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Empirical Study on 5G NR Cochannel Coexistence

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Abstract: The 5G non-public network deployments for industrial applications are becoming highly interesting for industries and enterprises owing to dependable wireless performance characteristics. With an increasing trend of network deployments in local licensed and/or shared spectrum, coexistence issues naturally arise. In this article, we present our detailed empirical results on the performance impact of a 5G NR indoor non-public network from a 5G NR outdoor network operating in the same mid-band spectrum. We present experimental results on the uplink and downlink performance impact of a non-public indoor network deployed on an industrial shopfloor. Our results quantify the impact on the uplink and downlink performance characteristics based on realistic traffic loads in a non-public indoor network when using synchronized and unsynchronized Time Division Duplex (TDD) patterns, different UE deployment locations and interference levels. We also present results on mitigating interference effects through robust link adaptation techniques. We believe that this is the first article, which reports quantified 5G NR cochannel coexistence results based on a detailed and systematic study, and provides signficant insights on the cochannel coexistence behavior in realistic deployment scenarios of an industrial shopfloor.

Keywords: 5G NR; coexistence; empirical results; 5G performance; TDD; interference mitigation

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1. Introduction

The 5G-NR-based non-public networks are becoming increasingly popular especially for industrial applications. This is owing to superior performance characteristics, mobility support, scalability and security aspects of 5G NR compared to other existing wireless technologies, e.g., Wi-Fi or 4G/LTE. Due to challenging requirements of industrial applications, these technologies do not adequetly meet the desired communication demands [1]. There are various 5G NR non-public network deployement options [2], either using spectrum licensed for public operator networks or locally licensed spectrum available in some markets. For instance, the 3.7–3.8 GHz spectrum is locally licensed for industrial use in Germany by the spectrum management authority (BNetzA) [3]. The increasing density of non-public network deployments in the local licensed and shared spectrum give rise to a cochannel coexistence problem, which has been discussed in the research community [4].

The performance characteristics of a non-public network may deteriorate due to spectral interference from coexisting networks. This performance impact depends upon a number of factors such as proximity of the interfering transmitter to the receiver of the non-public network and antenna directionality aspects, power levels of the transmitting node and that of the interfering entity, signal quality level at the receiver due to propagation characteristics, etc. While enhanced mobile broadband application use-cases target high data rates and peak throughputs in the best effort manner, industrial use-cases are typically characterized by mission-critical communication requirements of high reliablity and low-latency, albeit support for the best effort background traffic is also required [5,6]. Given that there is available system capacity for packet retransmissions, the overall throughput characteristics might remain unaffected even when packets need to be retransmitted due to interference from a coexisting network. However, the interference caused from the coexisting network may still lead to instantaneous link outages which are rectified by the error control mechanisms in the 5G NR protocol stack. These error correction mechanisms lead to instantenous latency spikes (e.g., due to Hybrid automatic repeat request (HARQ retransmissions), which can be intolerable for mission-critical industrial traffic.

There exists various analytical and simulation studies on the performance analysis of mission-critical services due to interference from coexisting networks [7,8]. However, so far there is no other systematic coexistence performance evaluation for a 5G NR non-public network based on real measurements. It is highly important to empircially quantify the impact of interference on throughput as well as latency, in both uplink and downlink directions, with different UE positions and under various traffic load conditions in realistic deployment scenarios. There is naturally a need to mitigate interference effects to guarantee the desired performance characteristics for mission-critical services.

In this article, we present detailed over-the-air performance evaluation results obtained on an industrial shopfloor considering realistic deployment scenarios of a 5G NR non-public indoor network coexisting in the same spectrum as a 5G NR outdoor network. The throughput and latency characteristics of the indoor network in various realistic interference scenarios due to a coexisting outdoor network are compared with their respective baselines without the presence of interference from the coexisting outdoor network. We present the empirical performance results for synchronized, as well as different unsynchronized, TDD patterns used by the 5G NR indoor non-public network. In this article, the term unsynchronized TDD patterns refers to a scenario where the indoor and outdoor networks are using different TDD patterns. However, also in the "unsynchronized" scenario, the two networks have a common time reference and their respective TDD patterns are slot-aligned. In such scenario, all transmission slots will be aligned, even if in opposite directions, so any interference from a given slot is confined to a single slot. Earlier research has shown that coexistence of different TDD patterns for cochannel and adjacent channel networks have a significant role in the interference characteristics [7,8]. We also investigate coexistence interference mitigation aspects in our measurement-based study.

The rest of the article is organized as follows: In Section 2, we give an overview on related works on 5G NR coexistence analysis. Section 3, describes the cochannel coexistence problem and illustrates the different types of interference situations encountered in a practical cochannel deployment setup. In Section 4, we describe our systematic measurement methodology and deployment setup. We also give an overview of the networks used in our empirical evaluation in this section. Section 5 presents the detailed performance results and their analysis. Finally, Section 6 concludes the article and outlines our current and future work directions.

