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Waveform and Scheduling Requests for 3GPP New Radio (NR) Uplink

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I. Waveform for NR Uplink (UL)

Motivation:

- UL Waveform must be power efficient (low PAPR/Cubic Metric)
- UL Waveform must offer long battery life (for MTC devices > 10 years)
- UL Waveform must offer robust performance and sufficiently high ACLR (low OOBE) with non-linear PAs
- For OFDM, per every one-dB reduction in PAPR, there is an increase on the order of 10% in PA efficiency [1]. This is significant to increase battery life for UL devices
- The above requirements offer a tough waveform design challenge

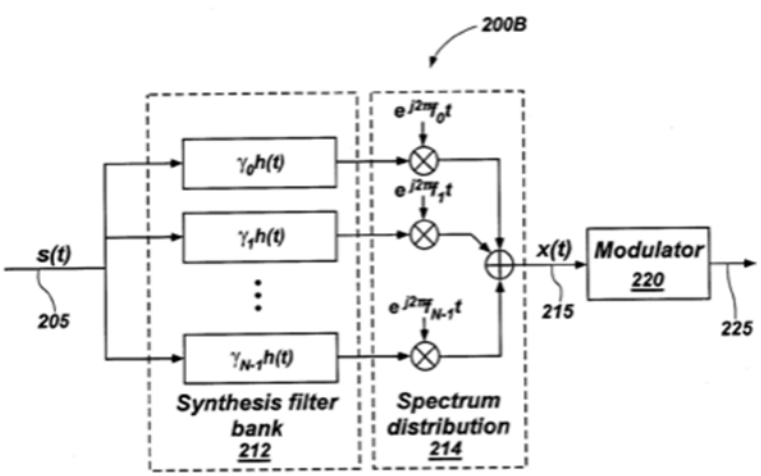
I. Waveform for NR UL (2)

- LTE already uses DFT-S-OFDM (SC-FDMA) with rectangular pulse shaping to reduce PAPR on the UL
- Consider a variant of DFT-S-OFDM with spectrum shaping to further reduce PAPR
- Spectrum shaping in frequency domain is equivalent to Circular Convolution in time domain → Single Carrier-Circularly Pulse Shaped Waveform

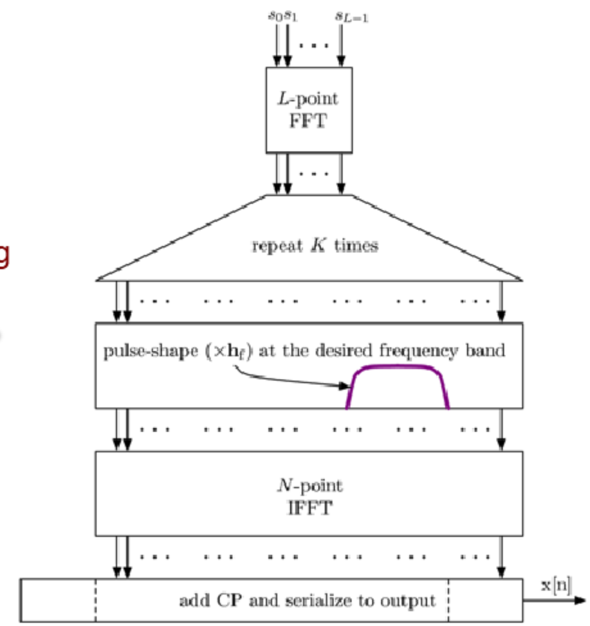
I. Waveform for NR UL (3)
INL's Technology Solves Practical Problems with Enhanced Solutions

INL's Contribution #1

- To address a Critical Requirements for Mission-critical and Smart Cities/IoT services
- Uses smart frequency-domain signal processing to lower the energy consumption by reducing out-of-band emissions and peak-to-average power ratio resulting in longer battery-life of the devices

