**3GPP TSG-RAN WG1 #122 <TDoc Number>**

**Bengaluru, India, August 25th – 29th 2025**

**Source: Moderator (Nokia)**

**Title: Feature Lead summary #1 on 6G waveform**

**Document for: Discussion**

**Agenda item: 11.3.1**

**Work Item: FS\_6G\_Radio**

# Introduction

3GPP RAN1#122 saw 40 contributions submitted to agenda item 11.3.1 6G waveforms of which one appears to be out-of-place [20]. In addition one document was submitted to agenda item 11, but moved under this agenda item [41].

This document summarizes and organizes the range of proposals in the submitted contributions and acts as a platform to further facilitate the related discussion.

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|  | **Tdoc#** | **Title** | **Source** |
| [1] | [R1-2505127](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505127.zip) | Waveform for 6G Radio Air Interface | Nokia |
| [2] | [R1-2505156](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505156.zip) | Considerations for 6G Waveform | Kyocera Corporation |
| [3] | [R1-2505172](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505172.zip) | Discussion on waveform for 6GR | Spreadtrum, UNISOC |
| [4] | [R1-2505183](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505183.zip) | Waveform for 6GR air interface | Huawei, HiSilicon |
| [5] | [R1-2505264](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505264.zip) | Waveform for 6GR Air Interface | Google |
| [6] | [R1-2505308](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505308.zip) | Discussions on waveform for 6GR | CATT |
| [7] | [R1-2505416](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505416.zip) | Discussion on Waveform for 6GR air interface | vivo |
| [8] | [R1-2505463](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505463.zip) | On 6GR waveform | Xiaomi |
| [9] | [R1-2505474](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505474.zip) | Waveform consideration for 6GR air interface | NICT |
| [10] | [R1-2505480](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505480.zip) | Discussion on waveform for 6GR air interface | TCL |
| [11] | [R1-2505510](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505510.zip) | Views on the waveform for 6G | ZTE Corporation, Sanechips |
| [12] | [R1-2505520](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505520.zip) | On 6G waveforms | Ericsson |
| [13] | [R1-2505584](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505584.zip) | Discussion on waveform for 6GR | Samsung |
| [14] | [R1-2505629](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505629.zip) | From Evolution to Revolution in 6G Waveforms using Zak-OTFS | Cohere Technologies |
| [15] | [R1-2505633](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505633.zip) | Waveform design | Tejas Network Limited |
| [16] | [R1-2505640](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505640.zip) | Discussion on 6G Waveform | NEC |
| [17] | [R1-2505649](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505649.zip) | Discussion on waveform for 6GR air interface | Pengcheng Laboratory |
| [18] | [R1-2505675](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505675.zip) | Discussion on waveform for 6GR air interface | Ofinno |
| [19] | [R1-2505679](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505679.zip) | Study on Waveform Enhancements | IITH and WiSig |
| [20] | [R1-2505680](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505680.zip) | Uplink Control Channel Enhancements for 6G NR | IITH and WiSig |
| [21] | [R1-2505702](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505702.zip) | Discussion on waveform for 6GR air interface | Panasonic |
| [22] | [R1-2505757](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505757.zip) | Discussion on waveform and multiple access for 6G Radio | OPPO |
| [23] | [R1-2505770](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505770.zip) | Discussions on waveform for 6G radio | Intel |
| [24] | [R1-2505781](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505781.zip) | On Waveform Considerations for 6GR Air Interface | Lekha Wireless Solutions |
| [25] | [R1-2505787](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505787.zip) | Discussion on waveform for 6GR | LG Electronics |
| [26] | [R1-2505792](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505792.zip) | Discussion on 6GR Waveform | Lenovo |
| [27] | [R1-2505827](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505827.zip) | Waveform for 6GR air interface | InterDigital, Inc. |
| [28] | [R1-2505913](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505913.zip) | Waveforms for 6GR air interface | Apple |
| [29] | [R1-2506020](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2506020.zip) | Waveform for 6GR air interface | MediaTek Inc. |
| [30] | [R1-2506065](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2506065.zip) | Discussion on 6GR waveform | ETRI, University of Surrey |
| [31] | [R1-2506097](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2506097.zip) | Discussion on the waveform design for 6G radio | CMCC |
| [32] | [R1-2506117](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2506117.zip) | Considerations for 6GR waveform | Sony |
| [33] | [R1-2506140](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2506140.zip) | Discussion on Waveforms of 6GR Air Interface | Rakuten Mobile, Inc |
| [34] | [R1-2506218](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2506218.zip) | Waveforms for 6GR | Qualcomm Incorporated |
| [35] | [R1-2506239](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2506239.zip) | Requirements for 6GR Waveform Design | AT&T |
| [36] | [R1-2506268](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2506268.zip) | Study on waveform for 6GR | Sharp |
| [37] | [R1-2506306](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2506306.zip) | Discussion on Waveform | NTT DOCOMO, INC. |
| [38] | [R1-2506320](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2506320.zip) | Discussion on Waveform for 6GR Air Interface | Indian Institute of Tech (M), IIT Kanpur, CEWiT |
| [39] | [R1-2506333](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2506333.zip) | Orthogonal Sequence Division Multiplexing for 6GR | Anemone Technology |
| [40] | [R1-2506359](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2506359.zip) | Waveform design for 6G | CEWiT, IITM, Tejas, IITK |
| [41] | [R1-2506383](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2506383.zip) | 6G Waveform Study considerations | Reliance Jio |

