5G Ultra-Reliable Low-Latency Communications in Factory Automation Leveraging Licensed and Unlicensed Bands

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Abstract

Factory automation (FA) applies ultra-reliable low latency communications (URLLC) to support closed-loop control systems with millisecond cycle times. Presently, many of these applications rely on maintenance-prone wireline bus systems since existing wireless technologies cannot meet the stringent latency and outage requirements. The cellular standards body, the Third Generation Partnership Project (3GPP), aims to change this predicament by incorporating support for FA and URLLC into the fifth generation (5G) communication networks. We investigate how combining operation in the unlicensed and licensed band can appropriately balance the technical, regulatory and economic constraints to enable large-scale deployments of bandwidth-hungry FA applications. We present 5G physical layer/MAC layer (PHY/MAC) designs, which carry the bulk of traffic in the cost-effective unlicensed band but switch to the licensed band within the available latency budget to circumvent unlicensed-band interference. We discuss design trade-offs between licensed band occupation, link outage and transmission power level.

Introduction

In the migration toward 5G mobile technologies, the cellular industry aims to incorporate support of ultra-reliable low latency communications (URLLC) for industrial Internet of Things (IoT) [1, 2]. A predominant use case is found in factory automation (FA), where closed-loop control applications run periodic cycles with cycle times between 0.25ms–50ms while demanding extremely low outage with packet error rates 10^{-9} [3]. Traditionally, these applications have been handled by wireline bus systems [4]. In recent years, a paradigm shift has set in to migrate FA communications from wireline to wireless. This trend is motivated by the various shortcomings associated with wireline solutions such as high installation and replacement cost of wiring as well as maintenance-prone support for moving sensors/actuators, which rely on trailing cable systems, slip rings or sliding contacts [5].

The present wireless communications systems in industrial automation generally use unlicensed technologies and operate in the industrial, scientific, and medical (ISM) radio band [6]. The wide bandwidths of these bands allow factories to handle the large traffic volume typical for FA applications. The existing commercial solutions, however, cannot achieve the stringent reliability targets for latencies below 10ms [2, 5, 7]. Also, operation in the unlicensed band demands careful coexistence planning to avoid or minimize interference from other systems [7]. Unlicensed-band technologies are further subject to stringent regulatory requirements. The European Telecommunications Standards Institute, for instance, limits the maximum equivalent isotopically radiated power for transmission to 100mW and demands listen-before-talk for transmission levels above 10mW [8]. In some cases, such power levels are too low to achieve the necessary reliability target. Listen-before-talk further implies tolerance to latency for back-off in case the medium is busy.

To our knowledge, there are presently no large-scale cellular deployments for URLLC in FA. One reason for this is that third generation/fourth generation (3G/4G) cellular technologies have not been designed with URLLC requirements in mind. The 5G cellular standard, however, promises to change this paradigm. In the licensed band, many limitations of the existing wireless solutions can be adequately addressed since resource allocation can be centrally managed and regulatory rules are less stringent. Recent research indicates that typical FA requirements can be met under these conditions [9].

Dedicating large quantities of licensed spectrum to bandwidth-demanding FA applications may be cost-prohibitive or erase the economic benefit of the wireline-to-wireless migration. Combining operation in the unlicensed and licensed bands therefore seems an adequate approach to leverage the advantages of both.

Such a strategy has been long supported in mobile broadband, where smart devices opportunistically select WiFi over cellular technologies. The cellular industry has further pursued efforts to expand into the unlicensed band to enhance capacity at low cost [10]. The economic reality of mobile broadband, however, is different than for FA. Since latency is far less stringent than in FA, resource contention in the unlicensed band does not discernably deteriorate the service experience. At the same time, cellular connectivity

The authors investigate how combining operation in the unlicensed and licensed band can appropriately balance the technical, regulatory and economic constraints to enable large-scale deployments of bandwidth-hungry FA applications. They present 5G PHY/MAC designs, which carry the bulk of traffic in cost-effective unlicensed band but switch to licensed band within the available latency budget to circumvent unlicensed-band interference.

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In FA, URLLC applications support discrete manufacturing and motion control processes, where strict temporal deadlines must be met. Examples are packaging and printing machines, machine tools and robotics. The spatial extensions of the communication links are typically a few meters.