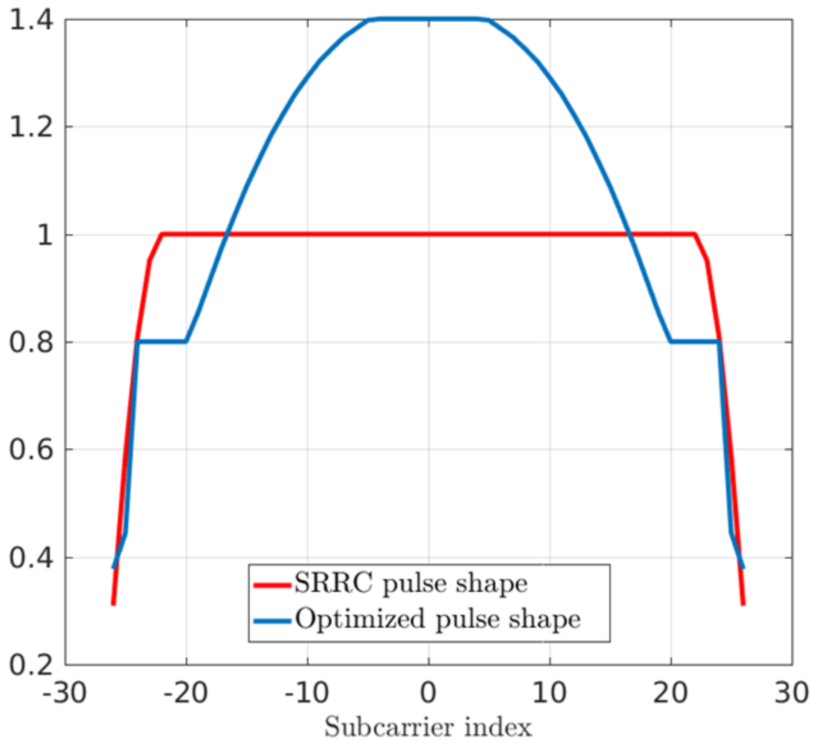


FB-MC-SS frequency-domain
Filtering helped develop
DFT-S-OFDM Signal processing

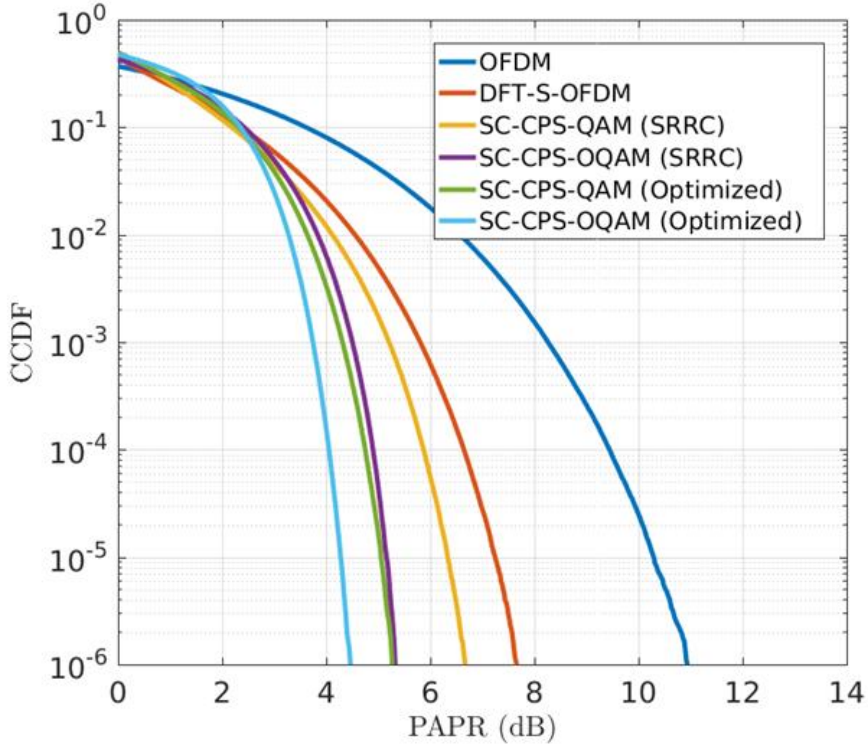


I. Waveform for NR UL (4)

SC-CPS PAPR results (see [3] for details)