# Proposed technologies

## Requirements for the waveform study

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| Kyocera | **Proposal 1:** If 5G NR waveforms are to be reused for 6G, we need a description of the enhancements needed to meet 6G requirements (e.g., IMT-2030 targets) with their performance improvement in given scenarios and added complexity.  **Proposal 2:** If new waveforms are to be considered/adopted for some scenarios, describe the new waveforms and performance advantages in those scenarios as well as the additional complexity wrt to 5G waveforms addressing coexistence/backward compatibility issues. Any decision on waveform coexistence should consider how widespread very high mobility deployments are. |
| Spreadtrum | **Proposal 4:** New OFDM-based waveform other than CP-OFDM and DFT-s-OFDM for 6GR communication can be considered only if enough performance gain is justified together with comprehensive implementation evaluation, e.g., compatibility, complexity, and specification impact. |
| Google | **Proposal 1:** The 6G waveform should be compatible with the CP-OFDM waveform with regard to MRSS.  **Proposal 2:** To maintain the same coverage for FR1 and FR3, low PAPR waveform for both DL and UL should be considered. |
| ZTE | **Proposal-1:** For 6G waveform design, the following targets should be considered:   * OFDM-based waveform with better performance, e.g., improved coverage and throughput * Unified waveform design to support multiple scenarios and needs, e.g., ISAC and other scenarios (e.g., high-mobility scenarios) |
| Tejas | **Proposal 1:** Study various waveforms beyond OFDM to support the KPI and use cases defined for 6G-R.  **Proposal 3:** OFDM should be supported as a baseline, and its advanced variants (e.g., CEOFDM, FM-OFDM, enhanced DFT-s-OFDM, BS-OFDM) need to be considered for further study as waveform candidates for 6G-R. |
| NEC | **Proposal 2:** 6GR strives for a unified waveform baseband generation and upconversion for all channels and signals including PRACH. |
| Pengcheng Laboratory | **Proposal 1**: Waveform design for 6GR should account for Inter-Symbol-and-Carrier Interference (ISCI) in high mobility scenarios to maintain reliable communication and sensing performance.  **Proposal 2**: A unified waveform design framework would be beneficial to simultaneously support communication and sensing functionalities (ranging/velocity estimation/imaging) in 6G systems. |
| IITH | **Proposal 3.** Codify single-symbol operation: normative intra-symbol DMRS formats, CP options, and scheduler hooks for one-shot transmissions. |
| Panasonic | **Proposal 1:** 6GR should allow certain time / frequency resources can be different waveform for forward compatibility perspective and to support MRSS.  **Proposal 2:** For 6GR waveform design, time/frequency grid should be allowed to be aligned and orthogonal with NR boundary.  **Proposal 3:** OFDM-based waveform should be supported for 6GR. The definition of “OFDM-based” is to have subcarrier mapping and IFFT to generate time-domain signal.  **Proposal 4:** To have multiple waveforms should be considered to satisfy diverse requirements of 6GR.  **Proposal 6:** Any enhancements to CP-OFDM or DFT-s-OFDM and/or any newly introduced waveform must demonstrate clear and justified advantages over 5G waveform. |
| OPPO | **Proposal 1**: A unified 6GR baseline waveform is studied to fulfil the requirements of 6G MBB (Immersive Communication) and 6G IoT (Massive Communication). The baseline waveform is used for 6G HRLLC.  **Proposal 2**: Study waveforms to fulfil the requirement of 6G Sensing and 6G NTN (Ubiquitous Connectivity). Strive for reusing the 6GR baseline waveform for 6G Sensing and 6G NTN. An additional waveform can be considered if significant gain over the baseline waveform can be justified for a specific vertical scenario, but only supported by the vertical BS/UE.  **Proposal 4:** For studying the 6GR baseline waveform, support up to 2 waveforms in DL and up to 2 waveforms in UL, e.g., one optimized for spectrum efficiency, one optimized for coverage. At least 1 waveform in DL and 1 waveform in UL are mandatory supported for all device types, e.g. CP-OFDM in DL and DFT-s-OFDM in UL. The 2nd waveform can be considered for 6G MBB s which shares the processing units with the 1st waveform as much as possible.  **Proposal 5:** Study multiple access (MA), targeting a single MA scheme for each waveform, to fulfil the requirement of all 6G usage scenarios using this waveform.  **Proposal 6:** Orthogonal multiple access (OMA) is the baseline for 6GR. Evaluate OMA proposals using 5G NR as the benchmark, with the consideration of following: Spectrum efficiency. Coverage. NW and UE side complexity. Compatibility and neutrality for proposals in other areas, i.e., no restriction to or bundling with specific proposals for 6G MIMO, modulation, channel coding, AI/ML enhancements, etc. Support flexible frequency-domain (e.g. RB-level) and time-domain (e.g. symbol-level) resource allocation. Support of efficient 5G/6G spectrum sharing. |
| LG Electronics | **Proposal 1:** Following principles form the foundation for the waveform study in 6GR and guide the evaluation of both continuity with 5G NR and the exploration of new waveform candidates.   * To ensure smooth evolution and coexistence with legacy networks, waveform design must maintain compatibility with 5G NR wherever possible. * Minimize complexity and support diverse 6G services such as TN/NTN integration, joint communication and sensing, and massive IoT. * Future enhancements or new signal/channel structures should avoid significant increases in implementation complexity to ensure broad feasibility and scalability. |
| Lenovo | **Proposal 1:** Study waveform enhancement techniques targeting 6GR coverage enhancement, energy efficiency improvement and support of sensing while maintaining compatibility with current waveforms’ structures, complexity constraints, and support of MRSS. |
| ETRI | **Proposal 1.** OFDM-based waveforms should be maintained as the baseline waveform candidate for 6G radio due to their maturity, ecosystem readiness, and easy migration from 5G  **Proposal 2.** RAN1 to investigate at least one additional waveform candidate alongside OFDM with the 6G Study Item.  **Proposal 3.** Any additional waveform considered should be closely related to OFDM waveform in structure and implementation, enabling smooth migration from existing NR designs and reuse of legacy HW. |
| CMCC | **Proposal 1.** A compatible waveform design suitable for a wide range or even full-range of target use cases is preferred, while the necessity of a specific design for some individual use case has to be carefully justified. |
| Rakuten | **Proposal 2:** For 6GR operating in the designated frequency ranges rather than FR1, any proposal involving a non-OFDM waveform must clearly justify the additional cost compared to OFDM and demonstrate ease of integration with multi-antenna technologies.  **Proposal 3:** 6GR should support optional pre-transformation techniques for peak-to-average power ratio (PAPR) reduction in uplink transmissions and also for downlink transmissions supported by space or airborne elements.   * For systems using the OFDM waveform, the legacy DFT-spread OFDM (DFT-s-OFDM) is proposed as a candidate. * If alternative waveforms are adopted for 6G, their PAPR characteristics must be thoroughly evaluated, and suitable pre-processing methods should be developed to achieve PAPR performance comparable to that of DFT-s-OFDM. |
| Ericsson | **Proposal 4:** Further study possible improvements to CP-OFDM and DFT-S-OFDM using 5G NR as a starting point. |
| Qualcomm | **Proposal 2:** Design considerations for 6G waveform study for communication purposes to include:   * new spectrum bands and associated requirements, e.g large BW * needs for new deployment scenarios, e.g. suburban macro, FWA, etc. * duplex operation, e.g., subband full duplex * enhancing coverage, e.g. design of low PAPR waveforms * Support for high power transmissions in uplink, e.g., higher power classes, MPR optimizations * integration with use cases such as sensing and positioning * Co-channel and adjacent channel requirements * Support for spatial multiplexing, beamforming, multiple access * Transceiver complexity associated with synthesis and reception; processing latency * Energy/power efficiency * Considerations on backward compatibility and coexistence with 5G * Scheduling flexibility and agility   **Proposal 3:** With backward compatibility, scalability, and flexibility in mind, and to leverage technologies and solutions developed for 5G, it is suggested that the 6G waveform study focus on the CP-OFDM and the DFT-S-OFDM family of waveforms. Potential enhancements or new waveform families must be compatible with the CP-OFDM framework, i.e., support time & frequency multiplexing with baseline waveforms & facilitate hardware reuse. |
| AT&T | **Proposal 1** The full capability of 6GR is realized with radio refresh in existing bands or in new greenfield bands while 6G deployment with existing open radios in legacy bands leveraging efficient 5G-6G MRSS is also possible.  **Proposal 2** After network attach, through RRC (re)configuration, novel air interface designs can be considered, as long as coexistence with the OFDM time-frequency grid as specified in 5G NR is ensured and the enhancement over 5G NR addresses an urgent, real-world need in a particular deployment or scenario. |
| Sharp | **Proposal 4:** To avoid excessive configurations, excessive UE capabilities and UE capabilities reporting, 6G waveforms should be applied to diverse use cases/device types. |
| NTT DOCOMO | **Proposal 1:** For 6GR study on waveform,   * Only OFDM-based waveform(s) should be considered (as described in the SID) * Any new waveform(s), even for OFDM-based, should be justified by clear gain * Unified design across scenarios/use cases is strongly preferred * Following the above, RAN1 can carefully assess the need in 6GR to introduce waveform(s) beyond 5G NR, targeting, e.g., PAPR performance improvement for better site coverage, especially for UL |
| IITM | **Proposal 4:** 3GPP should support multiplexing of waveforms as required. |
| Reliance Jio | **Proposal:** The new 6G Radio SI shall study possible new waveforms for multiple specific vertical use cases such as NTN, IoT, V2X, broadcast etc apart from eMBB. |