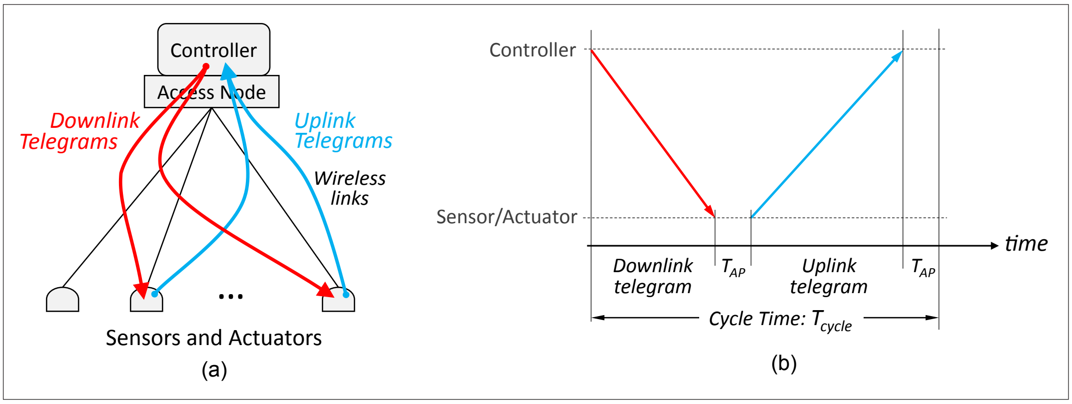

Figure 1. Application in FA using wireless URLLC: a) topology: controller exchanges downlink and uplink telegrams with sensors/actuators; b) application-layer time constraints per cycle (T_{AP} refers to application-layer processing time).

provides large-area coverage, which is a true differentiator over unlicensed-band hotspots. Finally, mobile operators can amortize the cost of the licensed band over a broad subscriber base.

In this article, we investigate cellular solutions for large-scale deployments in factory automation which combine unlicensed-band and licensed-band operation so as to appropriately balance technical, regulatory and economic constraints. We first develop a single-band solution using 5G specifications for a typical FA application. This solution requires large bandwidth indicating high cost when operated in the licensed band. Then, we study two dual-band solutions, which use different mechanisms to switch between the unlicensed and licensed bands. The first solution aims to handle the bulk of traffic in the unlicensed band, and it switches to the licensed band when channel sensing detects signs of contention. While this approach is easy to implement, a thorough analysis reveals that performance is highly sensitive to contention mechanisms of neighbor systems and to implementation tolerances. We conclude that channel sensing alone is not sufficient to drive band switching. The second solution applies a more elaborate ARQ-based mechanism, which overcomes the shortcomings of the first solution albeit at a higher resource demand. The main challenge of this approach is to conduct detection and retransmission within the stringent latency budget. We further discuss mechanisms for resource sharing between FA and other traffic in the licensed band, which is necessary to obtain the economic benefit from offloading factory traffic to the unlicensed band. Resource sharing in the licensed band introduces an inter-system coexistence problem that requires centrally managed traffic prioritization and over-the-air enforcement.

The Challenges of URLLC in FA

In FA, URLLC applications support discrete manufacturing and motion control processes, where strict temporal deadlines must be met. Examples are packaging and printing machines, machine tools and robotics. The spatial extensions of the communication links are typically a few meters. Each control mechanism follows a cyclic process with a deterministic number of messages, referred to as telegrams, exchanged between a controller and a set of sensors or actuators (Fig. 1a). The cycle time T_{cycle} represents a strict bound of the process, which can be divided into time intervals for telegram transport in the downlink and uplink direction and application layer processes (Fig. 1b). Typical cycle times reported lie between 0.25ms and 50ms while the telegram payload assumes values up to 50 B [4 ,5, 7]. FA further sets stringent targets on the permissible packet error rate around 10^{-9}, which is equivalent to the probability that the transaction time constraint cannot be met [5–7]. Depending on the application, the number of sensors or actuators per controller ranges between less than 10 to a few hundred.

