5G New Radio: Waveform, Frame Structure, Multiple Access, and Initial Access

Shao-Yu Lien, Shin-Lin Shieh, Yenming Huang, Borching Su, Yung-Lin Hsu, and Hung-Yu Wei

The authors offer a comprehensive overview of the state-of-the-art development of NR, including deployment scenarios, numerologies, frame structure, new waveform, multiple access, initial/random access procedure and enhanced carrier aggregation (CA) for resource request and data transmissions. The provided insights thus facilitate knowledge to design and practice further features of NR.

Abstract

Different from conventional mobile networks designed to optimize the transmission efficiency of one particular service (e.g., streaming voice/video) primarily, the industry and academia are reaching an agreement that 5G mobile networks are projected to sustain manifold wireless requirements, including higher mobility, higher data rates, and lower latency. For this purpose, 3GPP has launched the standardization activity for the first phase 5G system in Release 15 named New Radio (NR). To fully understand this crucial technology, this article offers a comprehensive overview of the state-of-the-art development of NR, including deployment scenarios, numerologies, frame structure, new waveform, multiple access, initial/random access procedure, and enhanced carrier aggregation (CA) for resource requests and data transmissions. The provided insights thus facilitate knowledge of design and practice for further features of NR.

Introduction

Cellular mobile networks have been deployed for several decades. In the past, these networks were developed to optimize a particular service primarily (e.g., voice/video streams), while other services were supported additionally (e.g., Internet browsing and Internet of Things deployment). Nevertheless, in the upcoming decades, manifold applications (to name a few, unmanned vehicles/robots, intelligent transportation systems, smart grid/buildings/cities, virtual/augmented/sensory reality, mobile social services, and ubiquitous remote control) are urgently desired. To empower these emerging applications with miscellaneous traffic characteristics, an engineering paradigm shift is needed in the development of fifth generation (5G) mobile networks.

Instead of solely enhancing data rates to optimize transmissions of a handful of traffic patterns, the International Telecommunication Union Radiocommunications Standardization Sector (ITU-R) has announced multifold design goals of 5G mobile networks known as International Mobile Telecommunications 2020 (IMT-2020) [1, 2], which include 20 Gb/s peak data rate, 100 Mb/s user experienced data rate, 10 Mb/s/m^2 area traffic capacity, 106 devices/km^2 connection density, 1 ms latency, mobility up to 500 km/h, backward compatibility to LTE/LTE-Advanced (LTE-A), and forward compatibility to potential future evolution. To meet these design goals, the Third Generation Partnership Project (3GPP) started a normative work plan in 2016. To deploy the first phase (Phase I) system in 2018 and the "ready" system in 2020, the standardization activity of *5G New Radio* (*NR*) has been launched, and the first 5G specifications are framed in Release 15 with the following scope.

Standalone and Non-Standalone NR Operations: Standalone operation implies that full control plane and data plane functions are provided in NR, while non-standalone operation indicates that the control plane functions of LTE and LTE-A are utilized as an anchor for NR.

Spectrum Below and Above 6 GHz: Subject to existing fixed spectrum allocation policies, it is a challenge to obtain available spectrum with a sufficiently wide bandwidth from frequency range below 6 GHz. Consequently, spectrum above 6 GHz turns out to be critical. On the other hand, accessing the radio resources below 6 GHz is still necessary to fulfill diverse deployment scenarios required by operators.

Enhanced Mobile Broadband (eMBB), Ultra-Reliable and Low Latency Communications (URLCC) and Massive Machine-Type Communications (mMTC): Offering urgent data delivery with ultra low latency and massive packet transmissions are of crucial importance for NR. In Release 15, three maJor use cases are emphasized. eMBB supports high capacity and high mobility (up to 500 km/h) radio access (with 4 ms user plane latency). URLCC provides urgent and reliable data exchange (with 0.5 ms user plane latency). NR also supports infrequent, massive, and small packet transmissions for mMTC (with 10 s latency).

To integrate these features, agile radio resource management is essential to achieve optimized network performance. Before developing advanced resource management, deployment scenarios, numerologies, frame structure, new waveform, multiple access, initial/random access, and enhanced carrier aggregation (CA) should be ready as THE inevitable foundation. In this article, insightful knowledge to the state-of-the-art standardization of NR is consequently provided. The performance in terms of random access (RA) latency of enhanced CA is also demonstrated, as a performance benchmark to facilitate future engineering practice.

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Shao-Yu Lien is with National Formosa University; Shin-Lin Shieh is with National Taipei University; Yenming Huang, Borching Su, Yung-Lin Hsu, and Hung-Yu Wei are with National Taiwan University.

