A Study of UE-to-UE Interference between TDD Systems

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***Abstract*— We study how UE-to-UE interference impacts the performance, considering transmitter out-of-band (OOB) emissions and receiver blocking characteristics for homogenous 20 MHz LTE systems. For co-existing TDD systems on different carrier frequencies within the same band, UE-to-UE interference may occur in certain situations. The impact of such interference is evaluated for a hotspot scenario and compared to a uniform user distribution scenario, and is found to be significantly worse. When the number of scheduled users in the aggressor cell is high (e.g. > 2), then receiver blocking impact, rather than the OOB emission, dominates the interference performance in hotspot scenario. Consequently, guard bands cannot be used to mitigate the receiver blocking impacts.**

I. Introduction

In recent years, increased interest in TDD has been seen from operators in different markets around the world. Recent spectrum auctions in countries such as India, Denmark, and Germany have made the coexistence between different TDD systems operating in neighbor frequency channels within the same overall frequency band a more urgent issue. Such TDD operation requires better understanding of interference between uplink (UL) and downlink (DL) transmissions, in contrast to FDD operations where downlink and uplink transmission inherently take place at different frequencies thus essentially avoiding any interference between UL and DL.

The interference between UL and DL transmissions in case of TDD operation may happen for different reasons. In case of unsynchronized TDD carriers close to each other, there may be overlapping uplink and downlink transmissions leading to adjacent-channel UL↔DL interference [1],[2]. Overlapping UL and DL transmissions may also occur between synchronized and time-aligned carriers if the UL/DL configuration is not coordinated between the carriers. Interference between UL and DL transmissions may in principle also occur between a TDD system and an FDD system if the TDD system operates close in frequency to either the downlink or uplink band of the FDD system. At the same time, in such cases, the band select filters mitigate the inter-system interference since FDD and TDD systems typically operate in different bands.

DL-to-UL interference is a more deterministic problem that can e.g. be handled with guard bands and carrier- and/or operator-specific filters at the base stations (BS) to ensure enough isolation. On the other hand, UL-to-DL interference between user equipments (UEs) is more challenging to handle due to the fact that the interference scenario (exactly what carrier frequencies are causing interference to each other) will typically vary between operators and regions, special-filter solutions are not feasible at the UE side.

There is a need to understand the impacts on performance of UE-to-UE interference between two TDD systems operating in the same band. This provides insight to what extent TDD operators operating close to each other within the same overall frequency band need to synchronize and coordinate the DL/UL configurations, and what additional guardband is needed between the systems if synchronization and joint configuration is not applied

The remaining part of the paper is organized as follows. The interference mechanisms considered in this paper are described in Section II. Section III presents the methodology used in the evaluation, followed by the numerical results in Section IV. Finally, conclusions are given in Section V.

II. UE-TO-UE INTERFERENCE BASICS

Figure II-1 illustrates the interference scenario being studied. In essence, UE-to-UE interference (thick red line in Figure II-1) adds to noise and other interference at victim receiver and reduces the victim downlink SINR and corresponding achievable data rate. The actual impact of the UE-to-UE interference depends on its relative level compared to other noise and interference at the victim receiver. Thus, system level evaluations are needed to fully understand the impact of the UE-to-UE interference.

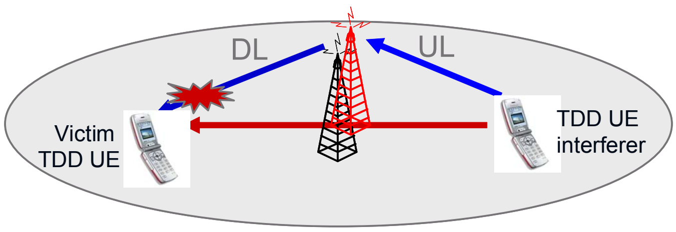

Figure II-1 UE-to-UE interference caused adjacent carrier TDD systems

UE-to-UE adjacent-channel interference will occur due to transmitter imperfections, leading to transmitter emissions within the victim UE receive channel (*transmission leakage*), as well as receiver imperfections leading to *receiver blocking*.

A. Transmission leakage

Transmitter emissions within the victim UE receiver channel happen due to out-of-band (OOB) emissions of the aggressor UE. Such emissions falling within the receive channel cannot be suppressed by the receiver channel-select filter. Thus, it adds un-attenuated as additional interference to the victim UE receive signal.

