5G New Radio for Automotive, Rail, and Air Transport

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Abstract—The recent and upcoming releases of the 3rd Generation Partnership Project's 5G New Radio (NR) specifications include features that are motivated by providing connectivity services to a broad set of verticals, including the automotive, rail, and air transport industries. Currently, several radio access network features are being further enhanced or newly introduced in NR to improve 5G's capability to provide fast, reliable, and non-limiting connectivity for transport applications. In this article, we review the most important characteristics and requirements of a wide range of services that are driven by the desire to help the transport sector to become more sustainable, economically viable, safe, and secure. These requirements will be supported by the evolving and entirely new features of 5G NR systems, including accurate positioning, reference signal design to enable multi-transmission and reception points, service-specific scheduling configuration, and service quality prediction.

Keywords: 5G networks, automotive services, high-speed train, urban air mobility, positioning, QoS prediction.

I. INTRODUCTION

Recent advances in wireless communications, real-time control, sensing, and battery technologies, collaborative spectrum management and sharing, and artificial intelligence are enabling the transport sector to become more cost efficient, secure, and sustainable [1]. Due to new requirements arising in road, railway, air and maritime transport, cellular connectivity, and reliable wireless communications between vehicles and road users are no longer a "nice to have", but are essential parts of cooperative intelligent transportation systems (C-ITSs) and smart cities [2]. Ericsson predicts that the number of connected cars in operation will rise to more than 500 million in 2025, and the railway sector is making the first steps to digitalize the European Rail Traffic Management System (ERTMS), which includes mission-critical control systems for train operations, including high-speed trains (HSTs). The unmanned aerial vehicle (UAV) and urban air mobility (UAM) (drone) market is expected to grow from the current estimated USD 4.4bn to 63.6bn by 2025 [3]. Apart from smart city applications, there is a growing interest in employing connected UAVs in surface mining, seaports, oil and gas, and other large industrial facilities or in public safety situations in order to improve and optimize industrial processes, enhance operational efficiencies, and create resilience.

The digitalization and increasing connectivity in the transport sector are driven by three key factors. First, there are increasing demands imposed virtually by all stakeholders – including passengers, cargo companies, vehicle (car, truck, locomotive, ship) manufacturers, public transport and rail operators, and infrastructure (road, rail, harbor) providers. This broad set of requirements includes being always connected to the Internet and enterprise networks, enjoying safe and secure journeys in urban and rural environments, and minimizing environmental impacts. At the same time, reducing capital and operational expenditures necessitates increasing digitalization, automation, and always-on connectivity, since these technologies make manufacturing, maintaining and operating transport equipment, infrastructure, and services much more efficient. Thirdly, the rapid deployment of 5G networks, and the recent advances in 6G research provide a technology push towards digitalized and connected transport services [4].

In parallel with the above trends in the transport industry, the release 15 (Rel-15) of the 3rd Generation Partnership Project (3GPP) specifications in 2016 marked the birth of the new cellular radio interface for the fifth generation (5G) systems, commonly referred to as New Radio (NR). Although mobile broadband (MBB) services continue to be the main driver for NR, this new radio technology generation inherently has much stronger support for verticals such as the transport industry, as compared to Long Term Evolution (LTE). Additionally, already in Rel-16, new technical features are introduced specifically for supporting critical machinetype communications including ultra-reliable and low latency communications (URLLC) vehicle-to-everything (V2X) services for automotive. Further enhancements targeting special connectivity requirements of the rail operations and remote control of UAVs are also being standardized in the upcoming releases.

Compared with 4G systems, 5G NR adopts a new design philosophy and novel technology components, including flexible numerology and waveform design for lower and millimeter-wave frequency bands, minimizing control signaling overhead, multi-hop support by integrated access and backhaul relay, enhanced positioning, and quality of service (QoS) handling mechanisms. Also, further enhanced multipleinput multiple-output (MIMO) techniques enable 5G networks to acquire accurate channel state information (CSI) for both analog and hybrid beamforming and spatial multiplexing applications, which are important for maintaining high spectral efficiency even in high-speed road and rail transport scenarios [5]. Finally, recent 3GPP releases of 5G radio access networks pave the way for advanced radio-based positioning techniques that efficiently complement and make positioning more precise than pure satellite-based positioning techniques [6], which are highly useful for automotive and drone use cases.