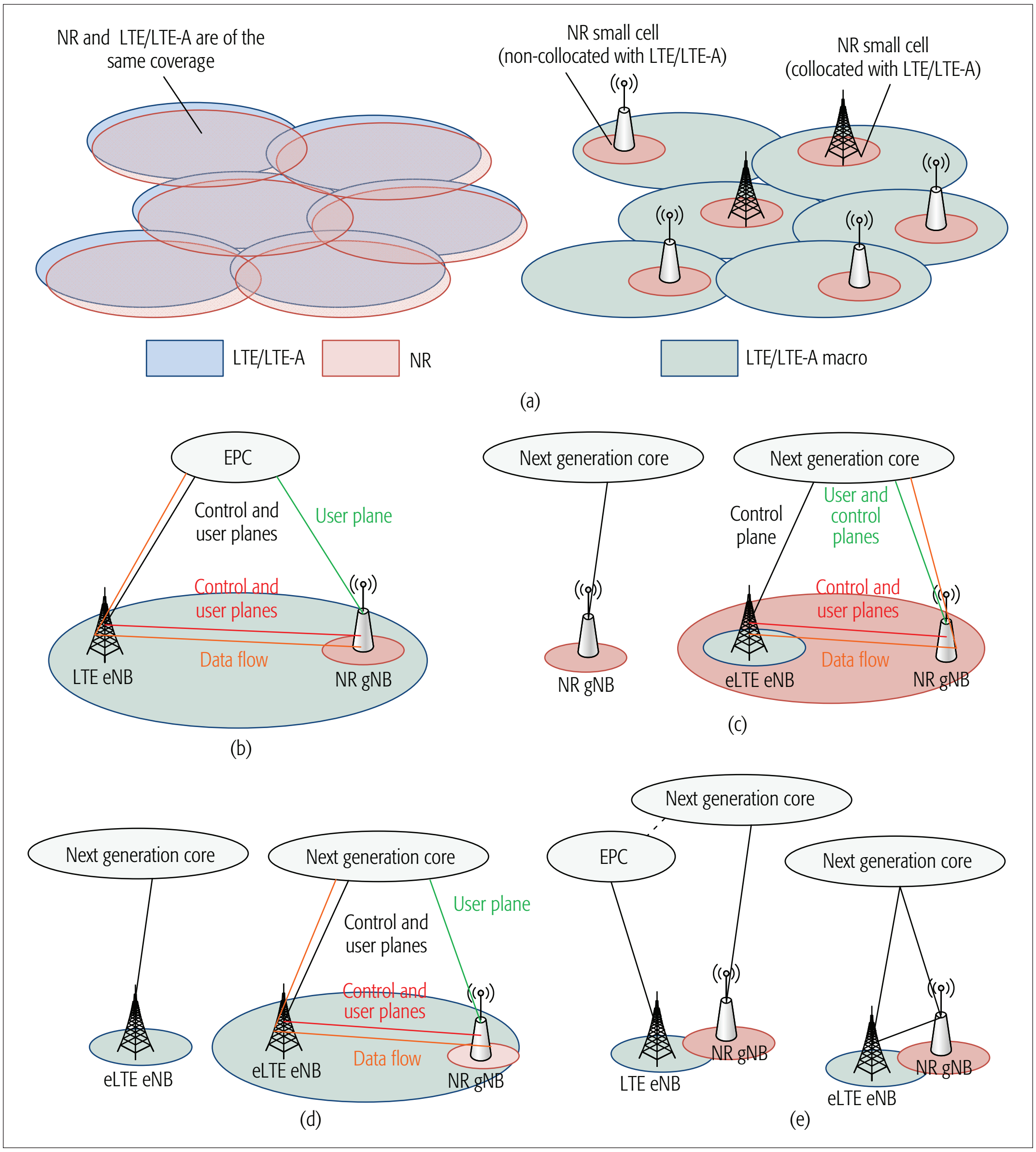

Figure 1. Deployment scenarios of NR.

A LTE/LTE-A eNB connects to the EPC, and a NR gNB connects to the next generation core, to support handover between eNB and gNB. An eLTE eNB can also connect to the next generation core, and handover between eNB and gNB can be fully managed through the next generation core.

Deployment Scenarios, Numerologies, and Frame Structure of NR

Deployment Scenarios

For backward compatibility with LTE/LTE-A, the architecture of NR is required to closely interwork with LTE/LTE-A. For this requirement, cells of LTE/LTE-A and NR can have different coverage (Fig. 1a) or the same coverage, and the following deployment scenarios are feasible.

LTE/LTE-A eNB Is a Master Node: An LTE/LTE-A eNB offers an anchor carrier (in both control and user planes), while an NR gNB offers a booster carrier. Data flow aggregates across an eNB and a gNB via the evolved packet core (EPC) (Fig. 1b).

NR gNB Is a Master Node: A standalone NR gNB offers wireless services (in both control and user planes) via the next generation core. A collocated enhanced LTE (eLTE) eNB is able to additionally provide booster carriers for dual connections (Fig 1c).

eLTE eNB Is a Master Node: A standalone eLTE eNB offers wireless services (in both control and user planes) via the next generation core, or a collocated NR gNB is able to provide booster carriers, as illustrated in Fig 1d.

Inter-Radio Access Technology (RAT) Handover between (e)LTE/LTE-A eNB and NR gNB: An LTE/LTE-A eNB connects to the EPC, and an NR gNB connects to the next generation core to support handover between eNB and gNB. An eLTE eNB can also connect to the next generation core, and handover between eNB and gNB can be fully managed through the next generation core (Fig. 1e).

The above scenarios reveal a heterogeneous deployment of NR with different coverage. Further considering user equipment (UE) mobility up to 500 km/h, multiple cyclic prefix (CP) lengths should be adopted in NR. In practice, the carrier frequency and subcarrier bandwidth may also affect the adopted CP length. Therefore, there can be multiple combinations of physical transmission parameters in NR, such as subcarrier spac-

OFDM is a mature technology broadly adopted in manifold products due to its several merits such as low complexity, easy integration with MIMO, plain channel estimation, and so on. It thus strongly motivates 5G NR still choosing OFDM as the basis of new waveform design.