### Questions

Main observations from the companies’ proposals as requirements for the waveform to be selected for 6GR:

* OFDM-based waveforms (as described in the SID)
* MRSS compatibility
* Reuse of 5G NR waveforms, any new waveforms should be justified a clear benefit over those used in 5G NR
* Unified waveform vs. use-case specific waveforms with waveform multiplexing

Please add your company name in the list if you’d like to indicate support or no support for a particular question posed. Additional points can be added to the second table.

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| **Question 2.1** | **Support: Yes** | **Support: No** |
| Only OFDM-based waveforms should be considered for 6GR | Ofinno, CMCC, Google, Xiaomi, InterDigital, Fainity, QC, Nokia, OPPO, Samsung, Rakuten |  |
| MRSS compatibility should be a requirement on communication waveform candidates | Ofinno, CMCC, Google, InterDigital, Fainity, QC, Nokia, OPPO, Samsung, Rakuten |  |
| Waveforms other than those of 5G NR need to be justified with a clear benefit over those used in 5G NR | Ofinno, CMCC, Google, Xiaomi, InterDigital, Fainity, Sony, QC, Nokia, OPPO, Samsung, Rakuten |  |
| RAN1 should strive for unified communication waveform across all the identified use cases | Ofinno, CMCC, Google, Sony, QC, Nokia, OPPO, Samsung |  |