The present paper serves two purposes. Firstly, we summarize the technical foundations of 5G NR which can fulfill basic requirements imposed by emerging use cases in the transport sector. Secondly, based on an in-depth review of connectivity requirements of transport use cases, we highlight several important new technology enablers which will play a key role in meeting the most stringent requirements. In particular, we focus on the following,

- Positioning techniques that take advantage of combining onboard sensors and cellular network measurements;
- Reference signal design and selecting the appropriate multi-transmission and reception point (TRP) option for spectrum-efficient operations of HSTs and other high-speed user equipments (UEs);
- Service-specific scheduling techniques for V2X communications that ensure high resource utilization and service differentiation between low-latency and delay tolerant (lower than best effort) traffic types;
- Novel QoS-prediction techniques that are useful in driverless and driver-assisted road, rail, and drone transport use cases.

II. TECHNICAL FOUNDATIONS OF 5G NR AND THE INITIAL NR EVOLUTION TARGETING THE TRANSPORT VERTICAL

A. Major Features in Rel-15 and Rel-16

As mentioned, Rel-15 and Rel-16 of the 3GPP specifications have been largely driven by requirements of MBB services, including requirements on enhanced data rates, latency, coverage, capacity, and reliability. However, starting already in Rel-15 and continuing in the subsequent 3GPP releases, NR enables new use cases by meeting the requirements imposed by transport use cases, such as connected cars, high-speed trains, and UAVs. While Rel-15 focused on supporting MBB and URLLC applications, Rel-16/17 includes UE power savings, operation in unlicensed spectrum, industrial Internet of Things (IoT) enhancements as well as special radio access network (RAN) features such as physical layer support for unicasting sidelink (device-to-device) for advanced V2X services [7].

A key distinguishing feature of 5G NR from fourth generation (4G) systems is the substantial expansion of the frequency bands, in which NR can be deployed. For transport applications, the following NR-specific features are particularly important (see Figure 1):

- Symmetric physical layer design with orthogonal frequency division multiplexing (OFDM) waveform for all link types, including uplink, downlink, sidelink, and backhaul;
- Wide range of carrier frequencies, bandwidths, and deployment options. 3GPP aims to develop and specify

3GPP Release	Area	Brief description	Relevant transport use cases
Release 15	Flexible numerology	Subcarrier spacing and CP for mmWave	Use cases using mmWave (short range and bandwidth hungry: e.g. AD, Gbit train)
	Latency-optimized frame structure	Mini slots for URLLC	Delay critical applications (e.g. control tower for rail/UAM)
	Massive MIMO	Large number of antenna elements	Pencil beams for high SNR (e.g. Infotainment, MBB services)
	Interworking between low and high frequency bands	Higher frequency NR system complements low-band	Densification and boosting throughput for urban deployments of ITS
	Ultra-lean transmissions	Energy efficiency through longer sleep times	Ultra dense deployments for automotive and high-speed rails
	Dynamic TDD	Setting UL/DL transmissions adaptively	Mix of uplink and downlink heavy automotive services (e.g. telematics, vehicle as a sensor and MBB services)
Release 16	Cross-link interference mitigation and remote interference management	Interference mitigation in small cell dynamic TDD deployments	See Rel-15 dynamic TDD use cases.
	MIMO enhancements	Enhanced beam handling and CSI feedback, support for transmission to a single UE from multiple transmission points (multi-TRP)	High-speed rail deployments with multi-TRP features.
	UE power savings	Wake-up signal and enhance- ments to control signaling and scheduling	Automotive and UAM scenarios in which battery lifetime is important.
	Dual connectivity (DC) and carrier aggregation (CA)	Reduced latency for setup and activation of CA/DC, thereby leading to improved system capacity and data rates.	Faster activation of CA/DC with less signaling for bandwidth hungry (MBB) automotive services.
	Integrated access and backhaul (IAB)	Support wireless backhaul as an alternative to fiber backhaul.	Can simplify deployments of small cells in dense urban networks or enable deployment of temporary sites used for special events.
	NR in unlicensed spectrum	Standalone operation in unlicensed spectrum is supported.	Flexible deployments in new bands as such become available.
	V2X enhancements and unicasting sidelink	Sidelink enables physical-layer unicast, groupcast, and broadcast communication.	Highly reliable communication links with appropriate quality of service (QoS) characteristics as demanded by ITS services.
	URLLC	Resource efficiency enhancement when mixing MBB/URLLC traffic.	URLLC is instrumental in enabling e.g. remote driving services.
	Positioning	New positioning methods, both downlink-based and uplink-based, are used separately or in combination to meet accuracy requirements.	Cooperative maneuvering, e.g. lane change, lane merge, C-ITS.
Release 17	Multicast/broadcast	MC/BC to multiple intended receivers.	V2X, public safety, SW update delivery, C-ITS.
	Non-terrestrial networks	Support for satellites and high- altitude platforms.	Additional coverage in rural areas for transport services and for PS.
	IAB enhancements	Support NW topology changes	Public transport (e.g. buses), trains equipped with an IAB node.
	Sidelink enhancements	Sidelink-assisted relaying	Out-of-coverage V2X and PS.
	Industrial IoT enhancements	Improved support for URLLC	Remote driving, AD, UAV control
	Positioning enhancements	Improved accuracy and mobility support	C-ITS, ADAS/AD, UAV control
	MIMO enhancements	Fast panel selection, enhanced multi-TRP CSI support	High bit rate V2X and railway services