One challenge of wireless URLLC is to meet the stringent latency budget with extremely high reliability. At present, the existing wireless technologies cannot achieve latencies below 10ms at the 10^{-9} outage target. In recent years, academic interest has risen to push this envelope into the sub-millisecond range. Channel simulations indicate that a high degree of diversity is necessary (around 8–16 branches) to achieve packet error rates ~10^{-9} with reasonable signal-to-interference-and-noise values [3, 9].

Another challenge of wireless URLLC relates to coexistence and regulatory constraints in unlicensed bands as discussed above. One remedy to this challenge is manual coexistence planning, which minimizes inter-system interference by optimizing band usage across the systems in the factory [7]. Alternatively, the operation is moved to the licensed band or to a band dedicated to FA.

The predominant commercial wireless solution in FA is the Wireless Sensor-Actuator Network (WSAN)-FA, which was developed by ABB [11]. WSAN-FA uses the 802.15.1 PHY-layer (Bluetooth) with a modified MAC layer to improve on latency. According to ABB, WSAN-FA achieves packet error rates around 10^{-9} within a latency bound of 15ms over distances of a few meters. ABB further provides an inductive coil mechanism to supply power to sensors. In this manner, sensors and actuators run completely untethered and without batteries.

A related segment of industrial IoT targets process automation, where energy-efficient operation with battery-powered sensor devices is sought over the area of an industrial plant (~1km^2) [12].

Predominant standards in this space are WirelessHART and ISA100.11a. Since process automation is mainly used for monitoring and supervisory control, latency requirements are typically less critical than for closed-loop control in FA.

A large set of IoT solutions fall under the rubric of Low Power Wide Area Networks (LPWAN), which aim for low cost, long range and low power consumption at moderate data rates [12]. These solutions target use cases in home automation, smart cities and industry.

5G PHY/MAC Design for Factory Automation

In the following, a 5G-based PHY/MAC design framework is devised that combines operation in the unlicensed and licensed band to appropriately balance cost and reliability subject to regulatory constraints. The challenge of this design is to retain the bulk of operation in the unlicensed band for cost-effectiveness while allowing efficient and effective switching to the licensed band in case interfering systems jeopardize the high reliability target of FA applications. Interference detection and switching must therefore occur within the stringent latency bounds. There is no precedence for such PHY/MAC designs in present wireless standards.

The design is tailored to an industrial printing machine application, which can be regarded as a representative URLLC candidate in the FA space [5], and which will serve for quantitative analysis of bandwidth demand below. This printing machine application is assumed to support 50 printing heads, which move over a distance of a few meters at moderate speeds and exchange telegrams with a controller. Within a cycle of T_{cycle} = 2ms, the printing heads receive one downlink telegram and reply with an uplink telegram, where each telegram carries a payload of 30 B. The tolerable packet error rate per telegram is assumed to be 10^{-9}. In case multiple printing machines are operated in close mutual vicinity, same-system interference must be considered.

Single-Band Design

In a first step, a PHY/MAC design is established using 5G cellular specifications, which operates in a single band of either a licensed or unlicensed nature. In the context of this work, the single-band design is used to estimate the bandwidth demand of the industrial printing application.

The design leverages periodic frame structure, numerology and orthogonal frequency-division multiplexing (OFDM) waveform as defined by 5G. The 5G numerology provides significant flexibility in the configuration of slot size and OFDM subcarrier spacing, which allows time-aligning PHY/MAC and an application-layer cycle to minimize end-to-end latency across the protocol stack.

To maximize transmission success within the strict latency bound, the time budget is allocated for a single data transmission per telegram (Fig. 2a). This approach differs from resource management schemes used for mobile broadband, which allow for multiple retransmissions and incremental redundancy to increase spectral efficiency. As a baseline, energy-efficient quadrature-phase shift keying and a channel coding rate around 1:2 is applied on all links.

Design	Without ARQ (downlink)	With ARQ (downlink)
Application bits per telegram including cyclic redundancy check	240	240
Telegram length (ms)	1	1
Subcarrier spacing (kHz)	30	60
Average symbol time (μs)	33.3	16.67
Slot time (ms)	1.0	0.5
Number of symbols per slot, total[1]	28	28
Number of symbols per slot for data[1]	27	24
Number of resource elements per symbol[2]	12	12
Number of resource elements per telegram	324	288
Number of resource elements for channel estimation	30	30
Number of resource elements for data	294	258
Quadrature-phase-shift-keying-coded data bits per link	588	516
Resulting coding rate	240:588	240:516
Bandwidth per link (MHz)	0.360	0.720
Bandwidth for 50 links without guard band (MHz)	18	36
Bandwidth for system with reuse[3] of 1:4	72	72

[1] See slot design in Fig. 2.
[2] Number of resource elements is selected so that a coding rate of approximately 1:2 is achieved.
[3] For dual band solution, reuse 1:4 is realized via 1:2 in TDD and 1:2 in FDD.