Additional comments

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| **Company** | **Comment** |
| CMCC | The waveform design for ISAC is preferred to be discussed in the agenda item of ISAC, as it involves too many sensing-specific requirements and technical details. This feature can focus on the waveform design for communication. |
| Xiaomi | For unified communication waveform, we think the OFDM based waveform is a good way forward for unification and this unification includes the applicability of DFT-S-OFDM waveform in downlink. Thus we prefer to elaborate the meaning of unified waveform as being OFDM based, i.e. the first point sufficient.  For MRSS, we believe DFT-S-OFDM waveform for DL requiring marginal or no hardware update is also a candidate fulfilling such requirement. Given people may confusion on whether this MRSS actually restricts DL waveform to CP-OFDM only or are open to OFDM based, we believe clarification is needed. |
| InterDigital | We should focus on communication related use cases only. Waveforms for sensing can be discussed after Q1 2026, as indicated in the Chairman’s schedule. For waveforms for sensing, the waveform for communication could be a starting point but different waveforms could be also studied to meet the sensing-specific requirements. |
| CEWiT | We prefer OFDM based waveform. Unified waveform for communication and sensing is not precluded, since this enables the usage of PRS for sensing. |
| Sony | A unified waveform ought to be friendly to ISAC, NTN and other use cases. We share Xiaomi’s assertion that MRSS can be ensured by other OFDM-based waveforms that are not necessarily CP-OFDM. |
| OPPO | Suggest focus on 6GR communication (MBB and IoT) usage scenarios for designing 6GR baseline waveform. 5G NR waveform should be considered for 6GR baseline waveform. The 6GR vertical waveform (Sensing, NTN) can be further studied in Agenda 11.12 and 11.14. Should strive for reusing the baseline waveform for Sensing, NTN. But study on Sensing-specific and NTN-specific can be studied, and can be considered if significant gain is justified. |
| Lenovo | The focus should be on communication waveform. The discussion on use-case specific waveforms, i.e. sensing can be carried out later aligned with the discussion of PHY aspects of sensing. |
| Rakuten | Regarding MRSS, we view that MRSS in FR1 is must while MRSS in other frequency ranges are optional. Therefore, we support using only 5G waveforms in FR1. |

## Waveform evaluation criteria

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| Spreadtrum | **Proposal 4:** New OFDM-based waveform other than CP-OFDM and DFT-s-OFDM for 6GR communication can be considered only if enough performance gain is justified together with comprehensive implementation evaluation, e.g., compatibility, complexity, and specification impact. |
| Huawei | **Proposal 4:** In evaluation of low PAPR waveform, the coverage gain should comprise of both Tx power gain and the potential required SNR loss/gain under same data rate/spectral efficiency and same occupied T/F resources.  **Proposal 5:** The Tx power gain evaluation should be based on PA model(s) and RF requirements, where the polynomial PA model in [3] and 5G FR1 RF requirements could be considered as a start point before any update from RAN4, or reported by companies. |
| Vivo | **Proposal 4:** Support DCM as a metric to evaluate power domain performance of 6GR waveform. |
| CATT | **Proposal 1:** Lower PAPR schemes shall be studied with considering following aspects in 6GR: Larger FFT size (e.g., from 4096 to 8192). Larger transmission channel bandwidth |
| Xiaomi | **Proposal 1:** The following net gain evaluation metric is used for 6GR OFDM based waveform determination and RAN1 shall liaise with RAN4, if necessary, on RF dependent net gain assessment to identify the 6GR waveform that is coverage beneficial. *Net Gain =* Δ𝑆𝑁𝑅 + Δ𝑃𝐴𝑃𝑅 |
| ZTE | **Proposal 8:** The following aspects are recommented to be considered for the 6G waveform evaluation:   * Performance metrics: PAPR, BLER, OOBE; * The PA modelling with more realistic assumption |
| Tejas | **Proposal 2:** We propose to adopt the KPIs — PAPR, pilot overhead, MRSS compatibility, computational complexity (transmit and receive), MIMO scalability and spatial diversity, spectral efficiency, robustness to multipath and Doppler, and OOB emissions — for evaluating 6G-R waveforms, and to provide a qualitative assessment of candidate waveforms, namely OFDM, FBMC, GFDM, AFDM, and OTFS, for further study. |
| IITH | **Proposal 5.** Develop mobility benchmark with per-symbol DMRS to benchmark high-Doppler performance. |
| OPPO | **Proposal 3:** For studying the 6GR baseline waveform, evaluate waveform proposals using 5G NR waveform (i.e. CP-OFDM for DL and CP-OFDM/DFT-s-OFDM for UL) as the benchmark, with the consideration of following: Spectrum efficiency. Coverage. NW and UE side complexity. Compatibility and neutrality for proposals in other areas, i.e., no restriction to or bundling with specific proposals for 6G MIMO, modulation, channel coding, AI/ML enhancements, etc. Support flexible frequency-domain (e.g. RB-level) and time-domain (e.g. symbol-level) resource allocation. Support of efficient 5G/6G spectrum sharing.  **Proposal 6:** Orthogonal multiple access (OMA) is the baseline for 6GR. Evaluate OMA proposals using 5G NR as the benchmark, with the consideration of following: Spectrum efficiency. Coverage. NW and UE side complexity. Compatibility and neutrality for proposals in other areas, i.e., no restriction to or bundling with specific proposals for 6G MIMO, modulation, channel coding, AI/ML enhancements, etc. Support flexible frequency-domain (e.g. RB-level) and time-domain (e.g. symbol-level) resource allocation. Support of efficient 5G/6G spectrum sharing. |
| Lekha | **Proposal 1:** Standardization of new spectrums for cellular and non-cellular deployments adds to issues like PA efficiency, phase noise, and high Doppler in traditional OFDM systems. As such, new waveforms are being considered, each of which comes with unique use-cases and benefits, hence requiring evaluation in various scenarios, keeping OFDM as baseline. |
| Lenovo | **Proposal 1:** Study waveform enhancement techniques targeting 6GR coverage enhancement, energy efficiency improvement and support of sensing while maintaining compatibility with current waveforms’ structures, complexity constraints, and support of MRSS. |
| Apple | **Proposal 1:** future low PAPR waveform evaluations should adopt a multi-dimensional metric framework centered on Net Gain, spectral compliance, and realistic RF and receiver assumptions. |
| ETRI | **Proposal 4.** RAN1 to consider the following criteria for 6GR waveform evaluation:   * Extensibility from OFDM waveform for ease of migration from 5G NR * Enough level of performance benefits for selected target use cases * Implementation complexity and power efficiency * Support for diverse deployment scenarios * Feasibility within 6G SI timeline |
| CMCC | **Proposal 2.** The following aspects need to be considered for the justification of PAPR reduction design:   * The PAPR reduction gain, for which PAPR, MPR, or other new metric (e.g., cubic metric) can be used. * Impact on signal quality, for which the degradation of e.g., EVM and/or link performance can be used. * Overhead, which can be represented as the percentage of the decreased data rate comparing to the case without the proposed PAPR reduction method. * Impacts on implementation, which is to identify the potential significantly increased complexity or big change to the conventional OFDM scheme. |
| Rakuten | **Proposal 3:** 6GR should support optional pre-transformation techniques for peak-to-average power ratio (PAPR) reduction in uplink transmissions and also for downlink transmissions supported by space or airborne elements.   * For systems using the OFDM waveform, the legacy DFT-spread OFDM (DFT-s-OFDM) is proposed as a candidate. * If alternative waveforms are adopted for 6G, their PAPR characteristics must be thoroughly evaluated, and suitable pre-processing methods should be developed to achieve PAPR performance comparable to that of DFT-s-OFDM. |
| Qualcomm | **Proposal 2:** Design considerations for 6G waveform study for communication purposes to include:   * new spectrum bands and associated requirements, e.g large BW * needs for new deployment scenarios, e.g. suburban macro, FWA, etc. * duplex operation, e.g., subband full duplex * enhancing coverage, e.g. design of low PAPR waveforms * Support for high power transmissions in uplink, e.g., higher power classes, MPR optimizations * integration with use cases such as sensing and positioning * Co-channel and adjacent channel requirements * Support for spatial multiplexing, beamforming, multiple access * Transceiver complexity associated with synthesis and reception; processing latency * Energy/power efficiency * Considerations on backward compatibility and coexistence with 5G * Scheduling flexibility and agility |
| Sharp | **Proposal 5:** RAN1 should study nonlinear PA effects.  **Proposal 6:** For FR2, RAN1 should study the phase noise effects.  **Proposal 7:** RAN1 should study phase noise effects under multiple phase noise models for diverse devices.  **Proposal 8:** RAN1 should study the doppler shift effects. |
| NTT DOCOMO | **Proposal 1:** For 6GR study on waveform,   * Only OFDM-based waveform(s) should be considered (as described in the SID) * Any new waveform(s), even for OFDM-based, should be justified by clear gain * Unified design across scenarios/use cases is strongly preferred * Following the above, RAN1 can carefully assess the need in 6GR to introduce waveform(s) beyond 5G NR, targeting, e.g., PAPR performance improvement for better site coverage, especially for UL |