2. Related Work

The coexistence issue for different technologies is widely studied. The survey in [9] presents inter-technology techniques of spectrum sharing in wireless technologies. The survey describes the inter-technology coexistence (in shared spectrum bands) for technologies with a hierarchical and flat regulatory framework with equal access rights. Furthermore, it briefly presents the inter-technology coexistence for different access rights in the hierarchical regulatory framework and for the integration of technologies in different spectrum bands. The complexity of testing interference and the coexistence of wireless systems in critical infrastructure has been reported in [10]. The report highlights the need for studying test methods and performance metrics that allow designers, manufacturers, and customers of new smart communications systems to understand and predict the ability of a device or system to resist interference and coexist within a particular radio frequency environment. According to the type of the spectrum, whether it is dedicated or shared with other technologies, different coexistence problems might emerge for 5G NR deployments. The coexistence in the unlicensed bands is studied in [11,12], with results of the coexistence between 5G NR and Wi-Fi in the 6 GHz frequency band available for unlicensed use. Related to the multiple licensed spectrum bands allocated to 5G NR technologies, multiple studies analyzed the coexistence issue with inter- and intra-technologies. Authors in [13] demonstrated on an experimental setup the efficient spectrum sharing for 5G NR, LTE-A Pro and NB-IoT aiming to take advantage of the 700 MHz propagation aspects. Similarly, a field trial study in [14] presents the coexistence between LTE and NR based on a frequency division duplexing (FDD) system under dynamic spectrum sharing (DSS). Furthermore, authors in [15] and [16] study the coexistence between the 5G system and fixed satellite communications in the mid- (3.4 GHz–3.6 GHz) and high-frequency bands (40 GHz), respectively. The results from the coexistence of fixed satellites and 5G in mid-band, based on simulations, and lab and field tests, demonstrated that 5G systems could be deployed on a large scale for commercial deployments. The coexistence aspects for FSS (fixed-satellite services) and FS (fixed services) are discussed in [17]. For the mmWave band, it was demonstrated that 5G IoT systems can meet the interference protection criteria of the FSS from at least several hundred base stations and thousands of IoT terminals simultaneously. Additionally, related simulation-based studies considered the coexistence between different 5G networks in the mid-band spectrum as well. For 5G system operating in the mmW range, mitigation of cochannel interference using multiple beam formations, including directivity of beams and the distance between the base station and terminal device, is proposed in [18] with mathematical analysis and simulations.

In [7], cochannel and adjacent channel performance evaluation in the mid-band frequency range of 3.5 GHz between an enhanced mobile broadband (eMBB) macro network and an ultra-reliable low latency communication (URLLC) factory network demonstrated that macro downlink interference results in reduction in uplink and downlink capacity and service availability for certain synchronized and unsynchronized TDD patterns. The conclusion of the study highlights that a local factory can coexist with wide-area network when certain isolation is guaranteed to protect the URLLC traffic in the worst-case scenario. In a similar way in [8], the authors highlight that the coexistence of the public macro network and the non-public network is very difficult, unless the isolation between the networks is sufficiently large. These studies also point out the issue of the cross-link interference between public and non-public UEs. This is highlighted by authors in [19], where cross-link interference mitigation techniques from different authors from the literature are compiled. The proposals are divided into three sections: inter-cell coordination, advanced receiver and sensing techniques. For instance, clustering, scheduling and resource allocation, power control, beamforming, UL/DL configurations are solutions proposed based on inter-cell coordination. Advanced receiver and sensing solutions proposed are interference suppression, maximum likelihood, interference cancellation and listen-before-talk (LBT) techniques. The paper of [19] also deals with a survey of specifications based on signaling for Cross Link Interference (CLI) mitigation. Authors in [20] present enhancements of 5G NR TDD operation and performance to mitigate CLI between neighboring cells. A reinforcement learning algorithm adjusts the TDD configuration for both macro and indoor deployments considering URLLC and eMBB traffic coexistence based on the new features introduced in 3GPP NR Release-16 [21] to manage CLI, i.e., CLI-RSSI (received signal strength indicator), CLI SRS-RSRP (sounding reference signal-reference signal received power) and RIM (remote interference management). More recently, authors in [22] highlight the importance of UL traffic for industry use cases. Based on the coexistence issue and the traffic requirements of private networks, potential solutions are presented related to the coexistence issue, e.g., UL MIMO (multiple-input and multiple-output), carrier aggregation, full-duplex operation, or symbol blanking. Other recommendations are to implement different TDD configurations to minimize possible interference and the introduction of balanced or UL oriented TDD patterns.

Most of the existing coexistence studies are based on theoretical and simulation analysis, especially in the context of cellular networks. Despite several deployment scenarios envisioned for 5G NR and the increasing popularity of 5G non-public networks, no systematic experimental investigations on coexistence behavior have been conducted that quantify over-the-air performance impact in real deployments. In [2], we describe our measurement methodology and initial results on the cochannel coexistence performance between an indoor non-public 5G NR network and an outdoor 5G NR network. In this article, we present a deep analysis of the cochannel coexistence results. Moreover, we present results on mitigation through link robustness of the observed performance degradation caused due to the coexistence issue.