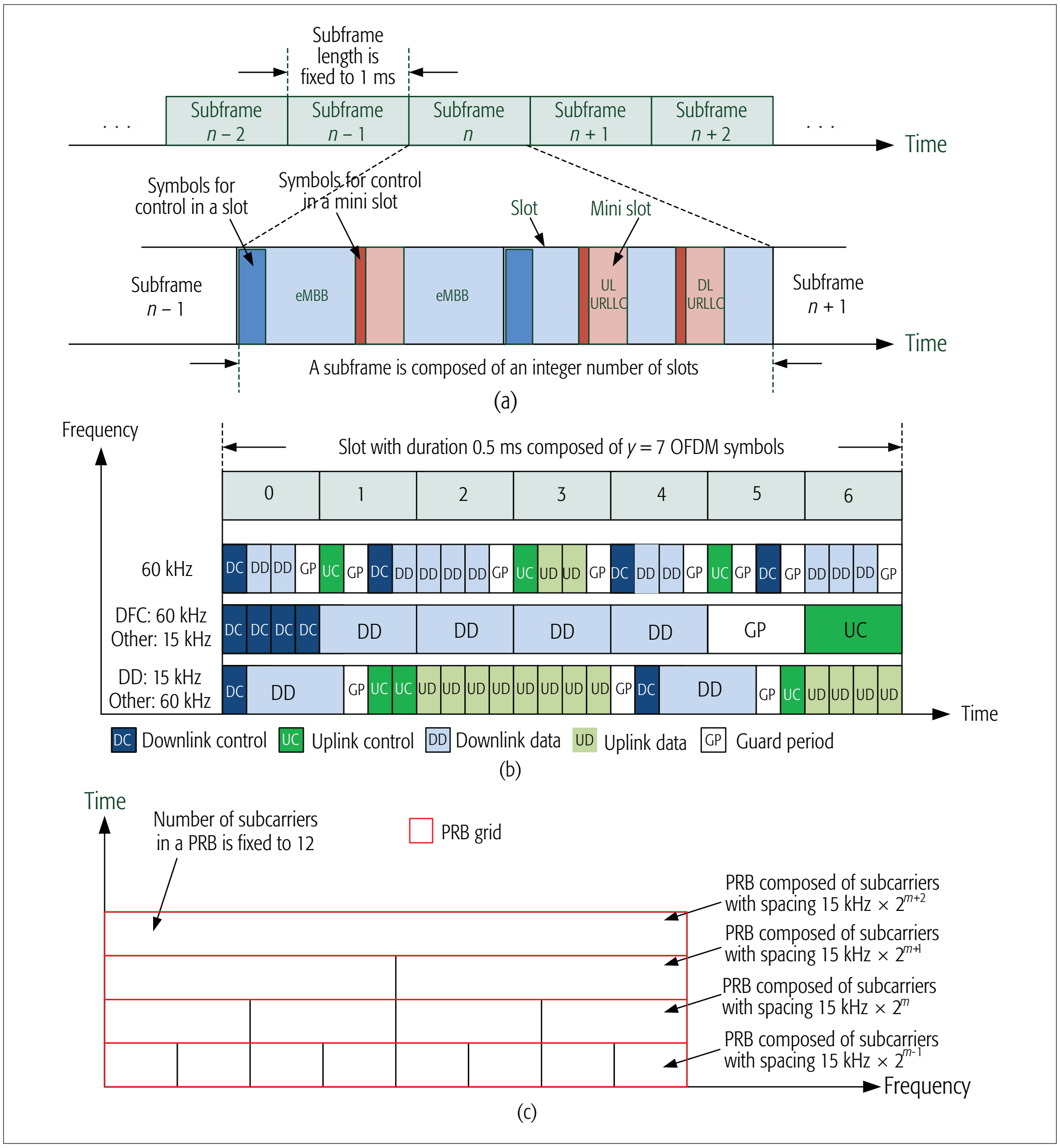

Figure 2. Frame structure of NR.

ings, orthogonal frequency-division multiplexing (OFDM) symbol durations, CP lengths, and so on. These physical transmission parameters are collectively referred to as *numerologies* in NR.

Numerologies of NR

In NR, transmitters and receivers may enjoy a wider bandwidth at high frequency bands. In this case, the subcarrier spacing can be extended (larger than 15 kHz as adopted by LTE/LTE-A, and potentially up to 960 kHz). In addition, high carrier frequencies are also vulnerable to the Doppler effect, and a large subcarrier spacing may facilitate inter-carrier interference (ICI) mitigation. On the other hand, NR should also support a small subcarrier spacing, such as 3.75 kHz as supported by narrowband Internet of Things (NB-IoT) [3], to enjoy better power efficiency at low frequency bands. Consequently, subcarrier spacings in NR are scalable as a subset or superset of 15 kHz. Feasible subcarrier spacings can be 15 kHz × 2m, where m can be a positive/negative integer or zero. For each subcarrier spacing value, multiple CP lengths can be inserted to adapt to different levels of inter-symbol interference (ISI) at different carrier frequencies and mobility.