### Questions

Main proposals for evaluation criteria, of which some are overlapping with each other.

* 5G NR CP-OFDM and DFT-s-OFDM as the benchmark
* Consider in the evaluation the following criteria
* MRSS compatibility
* Complexity
* Flexible frequency-domain and time-domain resource allocation
* Specification impact
* MIMO compatibility
* Spectral efficiency
* Coverage
* Pilot overhead
* Net Gain *=* Δ𝑆𝑁𝑅 + Δ𝑃𝐴𝑃𝑅
* PAPR
* Distortion Component Metric (DCM) for power domain performance
* EVM
* BLER
* Co-channel and adjacent channel requirements
* Phase noise
* Doppler
* Realistic PA model
* Larger FFT size
* Energy efficiency
* Sensing, positioning, NTN compatibility

Please add your company name in the list if you’d like to indicate support or no support for a particular question posed. Additional points can be added to the second table.

|  |  |  |
| --- | --- | --- |
| **Question 2.2** | **Support: Yes** | **Support: No** |
| **Which of the following criteria should be considered in the evaluation** |
| MRSS compatibility | CMCC, Google, Sony, QC, Nokia, OPPO, Samsung, Rakuten |  |
| Complexity | CMCC, Google,Sony, QC, Nokia, OPPO, Samsung |  |
| Flexible time and frequency domain resource allocation | InterDigital, QC, OPPO, Samsung |  |
| Specification impact | Samsung |  |
| MIMO compatibility | CMCC, InterDigital, Sony, QC, Nokia, OPPO, Samsung |  |
| Spectral efficiency | CMCC, InterDigital, Sony, QC, Nokia, OPPO, Samsung, Rakuten |  |
| Coverage | CMCC, Google, Sony, QC, Nokia, OPPO, Samsung, Rakuten |  |
| Pilot overhead | Sony, Nokia |  |
| Net Gain *=* Δ𝑆𝑁𝑅 + Δ𝑃𝐴𝑃𝑅 | Xiaomi, Sony, QC (replace Δ𝑃𝐴𝑃𝑅 with ΔPower) , Nokia, OPPO, Samsung |  |
| PAPR | CMCC, Google, InterDigital, Sony |  |
| Distortion Component Metric (DCM) |  |  |
| EVM | CMCC, QC, Nokia, Samsung |  |
| BLER | CMCC, InterDigital, QC, Nokia, OPPO, Samsung |  |
| Co-channel and adjacent channel requirements | Sony, QC, Samsung |  |
| Phase noise | Sony |  |
| Realistic PA model | CMCC, QC, Nokia, Samsung |  |
| FFT size |  |  |
| Energy efficiency | Sony, Nokia, Samsung |  |
| Sensing compatibility | Sony, Samsung |  |
| Positioning compatibility |  |  |
| NTN compatibility | Google, Xiaomi, Sony |  |