Table 1. Resource sizing for PHY/MAC designs with and without ARQ.

With the same payload, constellation, bandwidth and coding rate, downlink and uplink telegrams consume the same transmission time, making it possible to equally divide the 2ms cycle into two 1ms time slots (Fig. 2a). For OFDM-subcarrier spacing of 30kHz, the 1ms time slot accommodates 28 OFDM symbols; 27 of them are allotted to payload data while the last symbol remains idle for MAC-layer and application-layer processing. In this scheme, each link requires about 12 subcarriers per OFDM symbol to achieve the desired coding rate while leaving sufficient overhead for channel estimation.

From these design parameters, the overall bandwidth demand per printer is estimated to be 18MHz without guard band, or roughly 20MHz including guard band (Table 1). This estimation assumes that all links are simultaneously active. In case many printer systems are simultaneously operated in close vicinity, adjacent printers have to use different frequencies so as to avoid inter-system interference. This increases the factory-wide frequency demand. Assuming that frequencies can be reused by the next-nearest printers, the factory-wide bandwidth demand rises by a factor of four from 20MHz to 80MHz. This is commonly referred to as a resource reuse of 1:4.

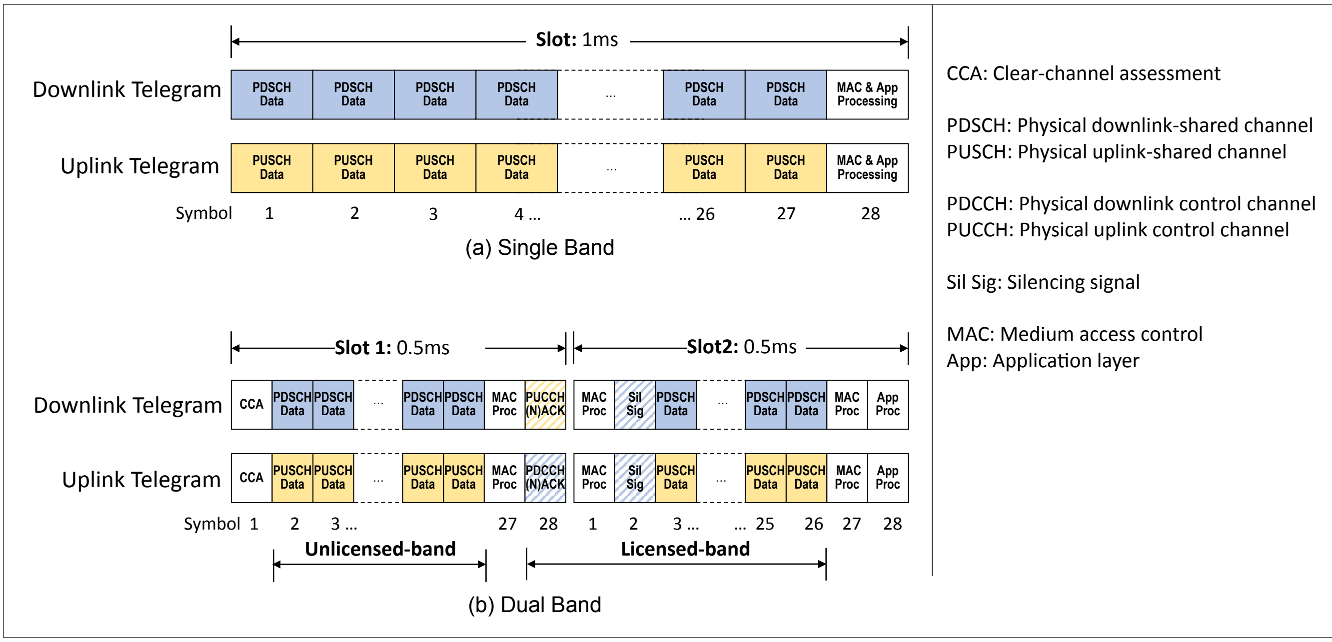

Figure 2. Frame structure for downlink and uplink telegrams: a) single-band operation; b) dual-band operation combining the unlicensed and licensed bands.