3. The Cochannel Coexistence Problem

The cochannel coexistence problem between two or more networks in 5G deployments is constrained to regional regulations. In this article, the coexistence scenario analysis is based on locally deployed networks for indoor industrial applications operating on the same spectrum as other neighborhood networks. As described in Chapter 5 in [2], there are three different scenarios that could be addressed in this coexistence study: (i) a local non-public network may have a license to operate in the same spectrum as other public 5G services in the wide-area, (ii) an indoor non-public network might make use of a local 5G license in close vicinity with another non-public network within the same spectrum with its own local license, and (iii) a local license may include multiple factory buildings but also an outdoor network section on the same industrial environment area. In the third scenario, the outdoor network requires coordination among other outdoor networks on the same or adjacent channels, thus the TDD configuration needs to be aligned with the public 5G networks.

As per [23], the indoor and outdoor networks have a common clock reference. Hence, the TDD pattern start is always synchronized in our measurements. Then, when the indoor and outdoor network use the same TDD pattern, the only present interference is the so-called near–far interference. Such interference situation occurs when both networks are either in DL or UL transmission mode at the same time. From the network perspective, the DL near–far interference arises when the coexisting base station is transmitting to its UE and creates interference to the neighbor UE. Hence, the UL near–far interference is the interference perceived on the base station due to the transmission of the neighbor UE. However, indoor network deployments might not be constrained to the harmonized outdoor TDD pattern and might choose a more balanced or UL-oriented TDD pattern in order to meet the system requirements of the use-cases within the non-public network. For instance, in Figure 1, the indoor and outdoor network TDD patterns are referred to as DDDU and DDDDU, respectively, where D and U represent downlink and uplink time slots, respectively. As already mentioned, the interference impact of the DL-to-DL and UL-to-UL slots is measured in the near–far interference. Moreover, due to the nature of the unsynchronized TDD pattern (indoors: DDDU, outdoors: DDDDU) the DL-to-UL and UL-to-DL interference is called the cross-link interference. This interference might arise when the interference network is transmitting in the opposite direction of the victim network.

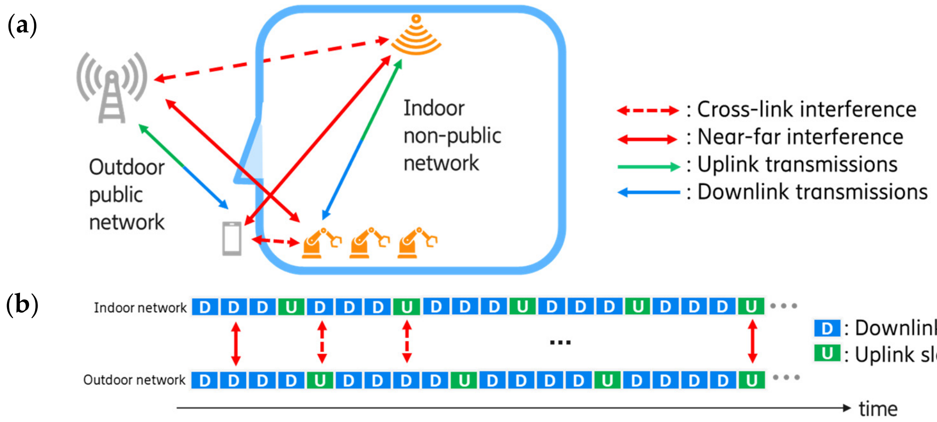


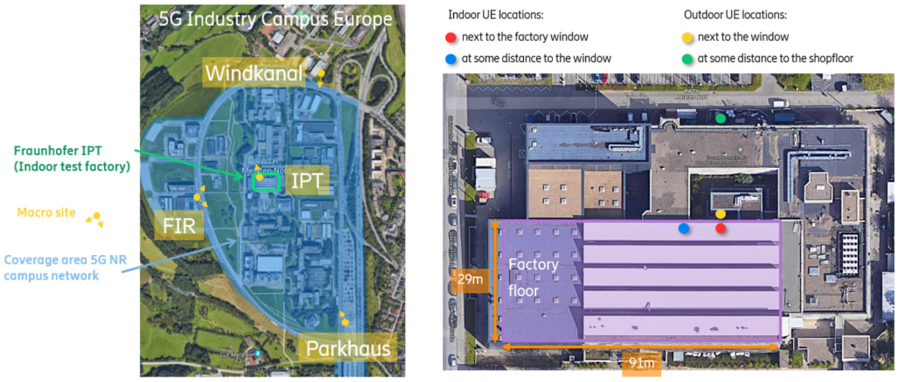
Figure 1. Illustration of interference situation caused by coexisting indoor and outdoor networks. (**a**) Interference links between base stations and UEs of indoor and outdoor networks when different TDD patterns are selected. (**b**) Different TDD patterns used in the indoor network compared to the outdoor network result in both near–far interference and cross-link interference.

4. Experimental Methodology

In order to systematically carry out the coexistence measurements, we developed a tool for configurable traffic generation and carrying out accurate one-way (DL/UL) latency and throughput measurements. We have first measured the baseline latency and throughput, i.e., without interference, and later measured latency and throughput in the presence of interference. The baseline peak throughput performance depends upon the system bandwidth configured. Higher peak throughput is achieved with a larger bandwidth and vice-versa. The amount of interference level and its direction (UL/DL) determines the performance loss compared to the respective baseline. Various aspects of interfernce impact on the performance of the indoor network has been evaluated.