Restrictions on OOB emissions are typically defined in two different ways, namely a Spectrum Emission Mask (SEM) and Adjacent Channel Leakage Ratio (ACLR), see, e.g., [8]. The corresponding requirements should be fulfilled in all cases including maximum UE transmit power of 23dBm and maximum uplink resource-block allocation. Thus, using these values as estimates for the actual UE out-of-band emissions for all transmit powers and for all possible resource allocations can be expected to over-estimate the actual UE OOB emission and lead to pessimistic conclusions on the impact of UE-to-UE interference. In this work we have instead, based on modeling of state-of-the-art UE technology, estimated the true OOB emission for different UE transmit power levels, different UE transmission bandwidth, and different instantaneous UE resource allocations (exact set of physical resource blocks used for the transmission). So the OOB emission that we have assumed in the evaluations represents what can be expected from an actual terminal, neglecting implementation margins. A representative plot of OOB emission levels is presented in Figure II-2. Here, one PRB (Physical Resource Block) consists of twelve OFDM subcarriers spaced 15 kHz apart; thus, one PRB corresponds to a bandwidth of 180 kHz, which is also the size of the aggressor allocation being used in Figure II-2. The offset is defined as the distance between the allocation in the aggressor system and the band edge, measured in PRBs. The curves in the figure represent the experienced OOB emission levels at different victim PRB locations for different transmit powers. The high peaks in OOB emission seen in the figure for some victim PRB locations are caused by inter-modulation products when the desired transmitted signal is subject to transmitter imperfections such as IQ imbalance, carrier leakage, and non-linear PA distortion.

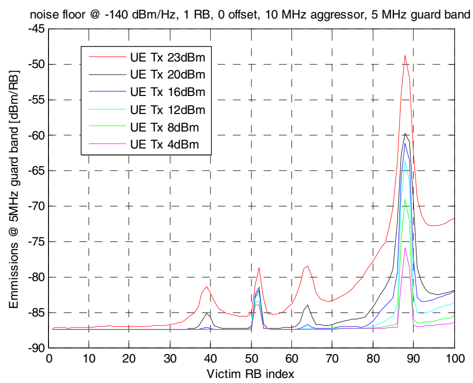

Figure II-2 Simulated emissions in adjacent carrier BW with 5MHz guard band for different UE transmission power levels and a one-PRB resource assignment for the aggressor UE

B. Receiver blocking

An ideal receiver would filter out any interference falling outside the frequency range of the desired signal. However, in a practical receiver with limited stop-band attenuation of the analog channel-select filter, a strong interferer in the vicinity of the desired frequency channel would lead to receiver blocking, which in turn may lead to degraded performance in reception of the desired signal. In our studies, we model the receiver blocking characteristics in the following way. We define the blocking parameters as described in Figure II-3. The impact of Low Noise Amplifier (LNA) and other analog blocks is neglected in the receiver blocking model, only quantization noise increment at the Analog-to-Digital Converter (ADC) is considered. The quantization noise increment happens due to excessive receiver signal power. The resulting noise is assumed wideband across the whole receiver band. The reason for neglecting the analog blocks is that the degradation caused by the ADC will happen at a lower interference power than for analog blocks to start going into compression.

BS_{1a} and BS_{2a} are base stations of the same system; similar pairing is done for BS_{1b} and BS_{2b} to denote the other system. Here one of them can be the victim system, while the other can be the aggressor systems. Solid lines in Figure II-3 denote the desired signal(s) and the dashed lines denote interfering signal(s). In this case, UE_1 and UE_3 are connected to aggressor systems (i.e. green BSs) in cell#1 and cell#2, respectively. Similarly, UE_2 and UE_4 are connected to the victim system (i.e. blue BSs) in cell#1 and cell#2, respectively.

We model the receiver blocking at DL receiver (i.e. UE_2) in cell #1. The desired power at UE_2 is, $P_d = d_{UE2}$. Total interference power at UE_2 is,

$$P_I = I_{UE1} + I_{UE2} + I_{BS2b} \qquad \textbf{(1)}$$

where I_x is the interference caused by x.

We let ENOB denote the effective number of bits at ADC. The required headroom could be, say, between 10 dB and 20dB. P_{QN} is the resulting quantization noise power at the ADC, which is estimated as:

$$P_{QN} = (P_I + P_d) - 6 * ENOB + Headroom \qquad \textbf{(2)}$$

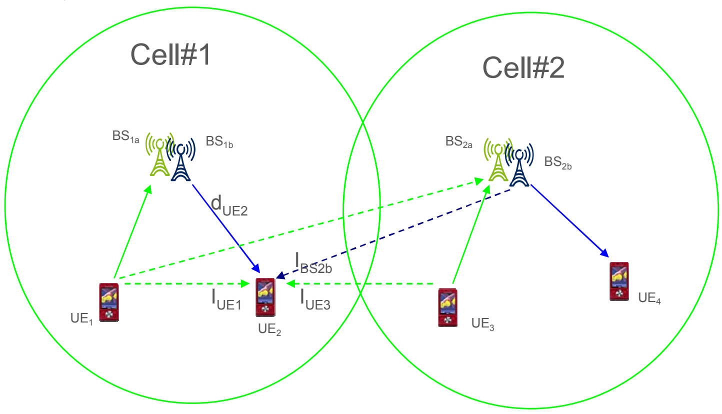

Figure II-3 Modeling receiver blocking characteristics

Here, all values are in dB scale. So, given an interferer of a certain bandwidth at a certain distance from the desired signal, we calculate what fraction of the interference leaks through the channel filter. Wideband noise levels are added to the receiver based on the quantization noise as derived in Eq. (2).

C. Analog channel select filter

The power levels P_d and P_I are defined after the analogue channel select filter. We assume a third order type I Chebyshev filter for our analysis, see [10]. Using the filter characteristics, it is possible to derive the attenuation of the blocker before reaching the ADC for aggressor allocations at different frequencies. It should be noted that the selectivity can be further improved with digital filtering, but the blocker level experienced at the ADC input is still determined by the analogue filter.

III. METHODOLOGY

A. Deployment scenarios

We consider two different homogenous scenarios for the evaluations with macro base stations. In the first scenario, we assume there is one *hotspot* in each cell, with the hotspot position being uniformly distributed within the cell area and with victim and aggressor UEs uniformly distributed within the hotspot. In the second scenario, aggressor and victim UEs are uniformly located over the entire cell area. In this case, the distance between aggressor UEs and victim UEs are on average much larger compared to the hotspot scenario, leading to less impact from UE-to-UE interference.

We consider co-sited aggressor and victim systems with re-use factor of one, since this is expected to overestimate the performance degradation of UE-to-UE interference. A total of 19 three-sector sites (57 cells) are simulated. The inter-site distance (ISD) is 500 m and the carrier frequency is assumed to be 2.5GHz.

B. Basic simulation approach

The following steps are performed in all iterations:

1. If applicable, one hot-spot (10m of radius) is dropped randomly and uniformly within each cell.
2. Victim and aggressor UE(s) are dropped randomly and uniformly within each hotspot, alternatively uniformly over the entire cell area.
3. 3GPP fractional UL power control is used to determine the UE transmit power for aggressor UE(s).
4. In order to model different network loads, neighbor cells are assumed to transmit at full power (43 dBm) in DL with probability, *ProbTX = load* and at zero power with probability $Prob_{No\text{-}TX} = 1 - load$.
5. The SINRs at the Victim UEs are calculated assuming no aggressor UEs are present ($SINR_1$) and also assuming aggressor UEs are present ($SINR_2$)
6. Victim UE achievable rate without and with aggressor UEs (R_1 and R_2) are calculated from $SINR_1$ and $SINR_2$ respectively.
7. Rate loss due to UE-to-UE interference is calculated as $R_{loss} = (R_1 - R_2)/R_1$.

The above steps are repeated sufficiently many times to get sufficient statistics for rate and rate-loss distributions. The parameters used for the simulations are listed in Table I.

C. Link SINR to system throughput mapping

We use simple link SINR per RB to link rate mapping model as:

$$R_{RB} = \alpha \log_2 (1 + \beta\gamma) \qquad \textbf{(3)}$$

where R_{RB} is the mapped rate in bps/Hz for every PRB and γ is the SINR in linear domain per PRB. In our current analysis, we assume $\alpha = \beta = 1$, which means that we assume an ideal mapping of SINR to achievable data rates. Thus, the absolute rate/throughput values should not be seen as indications of what rate throughput can actually be achieved. Rather, only the relative values should be considered. More realistic values for α and β are described in [9]. The resulting total rate is calculated as:

$$R_{Tot} = \frac{1}{M} \sum_{RB=0}^{M-1} R_{RB} \qquad \textbf{(4)}$$

where M is the number of PRBs granted to (victim) UE. R_{Tot} is the total rate in bps/Hz for the victim UE.

D. Simulation case

In our simulations, we consider a spectrum allocation as described in Figure III-1. Aggressor UEs are transmitting either in an UL slot, while a neighboring victim UE is receiving in DL slot. It should be noted that in the general case, a difference is that FDD and TDD are often separated by means of different channel select filters, whereas for multiple TDD carriers in the same band, which is the case under study in here, there is no additional isolation provided by channel select filters.