In case telegram exchanges occur with low duty cycle, the traffic of the 50 printing heads can opportunistically share a smaller number of links, which reduces the printer's overall bandwidth demand. Opportunistic scheduling is commonly used for mobile broadband. The achievable resource saving depends on the correlation of traffic activity among the printing heads as well as the tolerable blocking rate. This blocking rate captures the probability that more printing heads have traffic activity during a time slot than links available, which should not exceed the target outage rate. A detailed computation reveals that due to the stringent 10^{-9} target outage rate, a 10 percent duty cycle still requires 40 percent of the original bandwidth demand when traffic is uncorrelated. This value increases with the correlation of traffic activity among printing heads. The analysis demonstrates that only limited gains can be expected from such opportunistic scheduling schemes.

Bandwidth demand can also be reduced by choosing higher PHY-layer constellations at the cost of range and reliability. Moving from quadrature phase-shift keying to 256-quadature amplitude modulation, which is presently the highest constellation supported by 3GPP, lowers the 20MHz bandwidth demand per printer to roughly 7MHz, or the factory-wide bandwidth demand from 80MHz to 28MHz. At the same time, the necessary signal-to-noise ratio (SNR) grows by more than a factor of ten [9].

For the estimated bandwidth demand, the cost of operation in the licensed band might be significant. In case an FA application has low duty cycle, licensed-band resources can be shared with other traffic such as mobile broadband. This, however, introduces a licensed-band coexistence management problem, which becomes cumbersome when both traffic classes use independent networks. One solution to this problem is discussed below.

The single-band design can also be operated in the unlicensed band if the transmit power level is set below the threshold where listen-before-talk is required. In case listen-before-talk requirements have to be met, the transmitter performs a clear channel assessment (CCA) prior to transmission and backs off when the channel is found busy. CCA can be conducted on the first OFDM symbol of each slot, which slightly reduces the number of symbols available for data. To avoid latency from back-off, the factory needs to explicitly ensure that the unlicensed band is not used by other systems.

Dual-Band Design

The dual-band design opportunistically utilizes the unlicensed band, and it switches to the licensed band in case interference or resource contention jeopardizes reliable transmission in the unlicensed band. To minimize licensed-band usage, band selection is conducted for each telegram.

In one rather obvious approach, band switching is based on a CCA in the unlicensed band prior to telegram transmission. In case channel activity is found above a certain power threshold, the transmitter switches to the licensed band, otherwise it uses the unlicensed band.

Simulations show that this approach is very sensitive on the switching threshold selected. If set slightly too low, licensed-band usage rises to significant levels since switching is frequently triggered by thermal noise. If set slightly too high, interference causes unacceptable packet loss since switching is invoked to hesitantly. Figure 3 shows the trade-off between licensed-band usage, representing a cost metric for operation, and packet error rate, indicating performance degradation. The best point of operation lies around 5–6 decibels above noise.

In these simulations, interference is modeled in the form of random bursts, which are received at rate α and with the same average signal strength as the telegrams. Band switching is initiated on all channels as soon as the switching threshold is exceeded for one of them.

This band-switching approach is further faced with the problem that CCA by the transmitter misses hidden nodes, whose interference is only visible to the receiver. In case the receiver also conducts CCA and reliably conveys the outcome to the transmitter, the telegram still remains vulnerable to non-yielding interferers that begin transmission after CCA. The current unlicensed technologies use much higher CCA thresholds than the 5–6 decibels value found through simulation. WiFi systems, for instance, use a 20 decibel threshold, which makes them behave like non-yielding interferers. The CCA-based switching approach is therefore vulnerable to WiFi systems in its vicinity.

To overcome these shortcomings, an alternative band-switching mechanism is pursued that leverages Automatic-Repeat-Request (ARQ). The ARQ-based approach allocates two consecutive transmission opportunities for each telegram, the first using the unlicensed band and the second using the licensed band. If the unlicensed-band transmission fails or if CCA senses band occupation, transmission is conducted in the licensed band. Transmission success or failure is conveyed from receiver to transmitter via ACK/NACK feedback. In this design, channel sensing solely serves to meet regulatory compliance and has little performance impact.