Our over-the-air coexistence measurements have been performed in the 3.7–3.8 GHz 5G N78 TDD band, which is allocated with a local license for industrial application use in Germany. Our measurements have been carried out at the 5G Industry Campus Europe (5G ICE) in Aachen [24], which has an outdoor network deployment covering an area of approximately 1 km^2, with four outdoor macro sites colored in yellow in Figure 2a. As part of 5G ICE, we have selected the indoor network deployment on the shopfloor of the Fraunhofer Institute for Production Technology (IPT), shown as a green rectangle with an area of ca. 2700 m^2. The power levels for the indoor and outdoor networks are in the nominal operating range. During the empirical study, both the indoor and outdoor networks were exclusively used and we ensured no other device was operating in the two networks.

The coexistence measurements were conducted with four different UE locations, two indoor and two outdoor UE locations. The four scenarios are as described in Table 1 according to Figure 2b. The first scenario is the worst-case of interference, when the indoor and outdoor UE are close by to each other at a distance of around 50 cm from the window of the shopfloor. In the second scenario, the outdoor UE is in the same location and the indoor UE is moved at distance of 10 m from the window, close to a robot cell. Then, in the third scenario the indoor UE is moved to a location next to the factory shopfloor window, while the outdoor UE is moved away from the shopfloor to a distance of 15 m. Finally, the indoor UE was placed close to the robot cell, while keeping the outdoor UE away at a distance of 15 m from the shopfloor.



(**a**) (**b**)

Figure 2. (**a**) Outdoor campus network deployment in Industry Campus Europe (Aachen) and location of indoor test factory, Fraunhofer IPT. (**b**) Indoor and outdoor UEs deployment location for coexistence performance evaluation around the test factory hall [2]. The figure is based on Google Maps © 2021.

Table 1. Description of indoor and outdoor UE deployment locations for each of the scenarios.

Scenario	Indoor UE Location	Outdoor UE Location
1. Worst-case interference	50 cm across from the window (red)	50 cm across from the shopfloor window (yellow)
2. Robot cell	10 m away from the window (blue)	50 cm across from the shopfloor window (yellow)
3. Interference far away	50 cm across from the window (red)	15 m away from the shopfloor (green)
4. Robot cell—far away interferer	10 m away from the window (blue)	15 m away from the shopfloor (green)

As described in Table 2, both indoor and outdoor networks are based on a mid-band 5G non-stand alone (NSA) system with independent baseband and core networks. The 4G anchor cell of both networks is on the 2300 MHz B40 frequency band while the 5G leg of the NSA deployment uses the full 100 MHz bandwidth available within the n78 band of the 3.7–3.8 GHz spectrum, which fulfills the requirement for cochannel networks.

Table 2. Indoor and outdoor 5G network characteristics.

Network	5G Architecture	5G Frequency Band	4G Frequency Band	5G Bandwidth
Indoor	NSA	3.7–3.8 GHz (n78)	2300 MHz (B40)	100 MHz
Outdoor	NSA	3.7–3.8 GHz (n78)	2300 MHz (B40)	100 MHz

For our measurements, we used one test UE for the indoor network and one test UE for the outdoor network. Both the UEs are identical and based on Qualcomm x55 modem chipset. We ensured that no other devices were active besides the test devices when performing measurements.

5. 5G Performance for Industrial Control

Industrial automation and control applications are typically characterized by mission-critical traffic, where data from sensors to controllers and command messages from the controllers to actuators are to be delivered with low latency and high reliability [4,6]. The data traffic is thus in both UL and DL directions. In our empirical performance evaluation, we have studied the impact on the UL and DL latency and throughput of the non-public indoor network. The results have been analyzed with different TDD patterns, UE locations and interference directions in UL and DL from the outdoor network. The results presented in this article contain mission-critical traffic with a low to medium load, at which the overall throughput impact is insignificant. This is due to the inherent retransmission and error control mechanisms in the 5G NR protocol stack, and hence we focus only on the effect on the latency performance. Moreover, for mission critical traffic, latency characteristic is an important performance metric instead of throughput. Please note that the throughput impact due to interference becomes visible only at high traffic conditions of the indoor network, as there are not enough system resources available due to the error control mechanisms.

5.1. Synchronized TDD Patterns

Current cellular wide-area network deployments on the TDD spectrum use the same TDD pattern on all cells in order to avoid interference. According to the standardization technical specifications of 3GPP 38.401 Section 9.1, all networks must have a common clock reference. Hence, in order to keep the same harmonized TDD pattern DDDDU regulated for wide-area networks in Germany, the first set of tests were conducted to study the indoor network performance in the presence of interference from the outdoor network when both the networks use the same TDD pattern, referred to as synchronized TDD patterns. The interference for the synchronized TDD pattern scenario can only occur between slots on the same transmission directions, i.e., DL slots interfere only with the DL slots and UL slots interfere with the UL slots of the two networks. Therefore, the interference links for the synchronized TDD pattern in DL and UL are only the near–far interference links, as illustrated in Figure 1. The first scenario studied for cochannel interference and synchronized TDD pattern is for indoor and outdoor UE deployments next to the window, as shown in Figure 2b. For median values, the increase in latency compared to baseline for both indoor DL and UL slots is negligible, as can be observed from Figure 3. Similarly, for the 99th percentile value, the indoor DL latency increase due to the DL near–far interference being low, while results from UL near–far interference show higher delays of 0.7 ms and 5.3 ms, respectively. For the 99.9th percentile value, the increase in latency compared to baseline follows a similar trend. Here, the UL near–far interference impact is higher than the DL near–far interference. Compared to baseline, the increase in latency in the indoor DL and UL for the 99.9th percentile value are 5.1 ms and 7.5 ms, respectively.