Figure 1: Key areas and relevant transport use cases in NR Rel-15, Rel-16, and Rel-17.

components and physical layer numerology that can operate in frequencies up to 100 GHz. This implies several options for OFDM subcarrier spacing ranging from 15 kHz up to 240 kHz with a proportional change in cyclic prefix duration;

• Native support for dynamic time division duplexing (TDD) as a key technology component. In dynamic TDD,

parts of a slot can be adaptively allocated to either uplink or downlink, depending on the prevailing traffic demands;

• Support for massive MIMO, that is a massive number of steerable antenna elements for both transmission and reception, utilizing channel reciprocity in TDD deployments and a flexible CSI acquisition framework. The NR channels and signals, including those used for data transmission, control signaling and synchronization are all designed for optional beamforming.

In addition to flexible numerology, native support for dynamic TDD and advanced MIMO features, NR is designed using the principle of ultra-lean design, which aims at minimizing control plane and synchronization signal transmissions when data transmissions are idle. Inherent support for distributed MIMO, also referred to as multi-TRP, is introduced and fully supported in Rel-16. This feature is largely motivated by HST applications, since it allows UEs to receive multiple control and data channels per slot, which enables simultaneous data transmissions from multiple physically separated base stations.

B. Major Developments in Rel-17

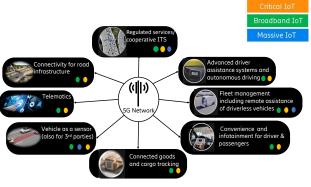
Looking beyond Rel-16, the NR evolution will be driven by industry verticals, including a variety of transport use cases, such as V2X communications, high-speed trains, UAVs and passenger aircrafts, and maritime communications. These use cases justify new features discussed and planned for Rel-17. MIMO enhancements are expected to support multi-TRP specific tracking reference signals, single frequency network deployments, and non-coherent joint transmissions by multiple base stations, which are particularly useful for providing connectivity to high-speed trains. Furthermore, Rel-17 is studying the integration of non-terrestrial and terrestrial networks in order to support use cases for which terrestrial networks alone cannot provide the required coverage and capacity, including maritime, UAV, and UAM scenarios.

III. OVERVIEW OF INTELLIGENT TRANSPORTATION SYSTEMS SERVICES AND REQUIREMENTS

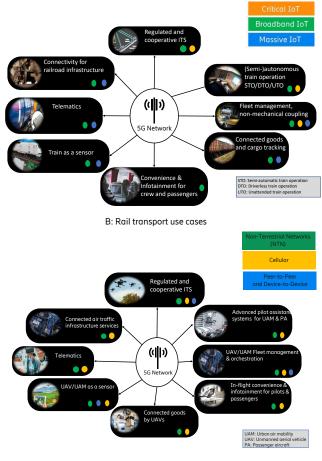
Figure 2 classifies the automotive, rail, and UAV/UAM use cases in use case categories, together with the key connectivity requirements per category.

Regulated C-ITSs provide international or governmental regulated services for road, rail and drone traffic efficiency, sustainability, and safety. Traffic efficiency use cases have relaxed latency requirements, while safety-related data often requires URLLC. A benefit of regulation is to facilitate original equipment manufacturer (OEM) cooperation in standardized information exchange. C-ITS services may also use dedicated spectrum in certain regions; for example, for direct shortrange communication using the 3GPP sidelink technology. For rail transport, C-ITS implies station dwell time control and speed/break control to optimize rail network utilization while ensuring safety.