Additional comments

|  |  |
| --- | --- |
| **Company** | **Comment** |
| CMCC | The performance gain/loss only by link-level simulation may not be able to sufficiently reflect the signal distortion introduced by e.g. some PAPR reduction techniques. EVM can be considered as an complementary metric for the evaluation.  The BS/UE energy saving gain by PAPR reduction is unclear currently, especially for the case of BS. A proper PA model is expected to help understand the corresponding principle and realistic gain better. It is recommended to agree the PA model before studying the energy saving gain of PAPR reduction. |
| Google | A unified design for TN and NTN is important. We think the waveform should also consider NTN compatibility. |
| Xiaomi | OFDM based waveform such as DFT-S-OFDM for DL delivering joint system and link level coverage performance for NTN is preferred. |
| Sony | A unified design for TN, NTN and ISAC is important. We also think specification impact should be deprioritised as SID emphasises non-backward compatibility. |
| QC | For evaluation of low PAPR waveforms,  While PAPR can give us some initial indication, it is not a reliable metric. We need to consider the additional transmit power that a UE is able to realize and use it to determine the net gain. Suggest adopting an evaluation methodology similar to that adopted in R18 coverage enhancements. This may need some discussions with RAN4.  For initial evaluations, if PAPR is to be used as a guideline, we suggest not using the raw PAPR for a waveform, and instead consider the PAPR obtained after a CFR scheme is used. |
| OPPO | Trade-off between unified design and use case-specific design is always a challenge. We suggest to prioritize the need of mature scaled markets (i.e. MBB, IoT) in the first release of 6G. Sensing, NTN, positioning should not be considered for selecting the 6GR baseline waveform.  The evaluation of PARP reduction scheme should be clarified. If PAPR reduction is for coverage enhancement, the coverage KPI (e.g. BLER-SNR or 5% throughput) is more reasonable metric than PAPR/CM, and PAPR reduction should be compared with other coverage enhancement schemes. |
| Samsung | The waveform should be evaluated under realistic hardware impairments while ensuring compliance with RAN4 RF requirements such as ACLR, in-band emission, and EVM. |
| Lenovo | We agree with the listed evaluation criteria. In addition, some waveform enhancements depend on data characteristics, hence, require additional signalling. Signalling overhead/ signalling requirement should be considered in the evaluation. |

## CP-OFDM and/or DFT-s-OFDM for UL

|  |  |
| --- | --- |
| Nokia | **Proposal 2:** CP-OFDM and DFT-s-OFDM are the baseline waveforms for 6G uplink |
| Spreadtrum | **Proposal 1:** 5G NR Waveform should be adopted for 6GR waveform, including DL/UL CP-OFDM and UL DFT-s-OFDM. |
| Huawei | **Proposal 1:** As a waveform base, CP-OFDM waveform should be supported in 6GR for both downlink and uplink and DFT-s-OFDM waveform is also supported for uplink. |
| Google | **Proposal 3:** Study DFT-s-OFDM waveform for both uplink and downlink transmission. |
| CATT | **Proposal 2:** DFT-S-OFDM can be used on uplink channel, and the bandwidth of the uplink channel in terms of resource blocks should fulfill, where is a set of non-negative integers.  **Proposal 3:** The DFT-S-OFDM on RANK=2 transmission should be considered to reduce the PAPR in 6GR. |
| Vivo | **Proposal 1:** NR should be the baseline for general communication waveforms, i.e., DL: CP-OFDM UL: CP-OFDM, DFT-s-OFDM |
| ZTE | **Proposal 4:** DFT-s-OFDM with rank 2 for uplink transmission can be considered in 6G waveform study. |
| Ericsson | **Proposal 2:** Support NR-based CP-OFDM and NR-based DFT-S-OFDM for UL transmission for all ranks [and numerologies]. |
| Samsung | **Proposal 1:** OFDM shall be the baseline waveform for 6GR DL/UL with DFT-s-OFDM for the coverage-limited environments in UL. |
| Tejas | **Proposal 3:** OFDM should be supported as a baseline, and its advanced variants (e.g., CEOFDM, FM-OFDM, enhanced DFT-s-OFDM, BS-OFDM) need to be considered for further study as waveform candidates for 6G-R. |
| Ofinno | **Proposal 2:** Consider CP-OFDM and DFT-s-OFDM uplink transmission as baseline candidates for the evaluation of the waveform in 6GR. |
| NEC | **Proposal 1:** CP-OFDM and DFT-s-OFDM in NR are baseline as 6GR uplink waveform. 6GR could study to support dynamic waveform switching during initial access. |
| Panasonic | **Proposal 5:** At least to support CP-OFDM for higher spectral efficiency (for both DL and UL) and DFT-s-OFDM for coverage enhancement (for UL) can be baseline. |
| Intel | **Proposal 1:** For 6G waveform, at least for eMBB service: For DL transmissions, RAN1 to consider CP-OFDM waveform as baseline. For UL transmissions, RAN1 to consider both CP-OFDM and DFT-s-OFDM waveform as baseline |
| LG Electronics | **Proposal 2:** CP-OFDM for both downlink and uplink, and DFT-s-OFDM for uplink should be adopted for 6GR as baseline waveforms. |
| InterDigital | **Proposal 2:** DFT-s-OFDM and CP-OFDM are the baseline uplink waveforms for 6GR; support additional waveforms including a new waveform only if strong justifications can be demonstrated |
| MediaTek | **Proposal 1:** CP-OFDM to serve as the baseline waveform configuration within the 6G waveform framework.  **Proposal 2:** With DFT as a pre-coder, DFT-s-OFDM should be supported within the 6G waveform framework.  **Proposal 3:** For enhancement and optimization of a given 6G usage scenario, the corresponding waveform enhancement should consist of a scenario-dependent pre-coder followed by CP-OFDM, or more broadly, a concatenation of scenario- dependent coded modulation and CP-OFDM.  **Proposal 4**: Under the pre-coded CP-OFDM framework described in Proposal 3, study the low PAPR pre-coder design for coverage enhancement. |
| CMCC | **Proposal 4.** Both CP-OFDM and DFT-s-OFDM waveform are the baseline for the uplink waveform of 6G radio. |
| Sony | **Proposal 1:** RAN1 should study OFDM and DFT-s-OFDM as baseline waveforms for 6GR as well as at least OTFS and AFDM as candidate waveforms. In this study, RAN1 should consider the following criteria for assessing the waveforms:   * Ease of multiplexing users (in time, frequency and spatially), reference and other signals * Time and frequency offset sensitivity * PAPR * DMRS overhead requirement * Ease of implementation in 6G using 5G as baseline * Flexibility – numerology * ISAC amenability * Latency * Modulation complexity * Channel estimation complexity |
| Rakuten | **Proposal 1:** For 6GR operating in FR1, the OFDM is only one the waveform adopted, with subcarrier spacing options supported by 5G NR. Restrict the selection of subcarrier spacing configurations within each FR1 band to a limited set suitable for deployment to prevent undue complexity in the specifications.  **Proposal 3:** 6GR should support optional pre-transformation techniques for peak-to-average power ratio (PAPR) reduction in uplink transmissions and also for downlink transmissions supported by space or airborne elements.   * For systems using the OFDM waveform, the legacy DFT-spread OFDM (DFT-s-OFDM) is proposed as a candidate.   If alternative waveforms are adopted for 6G, their PAPR characteristics must be thoroughly evaluated, and suitable pre-processing methods should be developed to achieve PAPR performance comparable to that of DFT-s-OFDM. |
| Qualcomm | **Proposal 3:** With backward compatibility, scalability, and flexibility in mind, and to leverage technologies and solutions developed for 5G, it is suggested that the 6G waveform study focus on the CP-OFDM and the DFT-S-OFDM family of waveforms. Potential enhancements or new waveform families must be compatible with the CP-OFDM framework, i.e., support time & frequency multiplexing with baseline waveforms & facilitate hardware reuse.  **Proposal 6:** For 6G Radio, support multi-layer DFT-S-OFDM transmissions in uplink.  **Proposal 7:** For 6GR waveform study, for DFT-S-OFDM waveforms, decouple the size of allocation from the DFT size. Define any DFT size that is a product of powers of 2, 3 and 5 as a valid DFT size. For any given allocation, determine the actual DFT size to use as the nearest valid DFT size smaller than the size of allocation.  **Proposal 8:** For 6GR waveform study, when considering DFT-S-OFDM waveforms, consider flexible frequency-domain mapping of the DFT output to the spectrum allocation.  **Proposal 9:** For 6GR waveform study, consider multi-tx enhancements for DFT-S-OFDM where different transmit ports transmit over different frequency domain allocations. |
| Sharp | **Proposal 1:** RAN1 should study CP-OFDM for 6GR  **Proposal 2:** RAN1 should study DFT-s-OFDM for 6GR. |
| NTT DOCOMO | **Proposal 1:** For 6GR study on waveform,   * Only OFDM-based waveform(s) should be considered (as described in the SID) * Any new waveform(s), even for OFDM-based, should be justified by clear gain * Unified design across scenarios/use cases is strongly preferred * Following the above, RAN1 can carefully assess the need in 6GR to introduce waveform(s) beyond 5G NR, targeting, e.g., PAPR performance improvement for better site coverage, especially for UL |
| IITM | **Proposal 2:** 3GPP should consider the use of DFT-s-OFDM in DL/UL at least for NTN and FR2 use-cases. |