To accommodate two transmissions per telegram, the 1ms slot is divided into two 0.5ms subslots, and the subcarrier spacing is doubled from 30kHz to 60kHz to retain the same number of OFDM symbols per transmission. The allotment of symbols to CCA, data transmission, ACK/NACK-feedback and processing is shown in Fig. 2b. The corresponding resource budget is summarized in Table 1.

The ACK/NACK feedback needs to be designed sufficiently reliable since each NACK-to-ACK conversion error translates into a packet error. When ACK/NACK is transmitted in the licensed band, this reliability can be achieved by coding the one-bit information over a sufficiently large resource space. A thorough analysis shows that one OFDM symbol is sufficient for this purpose in the present PHY/MAC design.

While the ARQ-based design enables recovery from transmission failure in the unlicensed band, bandwidth demand increases by a factor of two due to the doubled subcarrier spacing. In case multiple printers are used in close vicinity, this bandwidth increase can be recovered by alternating first and second sub-slot between adjacent printing machines. The resource reuse of 1:4 discussed above is hence split into a sub-slot reuse of 1:2 and a frequency reuse of 1:2. Obviously, the operation of printing machines needs to be time-synchronized in this case.

Since it is operating at twice the bandwidth, the ARQ-based dual-band design also requires twice the transmission power to achieve the same SNR in the licensed band as the single-band design. The transmission power increase allows the printing machine to meet the 10^{-9} target outage rate through operation in the licensed band even when the unlicensed band is completely jammed. While the transmission power increase

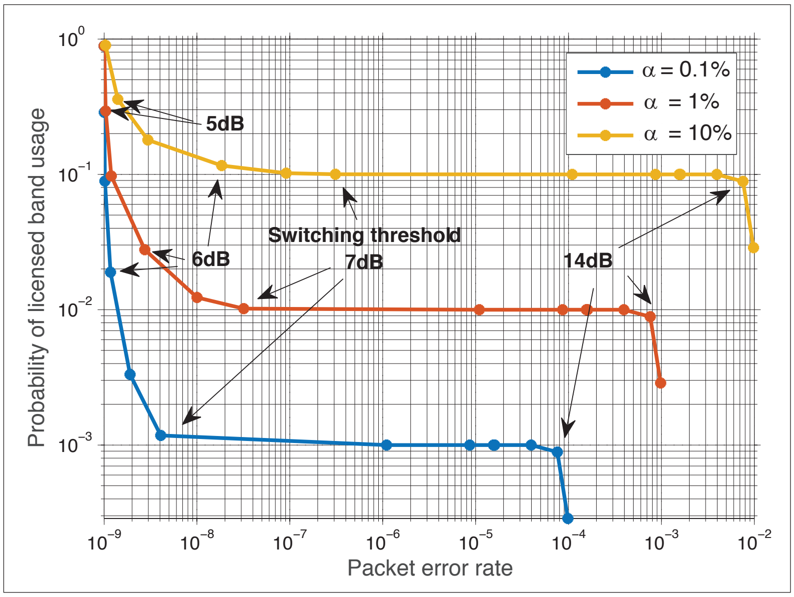

Figure 3. Trade-off between probability of licensed band usage and packet error rate. Plots shown for CCA-based band selection at different switching thresholds and interference activity rate .

is considerable, it only affects the licensed band where regulatory constraints are less stringent. In the unlicensed band, the transmission power can be reduced in case regulation or implementation pose a constraint. Such power reduction lowers the link SNR and creates more packet errors, which triggers more switches to the licensed band.

A simulation shows the tradeoff between licensed-band usage and unlicensed-band SNR (Fig. 4). In this simulation, interference bursts occur at rate α and are received at 5 decibels above noise. At low interference rates, for example α = 0.1 percent, licensed-band usage quickly falls to negligible values with rising SNR. At higher interference rates, for example α =10 percent, the tradeoff exhibits a flat plateau making licensed-band usage increasingly independent of unlicensed SNR. This behavior is beneficial as it provides robustness to resource dimensioning in the unlicensed band, where regulatory constraints on maximum transmission power levels are stringent.