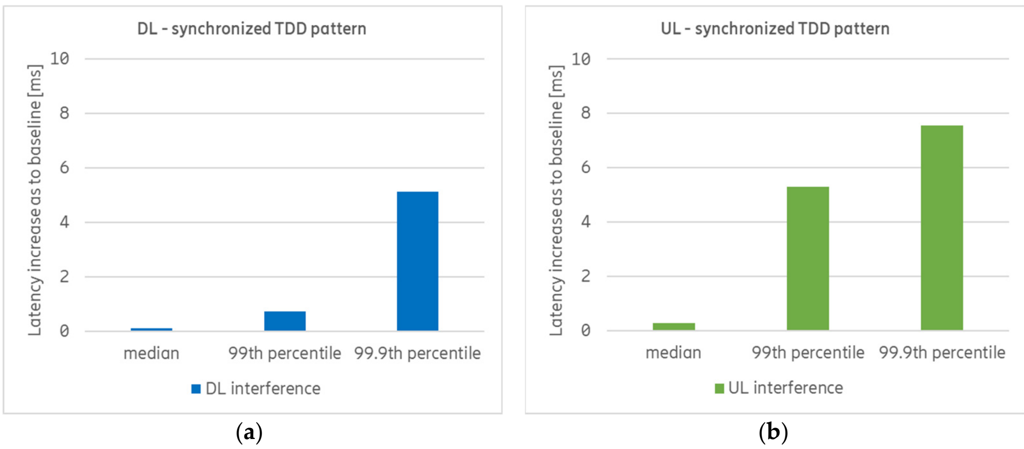
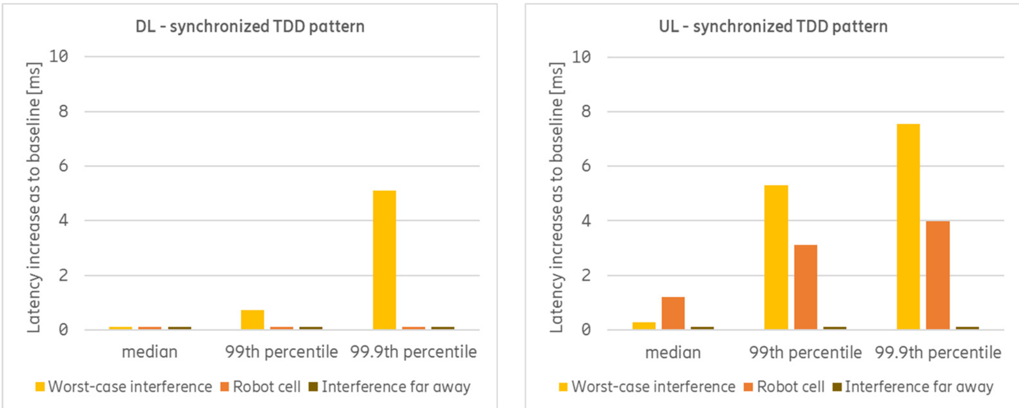


Figure 3. Increase in DL (**a**) and UL (**b**) latency compared to their respective baselines for synchronized TDD pattern (DDDDU) used by the indoor and outdoor networks.

The coexistence measurements were conducted with four different UE locations, two indoor and two outdoor UE locations. The four scenarios are as described in Table 1 according to Figure 2b. The first scenario is the worst-case of interference, when the indoor and outdoor UE are close by to each other at a distance of around 50 cm from the window of the shopfloor. In the second scenario, the outdoor UE is in the same location and the indoor UE is moved at distance of 10 m from the window, close to a robot cell. Then, in the third scenario the indoor UE is moved to a location next to the factory shopfloor window, while the outdoor UE is moved away from the shopfloor to a distance of 15 m. Finally, the indoor UE was placed close to the robot cell, while keeping the outdoor UE away at a distance of 15 m from the shopfloor.

For other UE deployment locations, it can be observed in Figure 4 that the DL (Figure 4a) and UL (Figure 4b) latencies increase compared to their respective baselines with a synchronized TDD pattern. The worst-case interference scenario is the previously analyzed result. The robot cell scenario is the result of the latency increase for a different indoor UE position (robot cell) within the test factory shopfloor and same outdoor UE position (next to the window). The remaining scenario is for the indoor UE close to the window and the outdoor UE at some distance from the shopfloor. The indoor DL performance for the robot cell scenario, where the victim of the indoor network is the indoor UE and the aggressor is the outdoor BS, shows no impact due to DL interference. Similarly, for the interference far away scenario, no impact is observed in the DL latency. Hence, it is observed that increasing the distance between the UEs helps to reduce the impact of DL interference. On the other hand, the indoor UL latency increase for the robot cell scenario is slightly greater and no latency increase is observed for the interference far away scenario.