Advanced driver assistance systems (ADASs) and autonomous driving (AD) are increasingly employed for both road and rail transport. In Europe, for example, the next generation of the ERTMS will support well-defined levels



A: Automotive and road transport use cases



C: Unmanned aerial vehicle (UAV) and urban air mobility (UAM) use cases

Figure 2: Use case categories in the automotive and road transport (upper), railway (middle), and UAV and UAM (lower) segments.

of automation, including semi-automated (assisted) driving, driverless and unattended train operation. Similarly, advanced pilot assistance systems for UAM and passenger aircrafts are envisioned by various stake-holders of the air transport industry. For this set of applications, URLLC communication and high-accuracy positioning play crucial roles.

Fleet management including remote assistance of driverless vehicles is an important application for road, rail, and UAV-based transport. This type of services aim at vehicle fleet owners such as logistics or car-sharing companies. The communication service is primarily used to monitor vehicle locations and the vehicle/driver status. With increasing level of automation in the rail industry and for UAVs, or for a fleet of driverless trucks, fleet management also includes communication support for operations monitoring and remote assistance from a control tower.

Convenience and infotainment, based on MBB services for drivers, crew, and passengers are equally important in road, rail, and future UAM transport use cases. Such services deliver content such as traffic news and audio entertainment for car drivers, and gaming and video entertainment for passengers. One specific example is the concept of "Gigabit train" services, which motivate the adoption of HST scenarios in 3GPP. For this set of use cases, the most important requirement is high data rate and low latency connections, which rely heavily on the capability of tracking wireless channels at high vehicle speed.

The primary focus in the logistics and connected goods category is on the tracking of transported objects (commodities, merchandise goods, cargo and so on) during the production and transport cycle of the object. Near real time tracking and status monitoring of goods are attractive for cargo companies, customers, and freight train operators.

In the vehicle-as-a-sensor use case category, sensors installed in the vehicle sense the environment and can also provide anonymized data to 3rd parties. In road transport, for example, the vehicle-mounted sensors provide information for solutions such as ADAS or AD as well as for monitoring city infrastructure and road status. For rails, railway track monitoring and anomaly detection are supported by various sensors mounted on the train, effectively operating the train as a sensor. Similarly, drones can be equipped with a lot of sensors that help collect data and perform distributed or federated computation for various purposes such as forecasting cloud formation, rain, and other hazardous weather conditions. Just as with the convenience and infotaiment category, the vehicle-as-a-sensor requires high data-rate connections between vehicles or between vehicles and the cellular network at high vehicle speed and dynamic interference conditions.

Telematics applications for vehicles include collecting vehicle diagnostics to monitor/adjust the vehicle, while rail telematics rail applications allow continuous status updates from trains to determine state, delay, cargo conditions, software (SW) updates, and geo-fencing. In this category, several applications (e.g. SW updates) tolerate delay, while others are more delay critical. Similarly, for air transport, telematics serve as a tool for collecting air vehicles diagnostics to monitor/adjust the vehicles. To make sense of the vast amount of data collected from vehicles in this group of use cases, the role of artificial intelligence (AI)/machine learning (ML) is utterly important. In the reverse direction, AI/ML can also play a meaningful role in determining when to perform a certain task to the vehicle in an efficient manner. For example, ML-based spare capacity prediction, which is part of the so-called cellular network QoS prediction, can be used to predict the most economical time for SW update for a set of vehicles [8], [9].

Connected road infrastructure services are operated by cities

and road authorities to monitor the state of the traffic and control its flow, such as physical traffic guidance systems, parking management and dynamic traffic signs. For railways, the communication between the rail infrastructure and the locomotive via specific transmission modules and eurobalises is used to send information from line-side electric units to the trains e.g., current speed restrictions for the coming rail segment. For UAV/UAM, an Unmanned Aircraft System Traffic Management (UTM) is used for traffic control, which requires high-accuracy 3D positioning and URLLC communication with the ground control system.

IV. PROPOSED NEW FEATURES AND SOLUTIONS TO SUPPORT INTELLIGENT TRANSPORTATION SYSTEM (ITS) REQUIREMENTS

Despite the recent and ongoing enhancements to 5G NR, there is still a need to further improve the technology to meet the growing demands of industry verticals. In this section, we summarize the state of the standardization of several specific features and introduce new solutions which can help fulfilling the stringent connectivity requirements of the transport sectors outlined in the preceding section. These components span both radio layers (physical, medium access control) and the service layer of the protocol stack.