Coexistence Management in the Licensed Band

Retaining the bulk of FA traffic in the unlicensed band translates into an economic benefit only if the remaining licensed-band resources can be used by other, less latency-critical traffic, such as mobile broadband. This introduces the need for coexistence management in the licensed band. It requires a traffic prioritization policy as well as a mechanism to enforce this policy on a short time scale such as one OFDM symbol (Fig. 2).

We describe the example where the FA application shares a licensed band with a cellular network, which uses an independent infrastructure. In such scenarios, policy enforcement has to occur over the air. For this purpose, the FA application is time-synchronized to the cellular network. This can be achieved by collocating the functionality of a cellular mobile device with the controller, which receives the corresponding synchronization

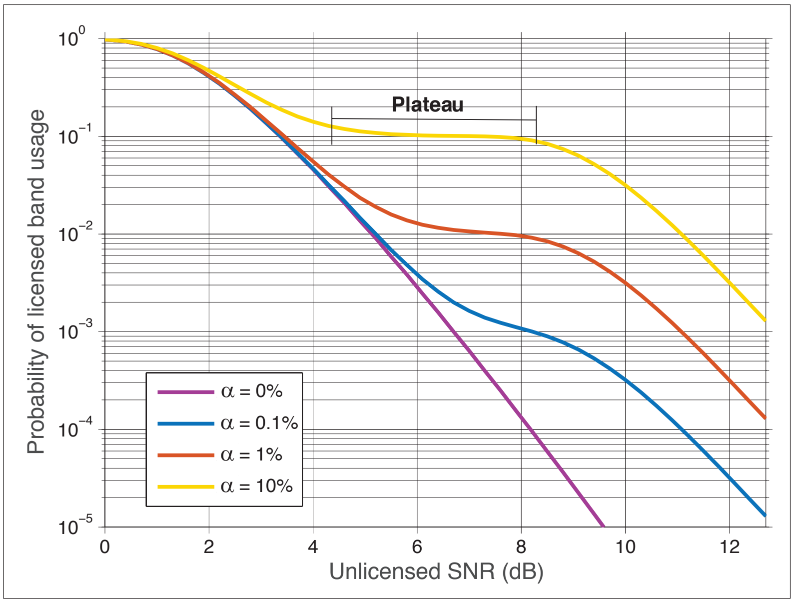

Figure 4. Trade-off between probability of licensed-band usage and unlicensed-band SNR for different interference rates.

signals from a cellular access node. The collocated mobile device may further connect to the cellular network and negotiate alignment of mobile broadband and the factory application. This may be necessary in case the factory requests a fixed licensed-band resource for ACK/NACK feedback, which hence becomes unavailable for cellular operation.

Whenever the FA application requires access to the licensed band, it invokes an over-the-air silencing mechanism to claim the licensed-band resource from the cellular network (Fig. 5). The silencing signal should be broadcast by the less power-constrained controller, for instance by using the collocated mobile-device function. The silencing signal is included in the dual-band design (Fig. 2b). Ideally, all cellular access nodes and mobile devices close to the factory system listen and yield to the factory's silencing broadcast. Alternatively, access nodes might be excluded from the silencing procedure assuming they are deployed at a sufficient distance from the factory environment and are therefore less hazardous to URLLC (Fig. 5, bottom). In this case, silencing suppresses only mobile uplink traffic.

Design Selection

The PHY/MAC designs presented demonstrate how the 5G cellular specifications can support an industrial printer application, which presently does not have a wireless solution. While the design focuses on one application, the flexibility in slot configuration and subcarrier spacing envisioned by present 3GPP efforts enables alignment with FA applications over a large scale of cycle times, creating a true alternative to wireline solutions. At the same time, the printer application illustrates that bandwidth demand of FA applications is rather extensive. Migrating FA applications to the licensed spectrum will therefore require economic justification.

The single-band PHY/MAC design presented allows operating the FA candidate application in either the licensed or unlicensed band. When operating in the unlicensed band, explicit measures must be taken to suppress coexistence with other systems since uncontrolled interference or resource contention via back-off are detrimental to URLLC performance. Operation in the licensed band circumvents these problems if the cellular PHY/MAC manages to appropriately prioritize URLLC- over other cellular traffic. Under such circumstances, the economic burden may be acceptable for FA applications with low duty cycles.