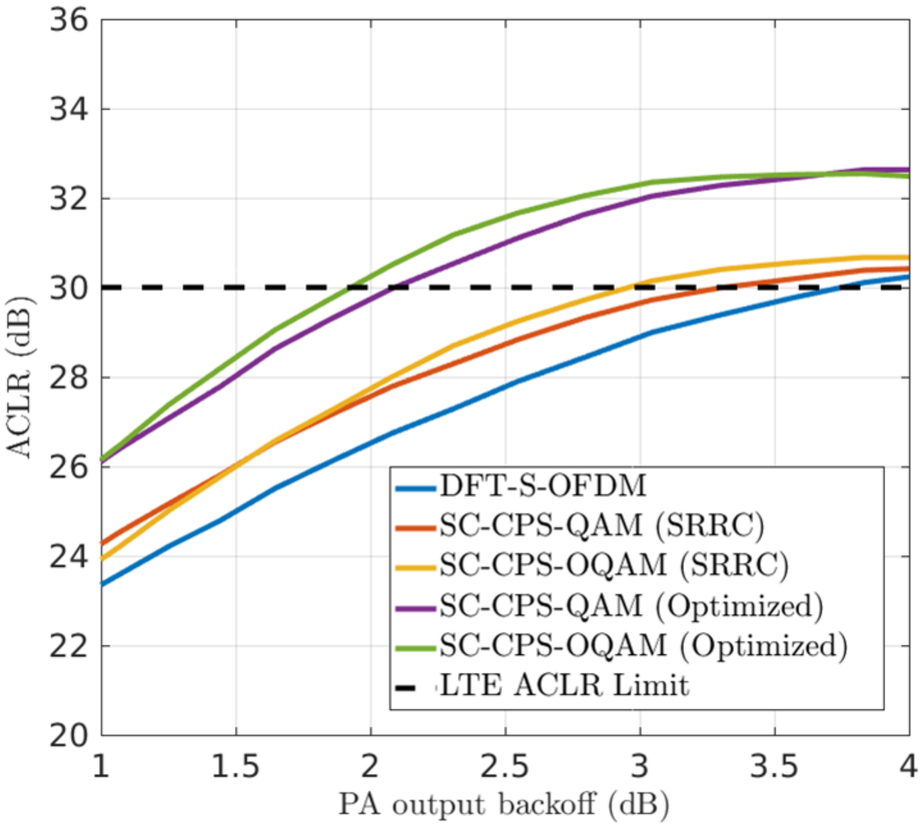
Optimum PAPR filter in the frequency domain for α = 0.1



PAPR results for QPSK

I. Waveform for NR UL (5)

SC-CPS ACLR results [3]



ACLR performance as a function of PA output backoff

🡐

With SC-CPS,PA can be operated closer to saturation while still meeting ACLR spec, thus improving efficiency and battery life

I. Waveform Summary

1) For QPSK modulation at CCDF = 1%, optimized SC-CPS waveform offers a 1.1 dB PAPR gain over the LTE UL baseline waveform, DFT-S-OFDM, with 0.3 dB additional gain possible through the use of O-QPSK for $\alpha = 0.1$. Additional PAPR gains can be obtained for larger α at the expense of higher excess bandwidth.

2) For the most robust modulation types (QPSK/O-QPSK) typically used for coverage-limited scenarios, SC-CPS waveforms offer at least a 0.5 dB CM advantage over DFT-S-OFDM, with a larger advantage with increasing excess bandwidth