(**a**) (**b**)

Figure 4. Increase in DL (**a**) and UL (**b**) latency compared to their baselines for synchronized TDD pattern of DDDDU with different indoor/outdoor UE deployment locations.

5.2. Unsynchronized TDD Pattern

As described in Section 5.1, the indoor network performance, with interference for the three different scenarios with a synchronized TDD pattern, is quite similar for median values and, with only a few milliseconds of a latency increase, has been observed for certain high percentiles. However, the TDD pattern DDDDU is DL oriented and might not be suitable for the application requirements of the indoor network. There are TDD patterns currently available in our test network with a downlink–uplink balance more suitable for the requirements of the new industry automation applications. However, it is still uncertain how the cross-link interference for a mid-band TDD spectrum could affect the indoor network performance in a real network deployment. In this article, we analyzed the impact of different TDD patterns for the indoor and outdoor network. In particular, the two TDD patterns studied, DDDU (75% DL–25% UL) and DDDDUDDDUU (70% DL–30% UL), are more UL oriented than the current harmonized DDDDU (80% DL–20% UL) pattern. For the unsynchronized TDD patterns, the coexistence of DL slots is different compared to the synchronized case. The DL slots of DDDU will collide arbitrarily 80% of the time with the outdoor DL (near–far interference) slots of DDDDU, while the remaining 20% of the time indoor DL slots will collide with outdoor UL slots (cross-link interference). As can be observed in the graph of Figure 5a, the DL latency increase compared to baseline for UL interference is above 300 ms. Due to the interference on this 20% of the indoor DL slots, the 5G system is not capable of handling the targeted medium load traffic. Instead, for the DL interference, the impact is similar, as seen in Section 5.1 with a slightly better performance due to less DL near–far interference. For the other unsynchronized TDD pattern (DDDDUDDDDUU), the indoor DL slots only collide with outdoor DL transmissions, as for the synchronized TDD pattern. Then, no cross-link interference is expected and, as can be observed in the graph of Figure 5b, no impact is coming from the UL interference. Nevertheless, with DL interference, the latency increase is higher compared to the other values on the Figure 5a.

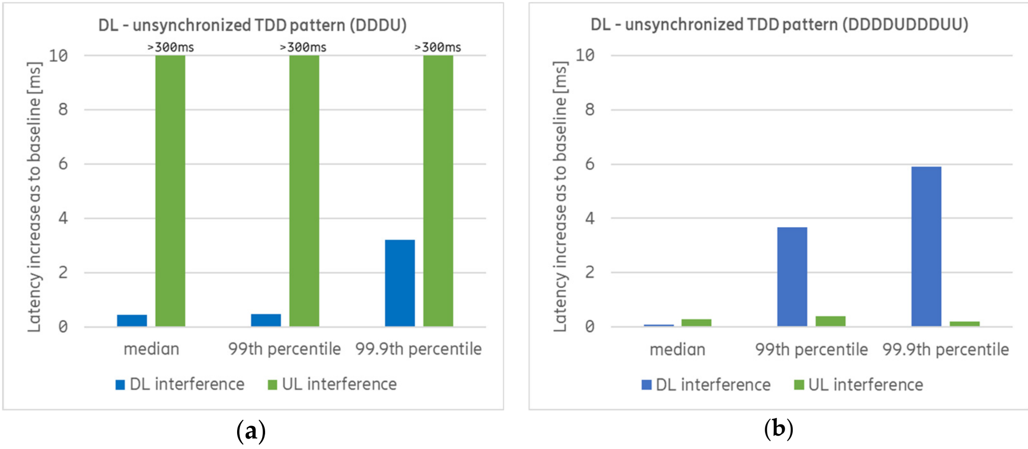


Figure 5. Increase in DL latency compared to its baseline for unsynchronized TDD pattern. (**a**) Indoor TDD pattern DDDU and outdoors DDDDU are configured. (**b**) Indoor TDD pattern DDDDUDDDDUU and outdoors DDDDU are configured.

The interference constellation for the indoor UL slots and unsynchronized TDD pattern is also different compared to the synchronized TDD pattern. For DDDU used indoors and DDDDU used outdoors, the near–far interference and cross-link interference for indoor UL slots are 20% and 80%, respectively. In Figure 6a, it can be observed that the near–far interference (UL interference) has a longer latency increase compared to baseline than the cross-link interference (DL interference) for high percentiles. For the 99th and 99.9th percentile, the difference is of around 1 ms and 2 ms, respectively. For DDDDUDDDDUU, the near–far interference is 67%, while cross-link interference is 33% of the indoor UL slots. From the graph of Figure 6b, the results of cross-link interference (DL interference) are slightly better compared to the results on the Figure 6a and the impact of near–far interference (UL interference) is similar, despite having more probability of such interference.