In case the FA duty cycle is too high for economical handling in the licensed band, the dual-band design presents an attractive alternative, that restricts licensed-band operation to occasions of coexistence conflicts in the unlicensed band, and it avoids other-system interference and contention-related back-off.

The detection of such conflicts, however, must be sufficiently reliable and fast by URLLC standards. CCA-based band selection appears straightforward, but it remains vulnerable to non-yielding interferers. ARQ-based band selection covers all interference scenarios at the price of higher bandwidth and licensed-band transmission power. Clever bandwidth coordination across multiple FA systems may eliminate the bandwidth disadvantage. The design, however, requires thorough

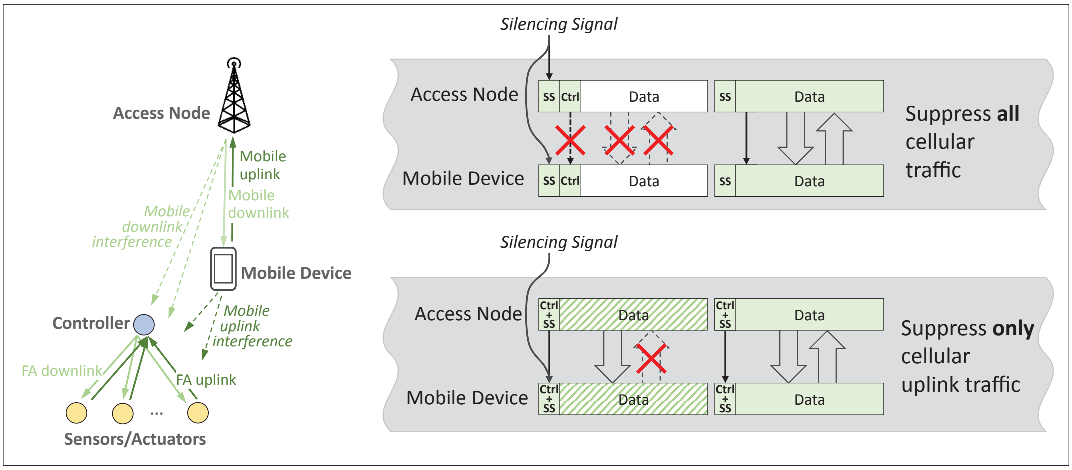

Figure 5. Over-the-air traffic prioritization via silencing signal (SS): top shows evaluation of silencing signal by access node and a mobile device; bottom shows overlay of silencing signal on mobile control channel.

analysis on how to balance transmit power in unlicensed band and licensed band utilization.

The economic effectiveness of the dual-band design critically relies on the concurrent availability of the licensed band for revenue-bearing cellular traffic. This introduces a new coexistence problem in the licensed band demanding a highly effective solution that is compliant with URLLC performance requirements. URLLC traffic prioritization and over-the-air policy enforcement are imperative features that need to be supported for this purpose. These features should be made available with the first standard releases of cellular 5G to avoid backward-compatibility issues at a later stage.

Future Work

Our work has demonstrated opportunities for cellular 5G to support FA applications that presently have no wireless solution. Considering the limitations to URLLC in the unlicensed band, we have shown that licensed spectrum can deliver an alternative for FA operation and enable a new cellular market segment at the same time. We demonstrate that economic viability can be addressed via integrated unlicensed-band/licensed-band operation on the PHY/MAC layer. More research is necessary that includes the economic component to the technical challenges of URLLC.

While our work leverages many 5G elements developed by 3GPP working groups, it still relies on a variety of URLLC features that need to be added to the cellular specifications. These include synchronized operation in the licensed and unlicensed band as well as over-the-air inter-system coordination to regulate resource utilization and priority enforcement. Further academic work may be advisable to guide standards bodies in their pursuit of the opportunities in URLLC.

While our work leverages many 5G elements developed by 3GPP working groups, it still relies on a variety of URLLC features that need to be added to the cellular specifications. These include synchronized operation in the licensed and unlicensed band as well as over-the-air inter-system coordination to regulate resource utilization and priority enforcement.

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