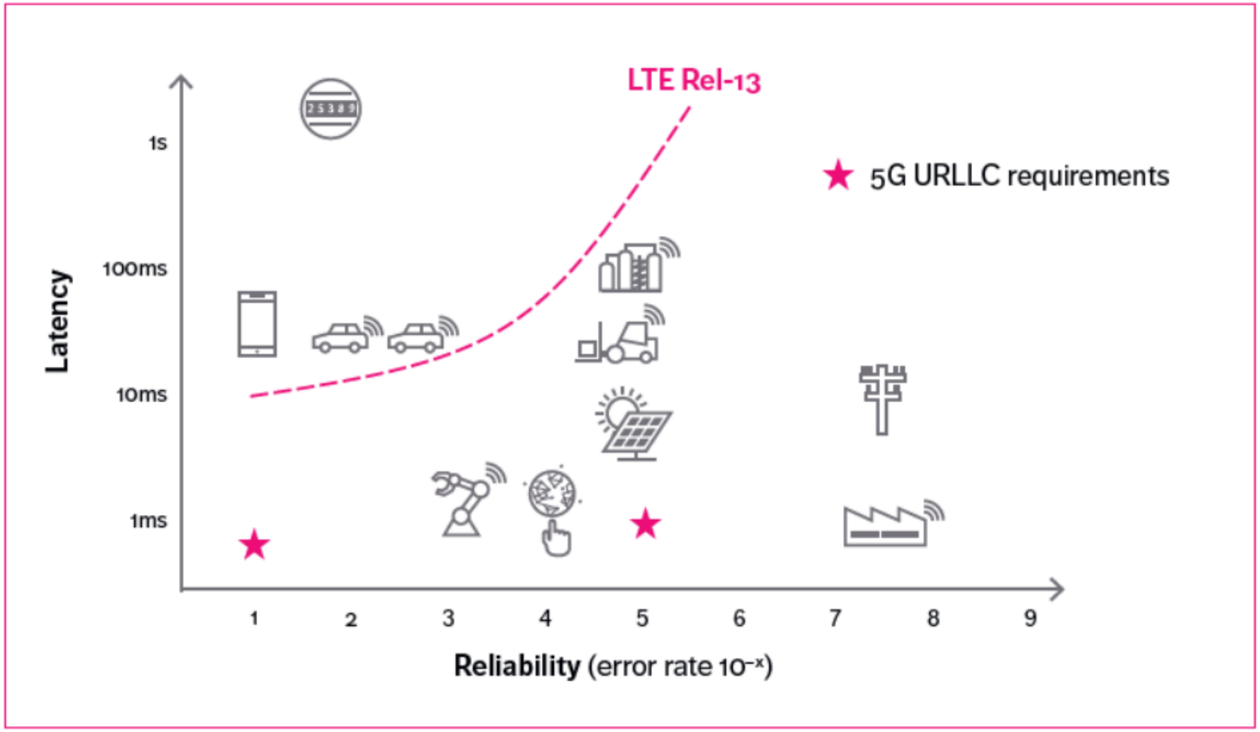
3) SC-CPS waveform, in addition to PAPR advantage, provide significant OOBE/ACLR benefits with respect to the LTE UL baseline waveform (DFT-S-OFDM) and allow for more efficient PA operation and longer battery life for devices at edge of coverage.

4) SC-CPS waveform is an option for NR UL

II. Uplink Scheduling Requests for NR

Motivation:

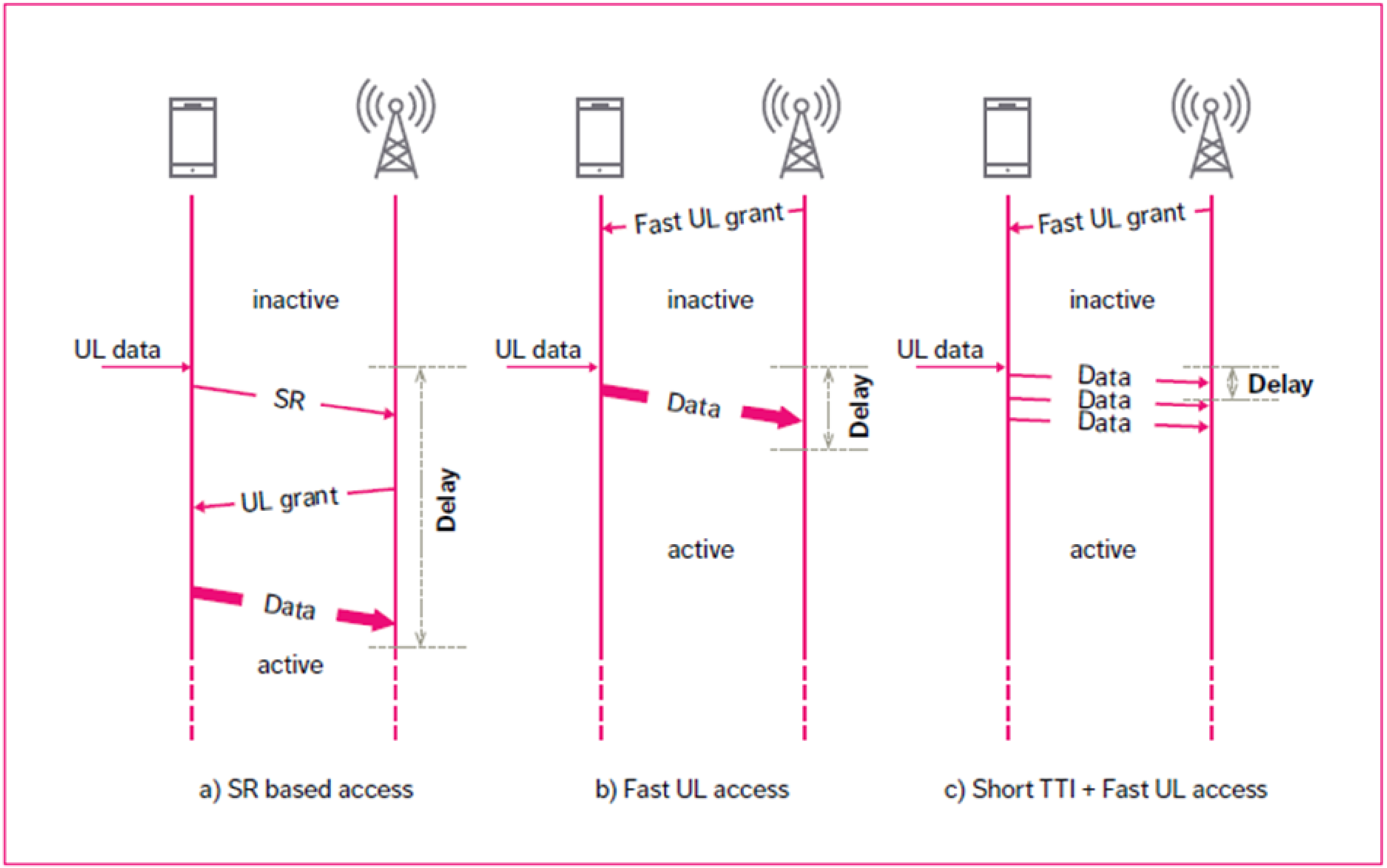
- Ultra-Reliable Low Latency Communications (URLLC) have stringent latency and reliability requirements [4], [5]
- Grant-based and Grant-free transmission options can be used to satisfy these requirements under a variety of conditions



URLLC Latency and Reliability requirement summary

II. UL SRs for NR (3)

UL Access Scheduling and Resource Grants [4]

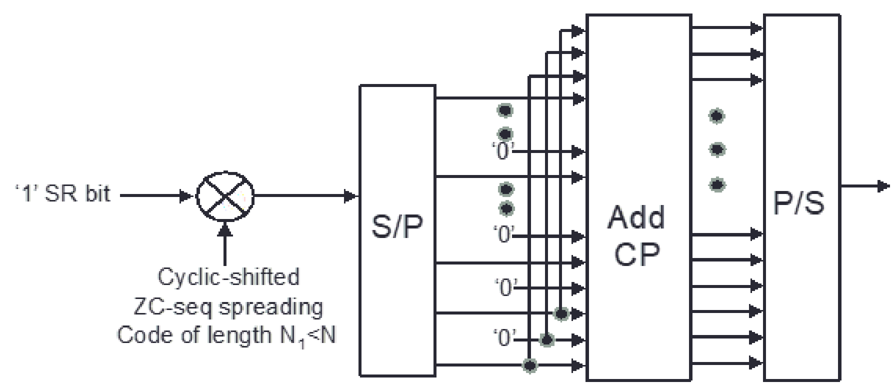


II. UL SRs for NR (3)

SR: one-bit signal from UE to eNB to request grant for UL transmission

LTE solution: SRs are transmitted based on a periodic method (wait time involved)