Frame Structure of NR

In the time domain, the subframe length of NR is 1 ms, which is composed of 14 OFDM symbols using 15 kHz subcarrier spacing and normal CP. A subframe is composed of an integer number of slots, and each slot consists of 14 OFDM symbols. Each slot can carry control signals/channels at the beginning and/or ending OFDM symbol(s), as illustrated in Fig. 2a. This design enables a gNB to immediately allocate resources for URLLC when urgent data arrives. OFDM symbols in a slot are able to be all downlink, all uplink, or at least one downlink part and at least one uplink part. Therefore, the time-division multiplexing (TDM) scheme in NR is more flexible than that in LTE. To further support small size packet transmissions, mini-slots are additionally adopted in NR, where each mini-slot is composed of z < y OFDM symbols. Each mini-slot is also able to carry control signals/channels at the beginning and/or ending

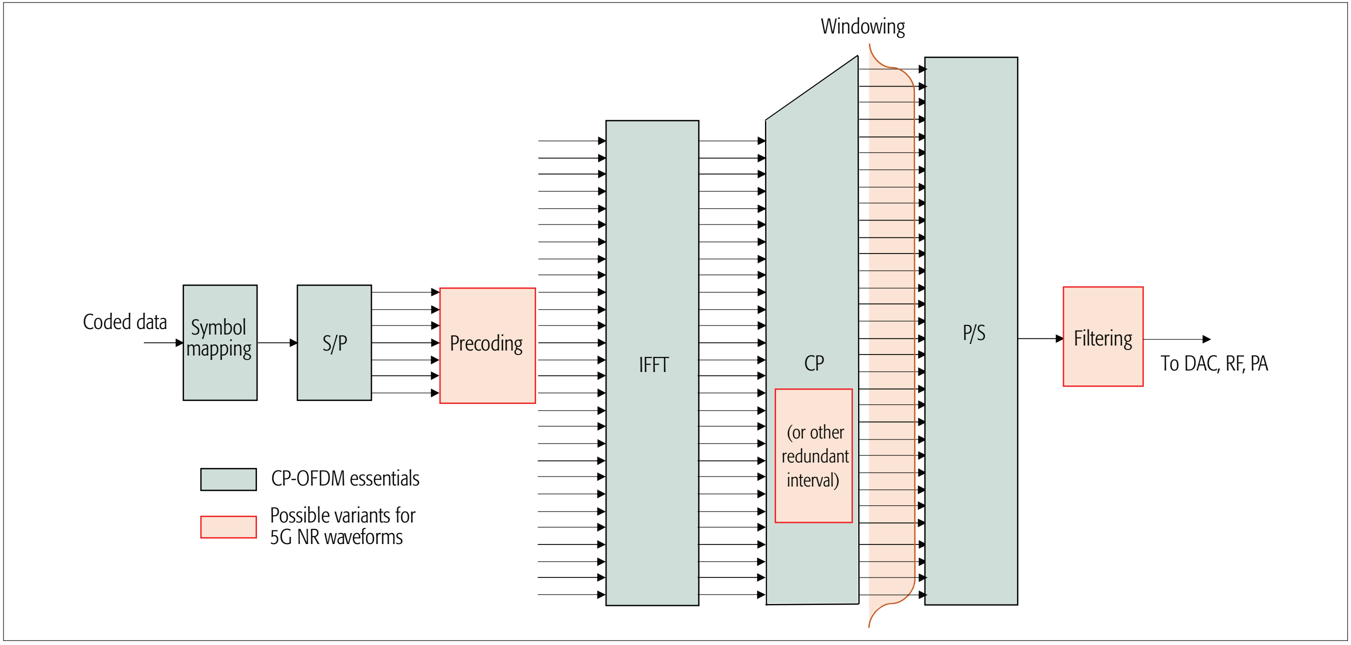

Figure 3. Transmitter structure of OFDM-based waveform for 5G NR.

OFDM symbol(s). A mini-slot is the minimum unit for resource allocation/scheduling.

In NR, different subcarrier spacings with the same CP overhead can be multiplexed within a subframe (Fig. 2b). To maintain 1 ms subframe length, there should be symbol boundary alignment within a subframe. For subcarrier spacing(s) larger than 15 kHz, the sum of these OFDM symbol durations (including CP length) should equal one symbol duration of 15 kHz subcarrier. On the other hand, the sum of OFDM symbol durations of 15 kHz subcarriers should equal one symbol duration of subcarrier spacing smaller than 15 kHz.

In the frequency domain, the basic scheduling unit in NR is a physical resource block (PRB), which is composed of 12 subcarriers. All subcarriers within a PRB are of the same spacing and CP overhead. Since NR should support multiple subcarrier spacings, NR supports PRBs of different bandwidth ranges. When PRBs of different bandwidth ranges are multiplexed in the time domain, boundaries of PRBs should be aligned. For this purpose, multiple PRBs of the same bandwidth should form a PRB grid, as illustrated in Fig 2c. A PRB grid formed by subcarriers with spacing 15 kHz $\times$ 2m, where m is a positive (resp. negative) integer, should be a superset (resp. subset) of PRB grids formed by subcarriers with spacing 15 kHz.

New Waveform in NR

There have been considerable discussions on whether a new type of transmission waveforms, on top of the incumbent CP aided OFDM (CP-OFDM), shall be used in NR. Schemes alternative to conventional OFDM, including filterbank multicarrier (FBMC), generalized frequency-division multiplexing (GFDM), and so on, have been studied for years. Many of them called for advantages in terms of increase of bandwidth efficiency, relaxed synchronization requirements, reduced inter-user interference, and so on, but at the same time met challenges in increased transceiver complexity, difficulties in multiple-input multiple-output (MIMO) integration, and specification impacts.