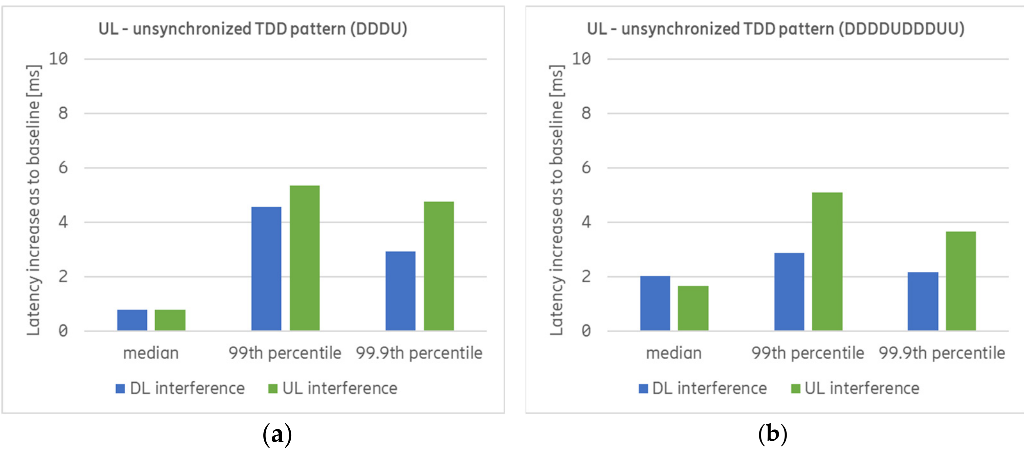
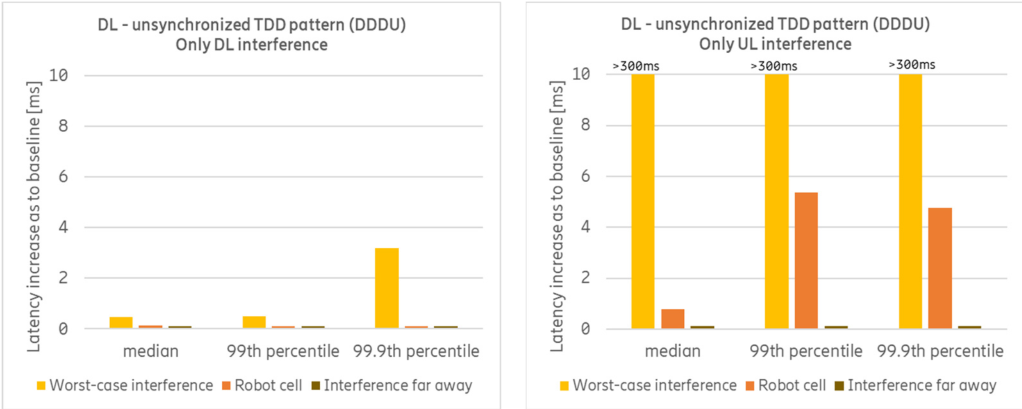


Figure 6. Increase in UL latency compared to its baseline for unsynchronized TDD pattern. (**a**) Indoor TDD pattern DDDU while outdoors DDDDU are configured. (**b**) Indoor TDD pattern DDDDUDDDUU and outdoor DDDDU are configured.

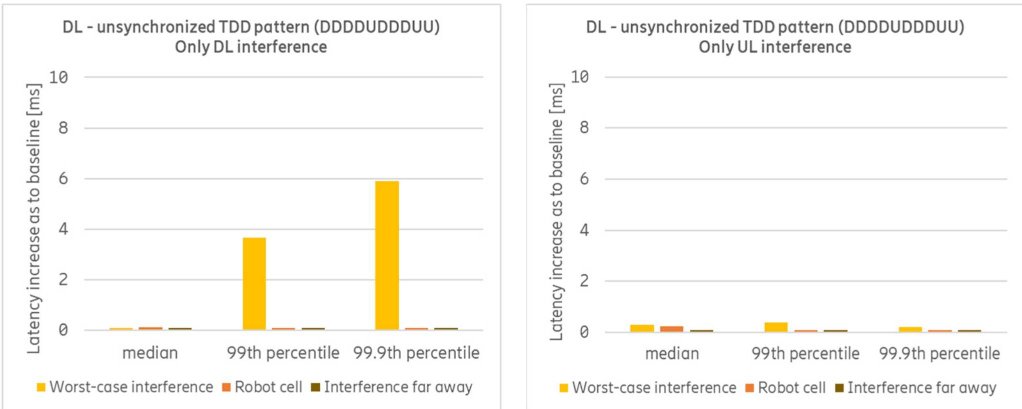
We break down the indoor DL and UL network performance to analyze the impact for different indoor–outdoor UE locations. In Figure 7, it can be observed that, as we increase the distance between UEs, the indoor DL latency increase compared to baseline is lower or non-existent. An interesting observation from Figure 7b, where UL interference was queuing up the 5G system in the worst-case of interference, is highly reduced for the robot cell scenario and it is not observed for the interference far away.