Underlay SR (USR) solution: SRs are transmitted over whole transmission bandwidth by spreading with known sequences and eliminating wait time [6]



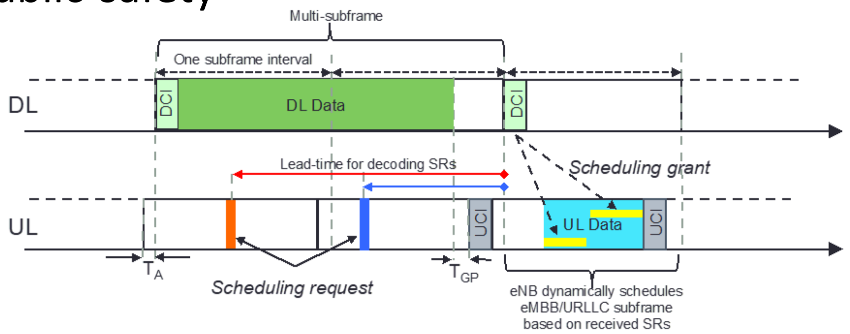
Generation of CP-assisted DSSS based scheduling request underlay signal

II. UL SRs for NR (4)

INL's Contribution #2

To address Ultra-Reliable Low Latency Communications (URLLC) Requirements for Robotics, Factory Automation, Public-safety Applications

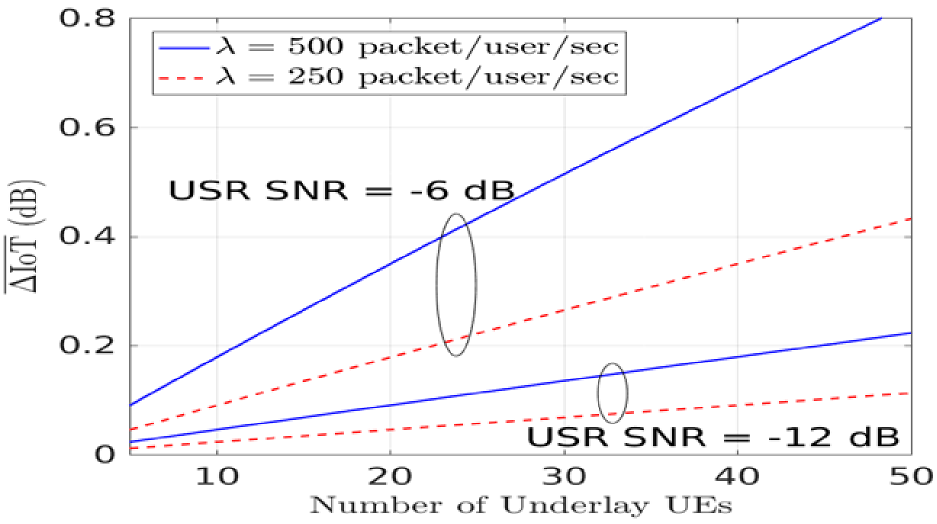
Description	Grant-based Case 'a' [6]	Advantage due to the Underlay SR based method
Average delay to next SR opportunity	125 µs	This delay is eliminated because the UE can transmit a SR almost immediately after the packet arrival
UE sends SR	17.84 µs	Both UE SR transmission and gNB decoding occurs in parallel (see Figure 2) resulting in no-delay from packet arrival at the UE to grant transmission by the gNB.
gNB decodes SR and generate grant	250 µs	
gNB sends grant	17.97 µs	17.97 µs
UE processing delay (decoding grant + encoding packet)	267.84 µs	267.84 µs
UL transmission	196.37 µs	196.37 µs
gNB decoding delay	150 µs	150 µs
Total	1025.02 µs	632.18 µs **Over 38% improvement!**

