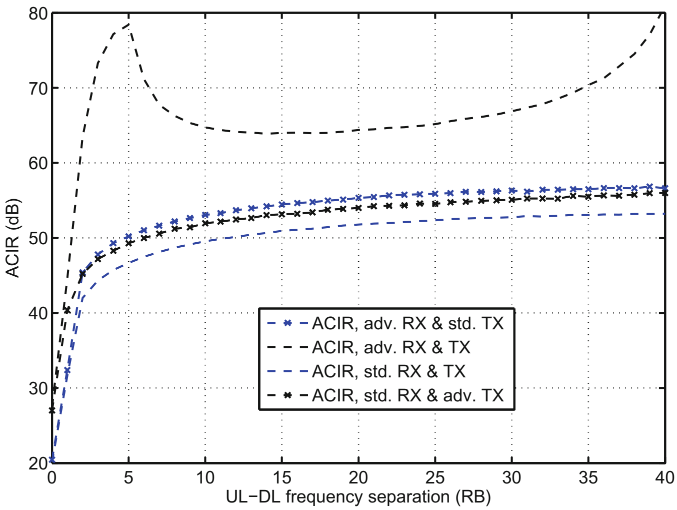

Fig. 6. Adjacent Channel Interference Ratio vs UL-DL frequency separation (0 RBs means that PUCCH and PDSCH overlap) with standard and advanced TX/RX.

separation of 2 RBs results in ACIR equal to 63.47 dB. It means that by proper signal processing, e.g., spectrum shaping at the transmitter [15,16] and windowing at the receiver [14] together with the application of guard subcarriers, a significant ACIR increase can be achieved. It is worth explaining why the curve representing ACIR for an advanced transmitter and receiver rises steeply for low frequency separation, and then it falls down. Such behavior is observed due to the specificity of the OCCS method which reduces the OOB most significantly in the adjacent subcarriers.

3.3 Influence on Transmission Opportunity in Neighboring Cell

In the most rigorous approach, Cell A can transmit according to the proposed scheme only if Cell B's transmission is not deteriorated (in practice, some deterioration should be acceptable). According to Table 8.2.1.1-6 in [20], the minimum SINR that should allow for transmission using QPSK modulation and $\frac{1}{3}$ coding rate is -0.4 dB. However, PUCCH reception should even be possible for lower SINR values, namely, -3.8 dB. Assuming the proposed scheme is used when only PUCCH is transmitted in Cell B's UL (although in general, other scenarios can be considered as well), it is visible that interference plus noise power can be increased by 3.4 dB without decreasing the effective Cell B radius. In order to evaluate this issue, the effective cell radius has been calculated using the COST 231 model for carrier frequency $f = 2$ GHz, base station antenna height $H_A = 30$ m, mobile terminal antenna height $h_{\mathrm{UE}} = 1.5$ m, and mobile terminal and BS gains $G_{\mathrm{UE}} = 0$ dBi and $G_{\mathrm{BS}} = 18$ dBi, respectively (according to [21]). Assuming the mobile terminal transmit power is $P_{\mathrm{UE}} = 23$ dBm and thermal noise power in 300 K increased by a Noise Figure (NF) of 5 dB [21], Cell B radius equals $R_{\mathrm{A}} = 0.83\,km$.

For the same system parameters, the interference plus noise power can be increased by 3.4 dB while transmitting PUCCH (instead of PUSCH), as discussed above. It can be calculated that the effective interference power from Cell A TX to Cell B RX should be equal or lower than -93 dBm. In Fig. 7, the minimum required ACIR value is plotted as a function of distance between the cell centers for different propagation parameters between these BSs. In the worst-case scenario, both BSs have the Line-of-Sight propagation condition (received power decreases with $n = 2$ power of the distance), and a maximum antenna gain of 18 dBi at both BSs is assumed. Even in such a case, the required distance between Cell A BS and Cell B BS equals only about 327 m for ACIR equal to 78.4 dB (advanced processing at both TX and RX), which is less than the calculated cell radius.

In the case of some reflections (received power decreases with $n = 2.5$ power of the distance), the required distance equals, e.g., 576 m for ACIR=50 dB that can be achieved even without any improvements at the TX/RX side. If the received power decreases with the third distance power ($n = 3$) and because of tilt, the antennas do not have maximal gains in their directions, i.e., $G_{\mathrm{AB}} = G_{\mathrm{BA}} = 10$ dBi, the required ACIR decreases even further.

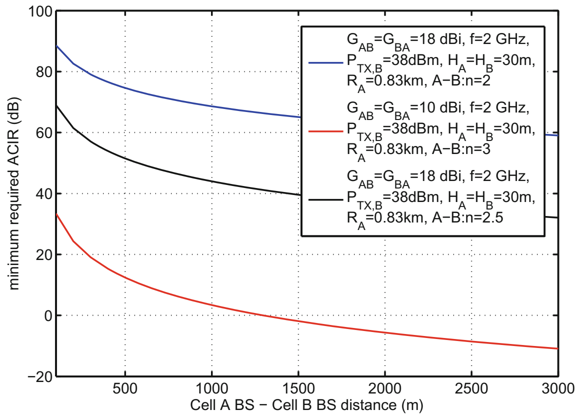

Fig. 7. Minimum required ACIR vs distance between Cell A and Cell B BS for different system parameters.

4 Conclusions

In this work, we have evaluated the possibility of simultaneous UL and DL data transmission in the flexible duplexing mode by the application of advanced spectrum shaping algorithms. Based on the achieved results, one can state that such a transmission scheme is possible, and the proposed technical solutions guarantee that the assumed maximum level of allowable interference is not exceeded. In some cases (by the application of guard subcarriers) even backward compatibility can be achieved. It means that the unused frequency resources in the UL channel can be utilized simultaneously for DL transmission, leading to better spectrum utilization. As the results are promising, one should consider investigating a situation where not only PUCCH is present in the UL band, but user data as well.

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