OFDM-Based New Waveforms

OFDM is a mature technology broadly adopted in manifold products due to its several merits such as low complexity, easy integration with MIMO, plain channel estimation, and so on. It thus strongly motivates 5G NR still choosing OFDM as the basis of new waveform design. Distinct from OFDM, new waveforms usually possess additional functionalities to deal with two challenging but crucial issues.

Spectral Containment: One of the major desired properties is to offer enhanced spectral containment, that is, lowered out-of-band emission (OOBE). A waveform with low OOBE may provide the following virtues. First, as NR will support different numerologies, the interference incurred due to orthogonality loss might be severe, which, however, could be mitigated. Second, it is now possible to relax stringent synchronization requirements. This merit may facilitate grant-free asynchronous transmissions. In addition, bandwidth utilization might be much more efficient than that of LTE, since the amount of guard band would be greatly decreased.

Peak-to-Average Power Ratio (PAPR): Another major desired property is low PAPR, more specifically, the transmit signal quality under the consideration of power amplifier (PA) nonlinearity. OFDM modulation has been known to possess rather high PAPR, and demands large power backoff to maintain the operation in the PA linear region. This issue is especially important to uplink transmissions at high carrier frequencies, since the corresponding impacts on battery life and coverage of user equipment (UE) are quite noticeable. Handling high PAPR also results in spectral regrowth that deteriorates the expected spectral containment property [4].

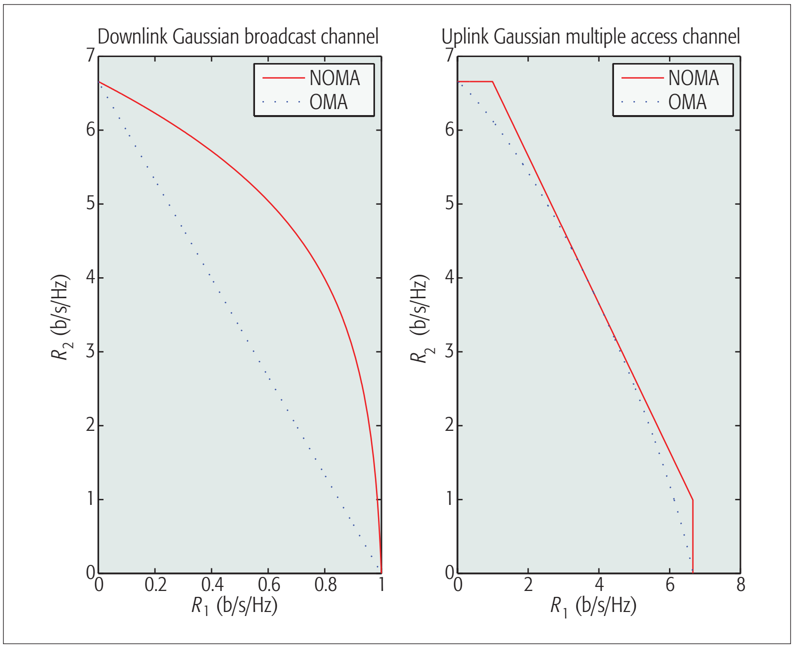

Figure 4. Capacity region examples for (left) downlink OMA and NOMA; (right) uplink OMA and NOMA.

Various Techniques in New Waveforms

Most waveforms studied by 3GPP for NR can be described as a special case, depicted in Fig. 3. Based on the inverse fast Fourier transform (IFFT) foundation, additional filtering, windowing, or precoding, are considered to achieve the desired enhancements.

Filtering: Filtering is a straightforward way to suppress OOBE by applying a digital filter with pre-specified frequency response. Candidate waveforms like filtered OFDM (f-OFDM) and universal filtered OFDM (UF-OFDM) belong to this category. However, the delay spread of the equivalent composite channel may eat up CP budget and guard period (GP) in time-division duplexing (TDD) mode, which leads to ISI and imposes burdens on downlink-to-uplink switch, respectively. Furthermore, the promised OOBE performance may degrade significantly when PA nonlinearity exists [4]. At the cost of increased PAPR, filtering techniques are generally known to be unfriendly to communication at high carrier frequencies.

Windowing: Windowing is to prevent steep changes between two OFDM symbols so as to confine OOBE. Multiplying the time domain samples residing in the extended symbol edges by raised-cosine coefficients (Fig. 3) is a widely used actualization as chosen by windowed OFDM (W-OFDM) and weighted overlap-and-add (WOLA) OFDM waveforms. This technique generally has little or no PAPR overhead and also lower complexity compared to that of filtering techniques. Nevertheless, the detection performance might be degraded because of ISI caused by symbol extension.