A. Advanced Positioning Support and Algorithms

With the introduction of NR, 3GPP targets improved positioning capabilities to cater for a number of new use cases, involving indoor, industrial, and automotive applications. Cooperative manoeuvring in the C-ITS category and several ADAS applications rely on accurate positioning, which must remain operational even in global navigation satellite system (GNSS)-problematic areas. Specifically in Rel-16, a set of positioning related features are introduced, which pave the way for enhanced positioning services. These new features include new and improved uplink (UL) and downlink (DL) reference signal design, allowing larger bandwidths and beamforming, assisted by additional measurements and enhanced reporting capabilities. By supporting larger bandwidths than in LTE, higher accuracy of range estimates can be achieved, and with angle of arrival (AoA) and angle of departure (AoD) measurements new positioning schemes exploiting the spatial domain can be supported.

Architecture-wise, similarly to LTE, NR positioning is based on the use of a location server. The location server collects and distributes information related to positioning (UE capabilities, assistance data, measurements, position estimates, etc.) to the other entities involved in the positioning procedures (base stations (BSs) and connected vehicles). A range of positioning schemes, including DL-based and UL-based ones, are used separately or in combination to meet the accuracy requirements in vehicular scenarios.

Specifically, in the millimeter-wave (mmWave)-bands, referred to as frequency range-2 (FR2) bands of NR, the AoA and AoD measurements can be enhanced by using large antenna arrays, which facilitate high resolution angular measurements. By unlocking the spatial domain, NR can significantly increase the positioning accuracies for many industrial and automotive use cases [10], [11]. Additionally, to further improve the accuracy and reliability of positioning in GNSSproblematic areas, we propose to fuse acceleration measurements provided by onboard inertial measurement units (IMUs) with measurements on the received NR DL reference signals from multiple NR BSs. Fusing local IMU measurements with measurements on multiple NR DL signals can reach decimeter accuracy in favourable deployments.

Furthermore, high accuracy spatial and temporal measurements facilitate the use of advanced positioning schemes such as simultaneous localization and mapping (SLAM), which utilizes consecutive measurements to build a statistical model of the environment, achieving high accuracy even in extreme scenarios by utilizing measurements on DL signals of only a single base station.

B. Further Enhanced MIMO to Support Multiple Transmission and Reception Points

HST wireless communication is characterized by a highly time-varying channel and rapid changes of the closest TRPs to the train, resulting from the extreme high velocities. Recognizing these challenges, NR has been designed to support high mobility from day one, and includes features to enable communications with HSTs [12]. Furthermore, several multi-TRP deployment options and features developed under the general MIMO framework can be exploited to support HST communications for the "Gigabit train", while minimizing the need for handovers. We expect this technology component will also play a very important role in UAV/UAM use cases.

The multi-TRP options that are the most relevant to HST communications are:

- Dynamic point switching (DPS): Data signals are transmitted from a single TRP at a given time, and the TRP used for transmission is dynamically selected based on the relative quality of channels between the train and a few closest TRPs;
- Single frequency network (SFN): All the TRPs in the SFN area transmit the same data and reference signals to the train;
- SFN with TRP-specific reference signals: The same data signal is transmitted from different TRPs, while some of the reference signals are transmitted in a TRP-specific manner.

The first and the third options rely on TRP-specific reference signals, whereas the second option uses common reference signal across the TRPs in the coverage area of the SFN. In addition to supporting TRP-specific reference signals, NR supports associating different reference signals with different channel properties, such as Doppler shift and delay spread, through NR's quasi co-location (QCL) and transmission configuration indication framework. In Rel-17, different QCL enhancements are investigated to better support advanced channel estimation schemes that can be implemented at the train and to evaluate the need for TRP-side pre-compensation algorithms. In Section V, we evaluate the necessity and performance of the multi-TRP options described above through link level evaluations. Furthermore, beam management enhancements necessary to support HST communications in the higher bands of NR are also investigated in Rel-17.

C. Service-Specific Scheduling

To accommodate MBB, URLLC, and machine-type communications services, NR networks employ scheduling algorithms that take into account the current service mix, prevailing channel conditions, traffic load, available carriers, and other factors. Scheduling in multiservice wireless networks has been researched for decades and a vast literature as well as practically deployed scheduling schemes exist. Interestingly, due to requirements imposed by the coexistence of URLLC and delay tolerant services, mmWave communications support in the FR2 bands and serving very high speed UE-s have stimulated renewed research interest in this topic [13].