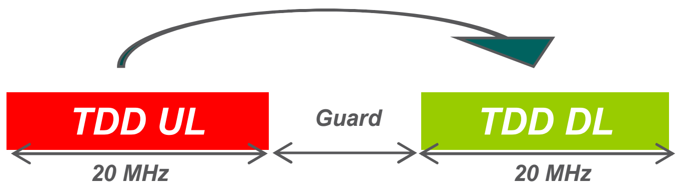

Figure III-1 Carrier arrangements

IV. NUMERICAL EVALUATIONS

A. Impact of DL resource block utilization

In the evaluations, we consider two cases:

1. When only transmitter leakage is considered as the source of UE-to-UE interference;
2. When the receiver blocking is also included together with transmitter leakage.

In this section, we analyze the impact of reducing the bandwidth allocated to the UEs. In the coming figures, we present the results in terms of rate loss in percentage. We study the system performance given the following assumptions:

1. The effective number of bits in the ADC is assumed to be 10 corresponding to a dynamic range of 60dB.
2. A third order Chebychev filter with 0.7 dB ripple and certain 3 dB cutoff frequency (e.g. 2.8MHz cutoff frequency for 5MHz of receiver bandwidth) is assumed as analogue channel select filter.
3. Automatic gain control to ensure headroom of 20dB for the ADC.

TABLE I. SUMMARY OF SYSTEM PARAMETERS

BS output power	43 dBm
MS maximum output power	22 dBm
BS antenna height	30 m
MS antenna height	1.5 m
BS noise figure	3 dB
MS noise figure	7 dB
BS antenna gain	18 dBi
MS antenna gain	0 dBi
Azimuth angle for HPBW	65 degree
Elevation angle for HPBW	6.5 degree
Mechanical antenna downtilt	8 degree
Aggressor bandwidth	20 MHz
Victim Bandwidth	20 MHz
UL power control (ULPC)	3GPP baseline fractional power control with alpha equal to 0.8 and SNR target 10dB

We present the following results for 10MHz guard band only and a traffic load of 50%. In the hotspot scenario, when we only consider transmitter leakage, decreasing the number of scheduled aggressor UEs per cell improves the system performance up to a certain number of UEs. As seen in Figure IV-1, when the number of aggressor UE is increased from 4 to 6, the DL rate starts to suffer.

When also receiver blocking performance is considered together with transmitter leakage, the DL performance is better when only two aggressor UEs are scheduled per cell. When more than two UEs are scheduled, the DL throughput suffers greatly. The corresponding performance for uniform user distribution is depicted in Figure IV-2. Here, we show the impact of different number of users in aggressor system for 10MHz guard band, with 50% load factor. There is no impact of reduced allocation to aggressor UEs on DL throughput. Looking at rate loss results, only 10% of the users experience more than 5% of rate loss when 6 aggressor UEs are allocated in the interfering system.

In Table II, we summarize the 5-percentile user throughput normalized by the throughput when no UE-to-UE adjacent channel interference is present. The results are presented for different guard bands between both systems. As expected, increasing the guard band increases the normalized throughput in single user/cell case; this is because transmitter leakage is dominant in one single wideband aggressor scenario, where larger guard band improves the performance. This is not true for multiple interferers (six in this case) as seen in last two rows in Table II, where receiver blocking becomes more prominent and having larger guard band does not improve the rate performance in all cases.

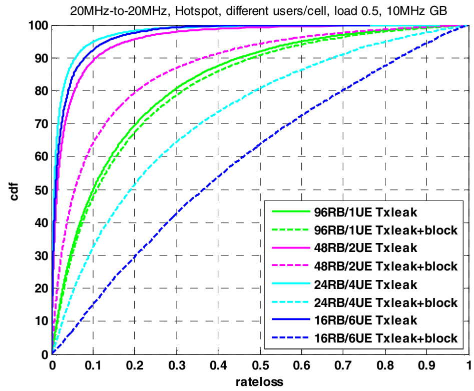

Figure IV-1 DL rate loss for different number of users in each cell in hotspot scenario

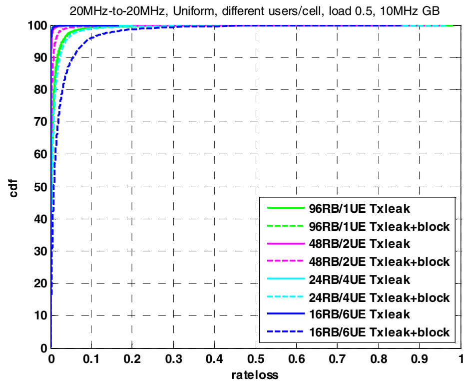

Figure IV-2 DL rate loss for different number of users in each cell in uniform user distribution scenario