Precoding: A linear processing of input data before IFFT is usually known as precoding, and may be helpful to improve OOBE and PAPR. One representative example is discrete Fourier transform spread OFDM (DFT-S-OFDM) waveform that has been adopted in LTE uplink transmissions because of its low PAPR. Numerous variants of DFT-S-OFDM have been proposed for NR. Zero-tail (ZT) DFT-S-OFDM aims at omitting CP by letting the tail samples approximate to zero. Guard interval (GI) DFT-S-OFDM superposes a Zadoff-Chu sequence to the tail samples for synchronization purposes. Unique word (UW) DFT-S-OFDM replaces zeros in front of the DFT by certain fixed values to adaptively control waveform properties. On the other hand, single carrier circularly pulse shaped (SC-CPS) and generalized precoded OFDMA (GPO) waveforms use pre-specified frequency domain shaping after the DFT for further PAPR reduction at the cost of excess bandwidth. CPS-OFDM can be regarded as a generalized framework that flexibly supports multiple shaped subcarriers in a subband. DFT-S-OFDM-based waveforms, in contrast to filter-based waveforms, usually make it much easier to maintain PA linear operation with less deterioration from lowering OOBE. Moreover, an appropriate modification of modulation schemes, such as $p/2$ binary phase shift keyint (BPSK), can greatly assist such waveforms in achieving an extremely low PAPR. Note that in the absence of redundant intervals, ISI still occurs. From DFT-based precoding techniques, other types of precoding matrices often have undesirable complexity and compatibility issues.

Some performance comparisons of the aforementioned waveforms can be found in [5, 6, references therein].

Multiple Access in NR

Previous generations of communication standards rely on orthogonal multiple access (OMA). Each time/frequency resource block is exclusively assigned to one of the users to ensure no inter-user interference. Toward NR, synchronous/scheduling-based OMA continues to play an important role for both DL and UL transmissions.

Non-orthogonal multiple access (NOMA) transmission, which allows multiple users to share the same time/frequency resource, was recently proposed to enhance the system capacity and accommodate massive connectivity. Unlike OMA, multiple NOMA users' signals are multiplexed by using different power allocation coefficients or different signatures such as codebook/codeword, sequence, interleaver, and preamble.

The fundamental theory of NOMA has been intensively studied in network information theory for decades. Theoretically, uplink and downlink NOMA can be modeled as a multiple access channel (MAC) and a broadcast channel (BC), respectively, with the capacity region shown in Fig. 4. The capacity region of the Gaussian BC can be achieved by power domain superstition coding with a successive interference cancellation (SIC) receiver. Meanwhile, the capacity region of a Gaussian MAC corresponds to CDMA, where different codes are used for the different transmitters, and the receiver decodes them in an SIC manner.

In general, a weak user (i.e., a user with poor channel condition) tends to allocate more transmission power, so a weak user decodes its own messages by treating the co-scheduled user's signal as noise. On the other hand, a strong user (i.e., a user with better channel condition) applies the SIC strategy by first decoding the information of the weak user and then decoding its own, removing the other users' information. Recently, some works [7] also discuss the replacement of the SIC receiver from the theory and practice points of view. It is observed that using a non-SIC receiver results in negligible performance degradation in many cases (see TR 36.895). The removal of the SIC significantly decreases the burden of decoding for the downlink case as the others' codebooks are no longer required.

The possibility and feasibility of practicing the promised gains of downlink NOMA have drawn huge attention. In order to improve multi-user system capacity, 3GPP approved a study on downlink multiuser superposition transmission (MUST) for LTE in December 2014 to study NOMA [8] and other schemes based on superposition coding. Through extensive discussion in 2015 and 2016, the MUST schemes and corresponding LTE enhancements are identified through an assessment of feasibility and system-level performance evaluations, and are included in Release 14 standard.

Moving toward 5G, in addition to the orthogonal approach, NR targets supporting UL non-orthogonal transmission to provide the massive connectivity that is desperately required for applications in mMTC as well as other scenarios. During NR study, at least 15 companies (see TR 38.802) have evaluated grant-free UL multiple access schemes targeting at least mMTC. Due to no need for a dynamic and explicit scheduling grant from eNB, latency reduction and control signaling minimization could be expected.

For uplink NOMA, fundamental network information theory suggests that CDMA with a SIC receiver provides a capacity achieving scheme. However, securing uplink NOMA gain requires further system design enhancement. As the number of co-scheduled users becomes large, so does the decoding complexity of the SIC receiver. The message passing algorithm (MPA) [9], a more complexity-feasible decoding algorithm, as well as other low-complexity receiver designs have recently drawn attention. Along this research line, several code-spreading-based techniques, including sparse code multiple access (SCMA) [10], multi-user shard access (MUSA) [11], and pattern division multiple access (PDMA) [12], have recently been proposed. It has been shown that one can potentially achieve higher spectral efficiency, larger connectivity and better user fairness with NOMA.

Initial/Random Access and Enhanced CA

Initial/Random Access

When a UE powers on, it needs to search for a suitable cell to launch initial access and the RA procedure. In LTE/LTE-A, both non-contention-based and contention-based RA procedures are supported. For non-contention-based RA, the network semi-persistently allocates radio resources to a UE to deliver resource requests. For contention-based RA, LTE/LTE-A adopt a four-message exchange procedure (Fig. 5a). A UE randomly selects a preamble (known as message 1) and delivers the preamble to an eNB at a physical random access channel (PRACH). If multiple UEs select the same pre-