Some recent works propose scheduling strategies to minimize end-to-end delay for time-critical services [14], or to optimize resource allocation for the coexistence of various services [13]. In NR, service-specific scheduling can also be configured to take into account the specific opportunities that are present in certain deployment scenarios. We propose to customize the scheduler in certain deployment scenarios, which can be illustrated by a scheduling configuration that is suitable for non-time-critical services. This can be applicable for background data transfer for SW updates or uploading sensor measurements in the vehicle-as-a-sensor category. This scheduling mechanism divides vehicles into a high and a low path-gain group. Vehicles belonging to the high pathgain group are eligible for medium access, while scheduling vehicles in the low path-gain group is postponed (dropped) until their path gain improves. The scheme is suitable for highly mobile users (including automotive or urban train use cases) in high-way, urban or suburban scenarios, and can be activated or de-activated based on velocity or other sensor measurements that help to configure the path gain threshold.

D. QoS Prediction

The NR QoS framework together with features like URLLC are successful in delivering a minimum guaranteed performance, especially in controlled scenarios. However, highly mobile UEs usually experience time-variant network performance, partly because the actual QoS often exceeds the minimum or guaranteed level, and partly because the system is occasionally not able to fulfill a QoS provision.

Interestingly, in many cases, including certain C-ITS, ADAS or telematics applications, these performance fluctuations are not a problem if they can be predicted in advance. Having access to real-time QoS predictions has generated a large interest from the automotive industry [8], as it would allow service providers, mobile network users, and automotive applications to dynamically adapt their behaviors to the prevailing or imminent QoS level. This would allow for enabling services relying on continuous guaranteed performance as well as for exploiting spare capacity for large bulk data transfers in lower than best effort services.

Despite the high expectations, QoS prediction is largely an open research topic. The realistically achievable performance and the applicability of this type of algorithms are still

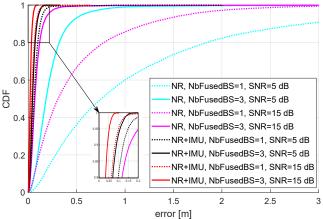


Figure 3: CDF of the obtained positioning accuracy when using NR only and fused IMU+NR positioning at 5 and 15 dB SNR.

unknown. To a large extent, QoS prediction is seen as a ML application with a broad data set consisting of network measurements, device measurements, and application data [9].

In practice, different types of information may be collected with different periodicities, time horizons, resolutions, and accuracies, depending on practical and business-related constraints. Understanding the relevance of each of them is ongoing work and will be instrumental in determining the relative merits and tradeoffs of the different architecture options, which range from network-centric to application-based. As a first step towards supporting predictive QoS in mobile networks, 3GPP enhanced the NR system architecture in Rel-16 to support services providing network data analytics in the 5G core network. To this end, application programming interfaces for exposing network-based predictions were defined, the necessary procedures for collecting the relevant data for the analytics from different network functions as well as from the operations administration and management functionality.

In addition, procedures providing analytics (e.g., load, network performance, data congestion, QoS sustainability and UE related analytics) to other network functions were introduced. As usual, the algorithms used to obtain the network analytics are not defined in the specification, and as said, they are a topic of ongoing research.

V. NUMERICAL EXAMPLES

A. Positioning

We consider a highway scenario with BSs equally spaced and placed at the side of the road. A moving vehicle following a snake-like trajectory is equipped with an onboard IMU sensor and an NR UE. A MIMO system is considered with square antenna arrays at the BS and the UE. A line-of-sight (LoS) downlink propagation is assumed with a grid of Discrete Fourier Transform beams transmitted by the BS. A sensor fusion-based positioning approach is proposed (similar to the one in [11]), for which a Kalman filter is used to fuse the measurements obtained from the IMU and the NR downlink such as the range and the angles-of-arrival. An extension to this is proposed allowing to fuse measurements from multiple BS.

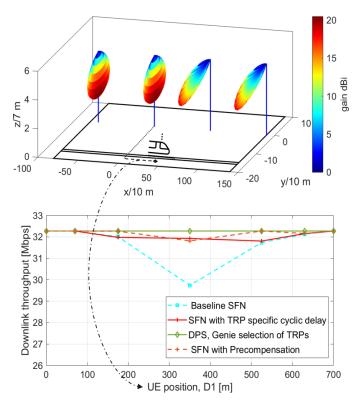


Figure 4: High-speed train multi-TRP scenario with four base stations (upper) and downlink throughput as a function of train position when using SFN without/with cyclic delay diversity (CDD), DPS and SFN with precompensation. (The x, y and z axes are scaled by 10, 10 and 7 respectively for better visualization.)