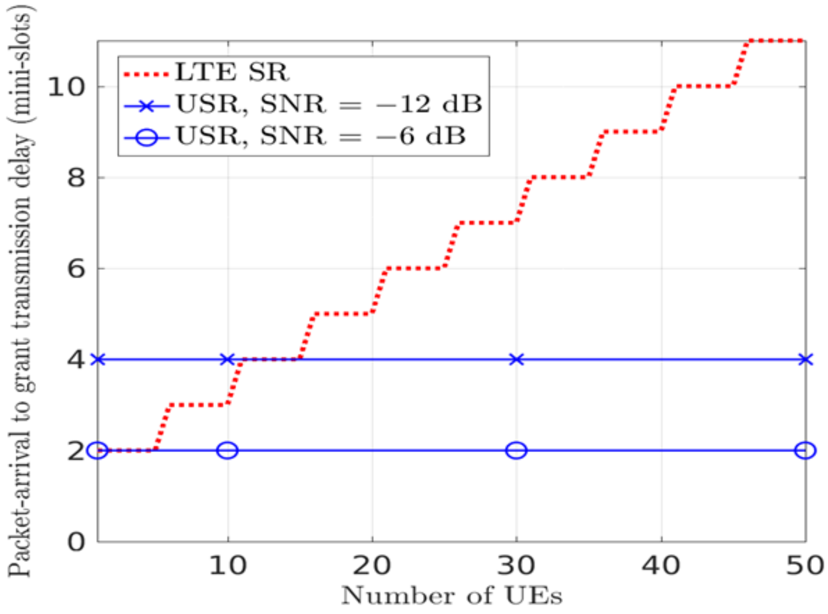


- INL's Underlay Control Channel (UCC) technology used to lower the uplink access latency without compromising the reliability of the wireless link. This is an essential aspect of URLLC applications
- Reliability (wrt to grant-free transmission) is increased because scheduling method is grant-based and SR signal has inherent diversity (DSSS over whole transmission band)

II. UL SRs for NR (5)

USR Performance [7]





Average IoT rise due to USR at the gNB receiver versus the number of UEs transmitting the underlay SRs

Packet-arrival to grant transmission by the gNB delay vs. the number of SR transmitting UEs for the LTE SR and the Underlay SR schemes

II. UL SR Summary

Category	PUCCH-based/LTE SR	Underlay SR
Wait time	Can be a significant part of overall delay	Wait time is eliminated
Delay granularity	Works with whatever granularity is chosen but remains fixed	Works with any chosen granularity (mini-slots, slots, sub-frames or multiple sub-frames) to adapt to transmission
Scheduler flexibility	Limited because efficiency is tied to SR period	High because scheduler can allocate resources much more efficiently due to the availability of longer lead times [5]
SR Resource Allocation	Needs time/frequency allocation as part of UL control channel (PUCCH)	Works over already allocated resources (i.e., no additional resources needed)
Implicit SR messaging	Not available	Available by assigning different SR codes for different traffic types resulting in reduction of message-exchange delay.

References

[1] S. Singh et al., "Effect of Peak-to-Average Power Ratio Reduction on the Multicarrier Communication System Performance Parameters," International Journal of Electrical and Electronics Engineering, January 2009, pp. 144-150.

[2] 3GPP R1-166494, "Low PAPR Single Carrier Circularly Pulse Shaped Waveform," Idaho National Laboratory, RAN1#86, Gothenburg, Sweden, August 2016.

[3] 3GPP R1-1608709, "Optimized PAPR/CM SC-CPS Waveform and Further Results," Idaho National Laboratory, RAN1#86bis, Lisbon, Portugal, October 2016.

[4] O. Teyeb et al., "Evolving LTE to fit the 5G Future," Ericsson Technology Review #1, January 31, 2017, pp. 1-16.

[5]3GPP R1-1704309, "SR grant-based transmission for eMBB/URLLC multiplexing in NR," Idaho National Laboratory, RAN1#88bis, Spokane, USA, April 2017.

[6] 3GPP R1-1701612, "Facilitating eMBB/URLLC UL Multiplexing with the Zero-wait-time Scheduling Request Underlay Channel," RAN1#88, Athens, Greece, February 2017.

[7] 3GPP R1-1710021, "Advantages of Underlay Scheduling Request method over PUCCH-based SR," RAN1 NR#2, Qingdao, China, June 2017.