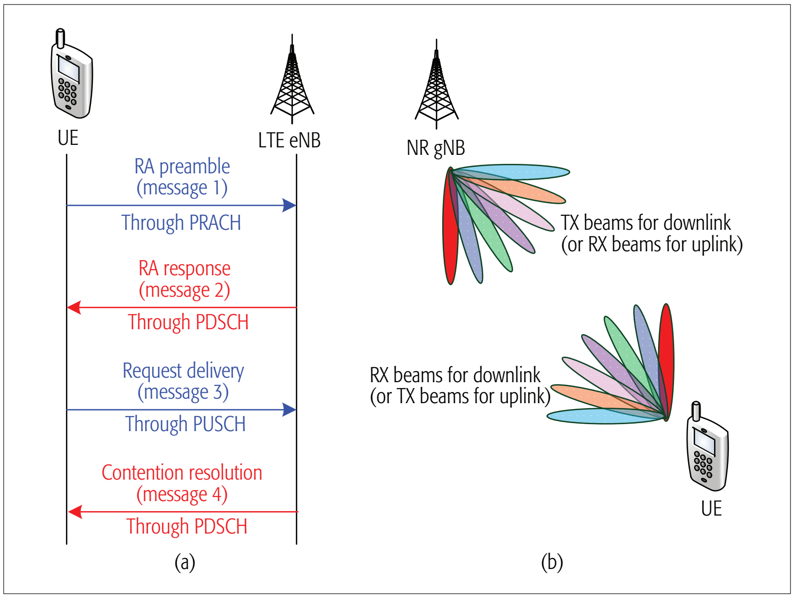

Figure 5. a) Contention-based RA procedure in LTE/LTE-A; b) in NR, beam steering should be performed in both the control and user planes.

amble, collision occurs. Upon receiving message 1, an eNB replies with message 2, carrying information on radio resources for UE to deliver the uplink transmission request. Upon receiving message 2, a UE sends the uplink transmission request (known as message 3) at the allocated radio resources. At this moment, an eNB is able to identify preamble collision. Then the eNB may reply with message 4 to grant/reject the resource request.

Although NR may enjoy wider bandwidth on frequency bands above 6 GHz, communications may suffer from severe path loss. Beamforming is thus an inevitable technology in NR in both the user and control planes, which can be performed at the transmitter side (known as TX beam) or receiver side (known as RX beam). Due to mobility, the locations of a transmitter and a receiver may change over time, and thus geographic space should be quantized into a number of directions. Both a transmitter and a receiver should sweep TX/RX beams over all directions to capture each other's location direction, which is known as *beam steering* (Fig. 5b).

For NR, PRACH beam direction is well known to a UE. A UE thus only needs to transmit message 1 toward the beam direction of a PRACH [13], but a gNB has to sweep an RX beam to receive message 1. A similar operation is also adopted when a gNB replies with message 2 to a UE. Then messages 3 and 4 can be exchanged via available directions derived from messages 1 and 2. For message 1 retransmission, NR should support a UE to increase TX power if the TX beam direction of a UE does not change, and the updated power level is determined based on the latest path loss estimation, which is known as "power ramping."

Beam steering may alleviate preamble collision, which motivates the two-message (two-step) RA procedure in NR, in which a UE sends data along with a preamble (message 1). Upon receiving the preamble, a gNB replies with message 2 to indicate successful/failed reception

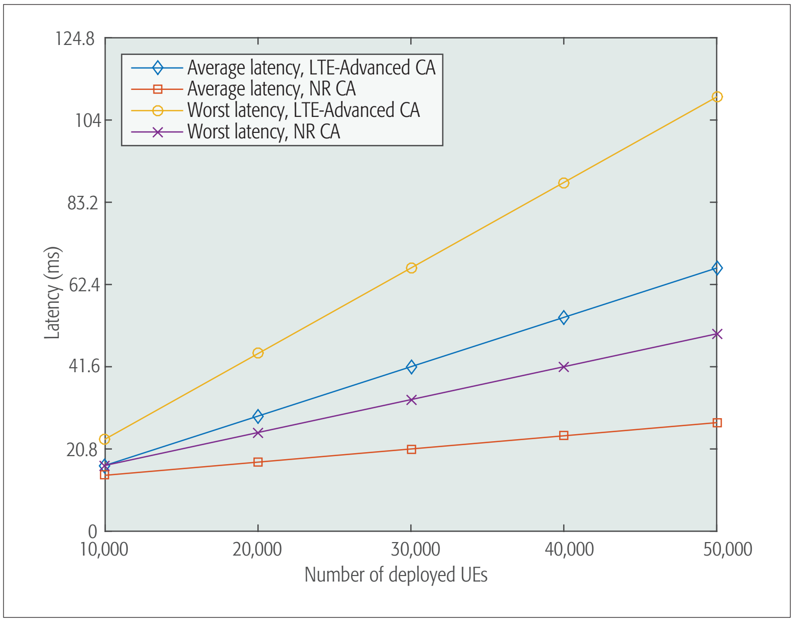

Figure 6. Simulation results of RA latency, where nine gNBs and a number of UEs are randomly deployed on a 500 × 500 × 10 m^3 area. The occasion of PRACH occurs every 1 ms, and 60 preamble sequences are available for UEs. The 3D channel model as per 3GPP TR 36.873 is adopted.

of data. Such two-message exchange RA is suitable for URLLC to reduce latency in uplink transmissions.