Positioning accuracy in terms of positioning cumulative distribution functions (CDFs) are compared in Figure 3 for NR-based method and for the sensor fusion-based method combining IMU with NR. It is assumed that the BSs operate at the millimeter wave frequency of 28 GHz with 256 antennas. There are 4 antennas at the UE, the UE speed is equal to 130 km/h, and signal-to-noise ratio (SNR) is equal to 5 and 15 dB. The BSs are placed at 40 m from the road with the inter-site distance equal to 200 m. The results are averaged over a total distance of 10 km. The number of BSs used to fuse the measurements from is denoted by NbFusedBS. The simulation results show that a large performance gain is obtained for the sensor fusion-based method as compared to the NR only-based method, especially at low SNR. Notice that fusion-based methods allow to achieve a decimeter level accuracy with greater than 90% probability, even at low SNR of 5dB.

B. Further Enhanced MIMO to Support Multiple Transmission and Reception Points

For evaluations, a four-TRP deployment at 2 GHz carrier frequency using 20 MHz bandwidth (50 resource blocks) with TRP hight of 35m, 30 kHz subcarrier spacing, and train speed of 500 km/h is assumed, as illustrated in Figure 4 (upper) is used. The TRP antenna orientation is set to 10 degrees downtilt with an antenna gain of 20.5 dBi. The channel between each TRP and the reception point at the train is modeled using

an extended clustered delay line (CDL) channel model. The SNR at train position D1 = 0 m is 16 dB in the SFN deployment, and an hybrid automatic repeat request (HARQ) scheme with a maximum number of 3 retransmissions is employed, using a fixed modulation and coding scheme (MCS) with 64-quadrature amplitude modulation (QAM), low-density parity- check coding with code-rate = 0.428.

Figure 4 (lower) shows the throughput as a function of distance in the different deployment options. In the baseline SFN transmission scheme, the throughput for UE locations, close to midpoint of two TRPs does not reach the peak throughput of the modulation and coding scheme used. This is due to the fact that the equivalent channel formed by the combination of the two dominant CDL channels with LoS components having equal and opposite Doppler shifts results in a less frequency selective channel with deep fades across some of the OFDM symbols in a slot.

This channel behavior can be modified by adding a TRPspecific cyclic delay diversity which converts the effective channel close to midpoint between TRPs to a frequency selective channel without deep fades across OFDM symbols. The throughput improvement with TRP-specific cyclic delay diversity is shown in the figure. A precompensation scheme where a TRP-specific Doppler frequency offset (DFO) compensation is performed also improves the throughput close to the midpoint, as seen in the figure. However, this scheme requires TRP-specific reference signals in order for the train to estimate the Doppler shifts and additional signaling in the uplink direction to feedback the estimates.

The figure also shows the performance of the DPS scheme with genie selection of the TRPs, where a single TRP closest to the train is used for data transmission. In case of DPS, the received SNR at a train position is smaller than in the case of SFN transmissions due to transmission from a single TRP. However, if sufficient SNR can be guaranteed using proper deployment, DPS achieves peak throughput of the MCS used at all train positions. The evaluation results show that a complex scheme, such as SFN with DFO precompensation, does not perform significantly better than the other alternatives. Also, a low-complexity and UE transparent scheme such as SFN with TRP-specific CDD, which can be readily employed and scaled to serve a large number of UEs, performs well by suitably altering the effective channel.

C. Service-Specific Scheduling

To illustrate the impact of customizing the scheduler to operate in specific deployment scenarios, we consider an automotive high-way scenario, in which the BS sites are deployed according to the 3GPP recommendation in [15].

Figure 5 shows that dropping low path-gain users improves the mean user throughput, especially in case of high traffic density. Specifically, when all users are scheduled simultaneously (marked as 0% Drop) the mean user throughput drops to close 0 when the traffic is around or higher than 1000 Mbps/km². When the scheduler is configured to distinguish low and high path-gain vehicles and postpones scheduling vehicles that are momentarily have low path-gain, the average throughput significantly increases. Dropping 50% of the low

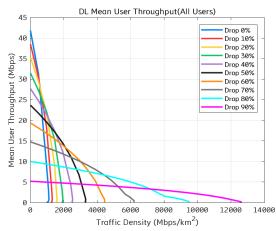


Figure 5: Downlink mean user throughput as a function of the traffic density when employing different drop rates in an automotive highway scenario, in which the base station sites are deployed with 1732m inter-site distance.

path-gain users (Drop 50% line), for example, improves the mean user throughput when traffic density lies between 1000-3000 Mbps/ km2.