### Questions

A large number of companies suggest CP-OFDM and/or DFT-s-OFDM to be the baseline waveform(s) for 6GR uplink

Please add your company name in the list if you’d like to indicate support or no support for a particular question posed. Additional points can be added to the second table.

|  |  |  |
| --- | --- | --- |
| **Question 2.3** | **Support: Yes** | **Support: No** |
| CP-OFDM should be the only baseline waveform for 6GR for uplink |  | Ofinno, CMCC, Sony, QC, Nokia, OPPO, Samsung |
| DFT-s-OFDM should be the only baseline waveform for 6GR for uplink |  | Ofinno, CMCC, InterDigital, Sony, Nokia, OPPO, Samsung |
| Both CP-OFDM and DFT-s-OFDM should be baseline waveforms for 6GR for uplink | Ofinno, CMCC, Google, Xiaomi, InterDigital, Fainity, Sony, QC, Nokia, OPPO, Samsung, Rakuten |  |
| If DFT-s-OFDM is adopted, should it be extended to support >1 layers? | Ofinno, Google, Sony, QC | CMCC, Nokia, OPPO |

Additional comments

|  |  |
| --- | --- |
| **Company** | **Comment** |
| CMCC | The applicable scenarios/assumptions and the corresponding performance gain of multi-layer DFT-s-OFDM should be clearly clarified and justified. |
| CEWiT | Both CP-OFDM and DFT-s-OFDM should be considered for UL. |
| OPPO | We think 11.8 is a more proper agenda to discuss proposals for multi-layer DFT-s-OFDM. 5G NR DFT-s-OFDM is compatible for MIMO enhancement. We do see anything new on this aspect. |
| Samsung | Based on our study, DFT-s-OFDM offers most benefit in terms of UL coverage gain only for rank-1 and (albeit quite limited) rank-2. Since we expect that 6GR supports up to rank-8 for UL, we see no need for supporting DFT-s-OFDM for rank>2. |
| Lenovo | For UL, both CP-OFDM and DFT-s-OFDM should be considered |