Enhanced CA for Resource Request and Data Transmissions

When uploading data arrives at a UE, the UE should perform the RA procedure to deliver a radio resource request to the network, but a resource request may be rejected when either the PRACH or the physical uplink shared channel (PUSCH) is congested. As previously mentioned, manifold wireless applications imposing different traffic characteristics (small size or large size data, infrequent or frequent transmissions, regular or irregular arrival, etc.) are expected to be supported by NR. These diverse traffic characteristics may lead to different levels of congestion on PRACH and PUSCH, which is a challenging issue in extending the system capacity to accommodate growing traffic volume. The major cause of this issue comes from the existing CA scheme in LTE-A, in which a UE can only send an RA preamble via PRACH offered by the primary cell (Pcell). If the RA procedure completes successfully, resources on a PUSCH could be allocated to the UE on the Pcell or secondary cell(s) (Scell(s)). In other words, resource accesses between PRACH and PUSCH are bound. Each UE is able to send resource requests through one Pcell only, and can only be served by PUSCH from the Pcell or a set of Scells associated with the Pcell. If either the PRACH or PUSCH is congested, the resource request is barred.

To tackle this issue, a promising solution is to forage an enhanced CA scheme, in which resource accesses between PRACH and PUSCH are not bound [14]. For a UE located at an overlapping area of multiple Pcells' coverage, a UE may dynamically select one Pcell enjoying a low congestion level to send resource requests. When a resource request is successfully delivered, any Scell/Pcell with a lower level of congestion can provide a PUSCH to serve the UE, to fully utilize both PRACH and PUSCH.

The RA latency performance of the enhanced CA in NR is evaluated in Fig. 6. Two kinds of RA latency are studied: average latency is defined by the average value over RA latency of all UEs, while worst cast latency is defined by the largest latency value among all UEs. From Fig. 6, both average latency and worst cast latency of enhanced CA in NR outperform that in the existing CA scheme in LTE-A. The latency performance falls on the order of 10 ms, which is applicable to the idle to connection latency requirement in NR.

Conclusion

In this article, foundations of radio access including deployment scenarios sustaining LTE/NR interworking, frame structure multiplexing multiple numerologies, DFT-S-OFDM- and CP-OFDM-based new waveforms, NOM-based multiple access, RA with beam steering, and enhanced CA for RA latency improvement are revealed. The insights provided thus boost knowledge not only for engineering practice but also for further technological designs. Nevertheless, NR is just at the beginning stage of development, and a number of issues and optimizations still remain open for further study.

Acknowledgment

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Biographies

Shao-Yu Lien was an assistant professor of the Department of Electronic Engineering, National Formosa University, Taiwan, starting in February 2013, where he has now been an associate professor since February 2016. He has received a number of prestigious research recognitions, including the IEEE Communications Society Asia-Pacific Outstanding Paper Award 2014, Scopus Young Researcher Award (issued by Elsevier) 2014, URSI AP-RASC 2013 Young Scientist Award, and IEEE ICC 2010 Best Paper Award. His research interests include LTE Pro, 5G New Radio, cyber-physical systems, and configurable networks.

Shin-Lin Shieh received his B.Sc. and M.Sc. degrees in electrical engineering from National Tsinghua University, Hsinchu, Taiwan, in 1999 and 2001, respectively, and a Ph.D. degree from the Department of Communications Engineering of National Chiao-Tung University, Hsinchu, Taiwan. In August 2010, he joined the Department of Communication Engineering at National Taipei University, Taiwan, where he has now been an associate professor since February 2017. He is currently a 3GPP standardization delegate of the Industrial Technology Research Institute (ITRI).

Yenming Huang is currently pursuing a Ph.D. degree in communication engineering at National Taiwan University (NTU). Since October 2014, he has been involved in a MediaTek-NTU cooperation project on designing non-orthogonal multicarrier modulation and multiple access, and has participated actively in 3GPP 5G New Radio standardization. His current research interests are mainly in signal processing for communications, including waveform design, transceiver optimization, and coexistence issues on heterogeneous systems.

Borching Su received his B.S. and M.S. degrees in electrical engineering and communication engineering, both from NTU, in 1999 and 2001, respectively, and his Ph.D. degree in electrical engineering from the California Institute of Technology, Pasadena, in 2008. He joined NTU in 2009. His research interests include signal processing for communication systems, particularly waveform and beamforming designs for next-generation communication systems.

Yung-Lin Hsu is a Ph.D student at the Graduate Institute Communication Engineering, NTU. He received his M.S. degree from the Department of Communications, Navigation and Control Engineering, National Taiwan Ocean University. His research interests include wireless communications and OFDM techniques. He currently focuses on 5G initial access and vehicular communications.

Hung-Yu Wei received his B.S. degree in electrical engineering from NTU. He received his M.S. and Ph.D. degrees in electrical engineering from Columbia University. He was a summer intern at Telcordia Applied Research in 2000 and 2001. He was with NEC Labs America from 2003 to 2005. He joined NTU in 2005. He is currently a professor with the Department of Electrical Engineering and Graduate Institute of Communication Engineering at NTU. His research interests include broadband wireless, vehicular networking, IoT, and game theoretic models for networking. He actively participates in wireless communications standardization activities. He was the recipient of the K. T. Li Young Researcher Award from ACM Taipei Chapter and IICM in 2012, CIEE Excellent Young Engineer Award in 2014, and the NTU Excellent Teaching Award in 2008. He also received the Wu Ta You Memorial Award from the Ministry of Science and Technology in 2015. Currently, he is the Chair of the IEEE VTS Taipei Chapter.