This simple example illustrates that adjusting the drop ratio (by adjusting the threshold between low and high path gain vehicles and setting the drop ratio in the low path-gain group) – according to the deployment parameters and prevailing traffic density – can optimize the system spectral efficiency. The basic rationale for this is that for non-latency-critical services, the user data transmission can wait until the user is moving into good coverage area, while users in poor coverage area can be dropped to improve both system resource utilization and spectral efficiency.

As an example, consider the highway scenario, in which vehicles drive at 140km/h. To guarantee 95% MBB-like service coverage (10 Mbps data rate for DL and 2 Mbps for UL), the DL capacity for the non-dropping case is 450 Mbps/km² (760 Mbps/km² for UL). It takes 50s (250s for UL) to transmit a 500M file in the DL. For the drop 50% case, for the same traffic density (450 Mbps/km2 for DL and 760 Mbps/km2 for UL), the transmission time is greatly reduced (19s for DL and 31s for UL). Although the Drop 50% case has about 50% coverage hole, this coverage hole lasts until the vehicles drive by a next BS, improve their path loss, and complete the ongoing file transmission.

D. QoS Prediction

The most fundamental question of predictive QoS is, perhaps, the accuracy of the predictions. We have studied multiple alternatives to predict DL throughput in different time horizons. Figure 6 summarizes our findings in terms of the CDF for different prediction horizons of the difference between predicted and delivered number bits B over a given time interval Δt :

$$e'(t, \Delta t) \triangleq \frac{\left|B_{\text{delivered}}(t) - B_{\text{predicted}}(t)\right|}{\Delta t}$$

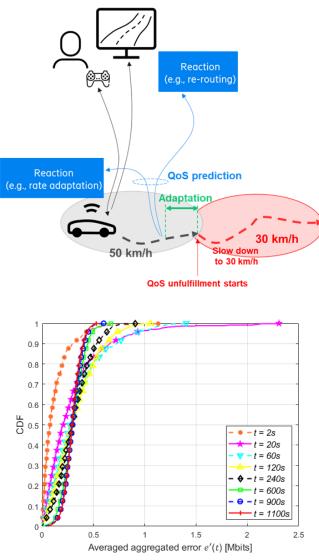


Figure 6: Predictive QoS: Linking network-level QoS level and the application layer (upper), Network-based prediction function utilizing ML (middle) and DL throughput prediction (lower).

Our results show that both short-term and long-term predictions are quite accurate in most cases. In the former case, this is due to the ability to predict short term channel quality fluctuations, while other system variables that are harder to predict (e.g., interference level, instantaneous cell load) are relatively stable. In the latter case, the longer interval averages out the instantaneous variations of channel quality and other short-term effects. In contrast, DL throughput prediction in the intermediate regime is much more challenging. In this case, rapid channel fluctuations are often not well predicted, while the averaging effect is still weak. How to bridge the gap between short- and long-term predictions is still an open question.

VI. CONCLUDING REMARKS AND OUTLOOK

5G NR was designed to enable various use cases, reach a broad range of aggressive performance targets and be deployed in both traditional and mmWave frequency bands. The initial release (Rel-15) of NR included support for flexible numerology, latency-optimized frame structure, massive MIMO, interworking between low and high frequency bands and dynamic TDD. The new features of NR in subsequent releases include enhancements for MIMO, V2X, high-speed UE, and URLLC services, more accurate positioning, and support for non-terrestrial and mission-critical communications. These new standardized features, together with proprietary and algorithmic solutions facilitate connected and intelligent transport services, including automotive, rail, air transport and public safety services.

Connected and intelligent transport systems will continue to rely on ubiquitous broadband connectivity as expectations by the automotive, rail and air transport and public safety stakeholders evolve, and new business models emerge. The contours of future 6G systems are already emerging, as the standardization and research communities and end-users in the transport sector define future requirements and solutions. Based on these discussions, 6G technology candidates include both further enhancements of existing features and entirely new features. The former group includes pushing the limits of frequencies towards the lower bands of THz spectrum, while examples for the latter include integrated communication and radar sensing, integrated terrestrial and non-terrestrial networks, and utilizing intelligent reconfigurable surfaces and full-duplex communications.

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