TABLE II. PERCENTILE USER THROUGHPUT NORMALIZED BY THROUGHPUT WHEN NO UE-TO-UE ADJACENT CHANNEL INTERFERER IS PRESENT

Guard band (MHz)	0	5	10	15
	1 user/cell			
100% load	18.8%	30%	43.3%	58.1%
50% load	13.4%	23.2%	36.3%	52%
	6 users/cell			
100% load	6.6%	7.4%	7.4%	7.5%
50% load	7.7%	8.8%	8.9%	9%

B. *Higher effective number of bits in ADC*

One way of increasing the receiver front end robustness is to increase the effective number of bits in the ADC. If we use 10 effective bits for the ADC, then we have 60dB of dynamic range at the ADC. In Figure IV-3, we present the throughput result when Effective Number of Bits (ENOB) in ADC is varied between 8 to 15 bits, i.e. a dynamic range between 48dB of 90dB. When we increase the ENOB at the ADC, we essentially increase the UE design cost also. As seen in the results, higher ENOB (by 2 bits) would provide much better results in this case, comparing red and blue curves in Figure IV-3. When ENOB = 15 bits, then the final throughput result is very close to the case without coexistence problems, corresponding to the black curve.

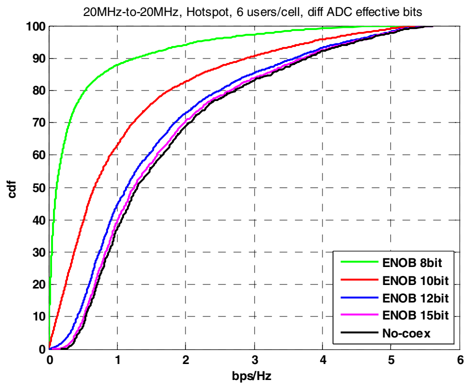

Figure IV-3 Impact of varying effective number of bits at ADC

C. Steeper channel select filter

So far, a 3rd order Chebyshev filter with 0.7dB pass-band ripple has been used. In Figure IV-4, we show the improvement in victim UE throughput when instead a 5th order Chebyshev filter is used. For both of these filter orders, the pass-band ripple and the 3dB cut-off frequency are kept the same, making the 5th order filter quite conservative. As seen in the figure, by introducing a new channel select filter, we can improve the victim system throughput very close to the case without coexistence problems. We have shown the throughput for both 5 and 10 MHz guard band in the figure to have a better understanding of different guard bands and higher order channel select filter.

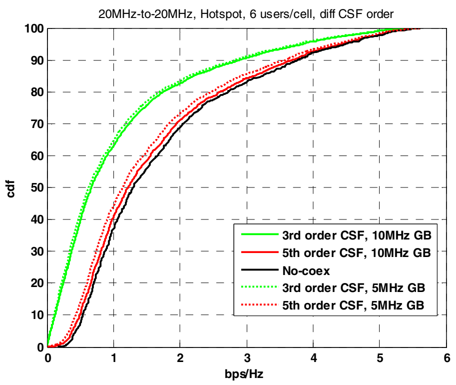

Figure IV-4 Throughput results with different Chebyshev filter orders when 5 and 10MHz guard band is used

Similar to improvements in ADC of victim receiver front end (as detailed in Section IV-B), higher filter order means that the terminal cost will be higher. Also, moving from 3rd order to 5th order channel select filter could become challenging in terms of real implementation in hardware.

V. Conclusion

In this paper, we have presented evaluations of the impact of UE-to-UE interference between two TDD systems operating in the same frequency band, by taking into consideration modeled UE transmitter and receiver characteristics. Compared to the uniform user-distribution scenario, throughput degradations are seen due to UE-to-UE interference in the hotspot scenario, in particular for low victim-system and high aggressor load. For fully loaded system, the co-channel interference levels are much higher such that the impact of additional adjacent-channel UE-to-UE interference does not impact the throughput very much. For uniform user distribution across the cell area, the UE-to-UE physical distances are usually larger, thus UE-to-UE interference is insignificant.

A combination of lower number of scheduled UEs (i.e. lower allocated bandwidth per UE) together with a reasonable guard band could be considered to mitigate the rate losses observed. When the system load is close to 100%, then there are not so much differences if the guard band is increased from 5MHz to 10MHz in all cases. The improvements on throughput for larger guard band increases for lower system load. Besides, we find that when the number of scheduled users in the aggressor cell is high (e.g. > 2), then receiver blocking impact dominates the interference performance in hotspot scenario. The impact of receiver blocking is experienced in the receiver as the increase of wideband quantization noise before receiver channel filtering. So, guard bands cannot be used to mitigate the receiver blocking impacts.

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