(**a**) (**b**)

Figure 7. Increase in DL latency compared to baseline for unsynchronized TDD pattern (indoors: DDDU, outdoors: DDDDU) and different indoor/outdoor UE deployment locations. (**a**) Result for only DL interference (near–far interference). (**b**) Result for only UL interference (cross-link interference).

On the other hand, DL results for the unsynchronized TDD pattern DDDDUDDDUU in Figure 8 show no impact due to UL or DL interference in the robot cell and interference far away scenarios.

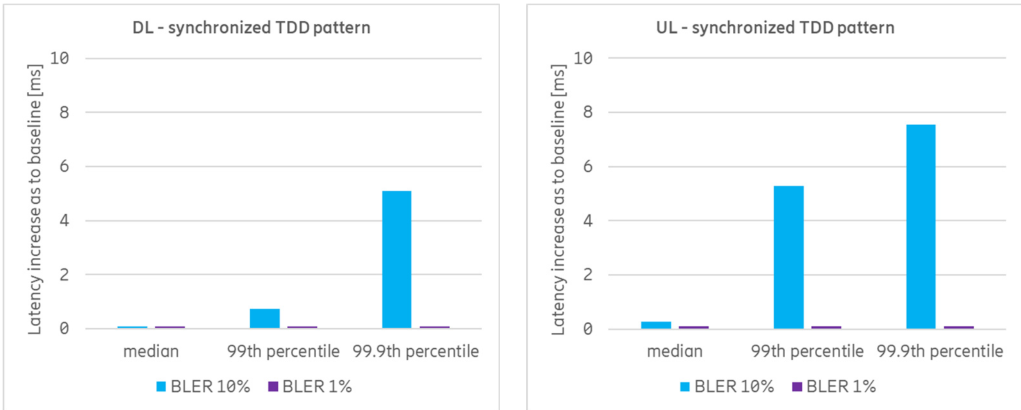


(**a**) (**b**)

Figure 8. Increase in DL latency compared to the respective baseline for unsynchronized TDD pattern (indoors: DDDDUDDDUU, outdoors: DDDDU) and different indoor/outdoor UE deployment locations. (**a**) Result for only DL interference (near–far interference). (**b**) Result for only UL interference (cross-link interference).

5.3. Interference Mitigation through Link Robustness

We have investigated the use of a more robust link adaptation algorithm for the indoor network in order to achieve resilience against cochannel interference coming from the outdoor coexisting network. We observed that link robustness for both uplink and downlink transmissions in the indoor network helps in mitigating interference effects. Link robustness leads to the selection of lower Modulation Coding Scheme (MCS) values via the link adaptation algorithm. Figure 9 shows that instead of configuring the default Block Error Rate (BLER) target of 10% for HARQ retransmission, as used in all of the above tests, when we set a BLER target of 1% for HARQ retransmission after the initial transmission, we get significantly reduced latency compared to the respective baseline results for both DL and UL transmissions. One downside of configuring a stricter BLER target for HARQ retransmissions is the use of extra radio resources. However, for small packet sizes, as often used in mission-critical traffic, it is not a big overhead and allows significant latency reduction by avoiding the need for retransmissions when encountering interference from coexisting networks. While the link robustness results for the indoor network in Figure 9 are for a synchronized TDD pattern, we have observed similar results when using unsynchronized TDD patterns indoors, as mentioned in Section 5.2.



(**a**) (**b**)

Figure 9. DL (**a**) and UL (**b**) latency increase compared to their baseline for synchronized TDD pattern when using different BLER targets in the worst-case deployment setup.

6. Conclusions and Future Work

In this article, we have presented our detailed empirical 5G NR cochannel coexistence results. We have systematically analyzed the impact of a coexisting outdoor network, which could resemble to any type of 5G network, on the latency and throughput performance of the indoor network for an industrial shopfloor in several different scenarios. These include the performance impact on the UL and the DL transmissions of a factory shopfloor network when there is interference from an outdoor network in UL and DL directions. Moreover, we have studied the impact of the TDD pattern used in the indoor network, and the indoor and outdoor UE deployment positions. Our results indicate that cochannel interference from an outdoor network can downgrade the performance of the indoor network, even for the same TDD pattern used indoors and outdoors, when the outdoor UE is close to the indoor shopfloor deployment. However, the interference effects gradually subside when the outdoor interfering UE moves away from the indoor deployment premises, and eventually disappears. While the performance loss is significant due to cross-link interference, when unsynchronized TDD patterns are used indoors for deployments of outdoor UEs close to the indoor shopfloor premises, there are certain TDD patterns which inherently mitigate the cross-link interference and thereby allow a better UL ratio in the TDD pattern UL/DL split. Detailed knowledge of the cochannel coexistence behavior may be an enabler for tailoring TDD configurations to the needs of industry users. Considering that industrial 5G use cases are typically characterized by a high demand for uplink capacity, appropriate TDD patterns should be considered. We have also observed, in our experimental results, that appropriate link adaptation for high link robustness provides resilience against interference from coexisting networks.

As part of our ongoing and future work, we are empirically evaluating the adjacent channel coexistence effects, where key performance indicators (KPIs) are studied for both indoor and outdoor networks due to adjacent channel coexistence. We plan to publish our detailed adjacent channel coexistence results and the key findings in a future article.

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