## CP-OFDM for DL

|  |  |
| --- | --- |
| Nokia | **Proposal 1:** CP-OFDM is the waveform used for communication in 6G downlink |
| Spreadtrum | **Proposal 1:** 5G NR Waveform should be adopted for 6GR waveform, including DL/UL CP-OFDM and UL DFT-s-OFDM. |
| Huawei | **Proposal 1:** As a waveform base, CP-OFDM waveform should be supported in 6GR for both downlink and uplink and DFT-s-OFDM waveform is also supported for uplink. |
| Vivo | **Proposal 1:** NR should be the baseline for general communication waveforms, i.e., DL: CP-OFDM UL: CP-OFDM, DFT-s-OFDM |
| Ericsson | **Proposal 1:** Support NR-based CP-OFDM for DL transmission for all ranks [and numerologies]. |
| Samsung | **Proposal 1:** OFDM shall be the baseline waveform for 6GR DL/UL with DFT-s-OFDM for the coverage-limited environments in UL. |
| Tejas | **Proposal 3:** OFDM should be supported as a baseline, and its advanced variants (e.g., CEOFDM, FM-OFDM, enhanced DFT-s-OFDM, BS-OFDM) need to be considered for further study as waveform candidates for 6G-R. |
| Ofinno | **Proposal 1:** Consider CP-OFDM for downlink transmission as baseline candidate for the evaluation of the waveform in 6GR. |
| NEC | **Proposal 1:** CP-OFDM and DFT-s-OFDM in NR are baseline as 6GR uplink waveform. 6GR could study to support dynamic waveform switching during initial access. |
| Panasonic | **Proposal 5:** At least to support CP-OFDM for higher spectral efficiency (for both DL and UL) and DFT-s-OFDM for coverage enhancement (for UL) can be baseline. |
| Intel | **Proposal 1:** For 6G waveform, at least for eMBB service: For DL transmissions, RAN1 to consider CP-OFDM waveform as baseline. For UL transmissions, RAN1 to consider both CP-OFDM and DFT-s-OFDM waveform as baseline |
| LG Electronics | **Proposal 2:** CP-OFDM for both downlink and uplink, and DFT-s-OFDM for uplink should be adopted for 6GR as baseline waveforms. |
| InterDigital | **Proposal 1:** CP-OFDM is the baseline downlink waveform for 6GR; support additional waveforms including a new waveform only if strong justifications can be demonstrated |
| MediaTek | **Proposal 1:** CP-OFDM to serve as the baseline waveform configuration within the 6G waveform framework. |
| CMCC | **Proposal 3.** CP-OFDM is the baseline for the downlink waveform of 6G radio. |
| Sony | **Proposal 1:** RAN1 should study OFDM and DFT-s-OFDM as baseline waveforms for 6GR as well as at least OTFS and AFDM as candidate waveforms. In this study, RAN1 should consider the following criteria for assessing the waveforms:   * Ease of multiplexing users (in time, frequency and spatially), reference and other signals * Time and frequency offset sensitivity * PAPR * DMRS overhead requirement * Ease of implementation in 6G using 5G as baseline * Flexibility – numerology * ISAC amenability * Latency * Modulation complexity * Channel estimation complexity |
| Rakuten | **Proposal 1:** For 6GR operating in FR1, the OFDM is only one the waveform adopted, with subcarrier spacing options supported by 5G NR. Restrict the selection of subcarrier spacing configurations within each FR1 band to a limited set suitable for deployment to prevent undue complexity in the specifications. |
| Qualcomm | **Proposal 3:** With backward compatibility, scalability, and flexibility in mind, and to leverage technologies and solutions developed for 5G, it is suggested that the 6G waveform study focus on the CP-OFDM and the DFT-S-OFDM family of waveforms. Potential enhancements or new waveform families must be compatible with the CP-OFDM framework, i.e., support time & frequency multiplexing with baseline waveforms & facilitate hardware reuse. |
| Sharp | **Proposal 1:** RAN1 should study CP-OFDM for 6GR |
| NTT DOCOMO | **Proposal 1:** For 6GR study on waveform,   * Only OFDM-based waveform(s) should be considered (as described in the SID) * Any new waveform(s), even for OFDM-based, should be justified by clear gain * Unified design across scenarios/use cases is strongly preferred * Following the above, RAN1 can carefully assess the need in 6GR to introduce waveform(s) beyond 5G NR, targeting, e.g., PAPR performance improvement for better site coverage, especially for UL |

### Questions

A large number of companies suggest CP-OFDM to be a baseline waveform for 6GR downlink

Please add your company name in the list if you’d like to indicate support or no support for a particular question posed. Additional points can be added to the second table.

|  |  |  |
| --- | --- | --- |
| **Question 2.4** | **Support: Yes** | **Support: No** |
| CP-OFDM should be the baseline for 6GR waveform for downlink | Ofinno, CMCC, Google, InterDigital, Fainity, Sony, QC, Nokia, OPPO, Samsung, Rakuten |  |

Additional comments

|  |  |
| --- | --- |
| **Company** | **Comment** |
| Company A | Comment |
|  |  |
|  |  |

## DFT-s-OFDM for DL

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| --- | --- |
| Spreadtrum | **Proposal 2:** DL DFT-s-OFDM waveform should be supported for 6GR in day 1. |
| Huawei | **Proposal 2:** 6GR shall study lower PAPR DFT-s-OFDM waveform under different spectral efficiency for both downlink and uplink. |
| Google | **Proposal 3:** Study DFT-s-OFDM waveform for both uplink and downlink transmission. |
| Xiaomi | **Proposal 2:** To support the coverage performance for NTN DL, low-PAPR waveform such as DFTS-OFDM can be considered. |
| ZTE | **Proposal 7:** Study DFT-s-OFDM for downlink to generate pulse signals for large sensing coverage. |
| NEC | **Proposal 3**: Study the support of low PAPR waveforms like DFT-s-OFDM for 6G downlink transmissions.  **Proposal 4**: Study the waveform configuration mechanism. This study should evaluate the trade-offs between a fixed configuration per cell and semi-static DL waveform switching.  **Proposal 5** Study multi-user scheduling techniques for downlink DFT-s-OFDM to balance throughput with low-PAPR properties. |
| LG Electronics | **Proposal 3:** Low-PAPR waveform (e.g., DFT-s-OFDM) for DL transmission(s) can be studied as a candidate waveform in the 6GR study. |
| Lenovo | **Proposal 4:** Evaluate the feasibility of DFT-s-OFDM in DL for NTN and IoT use cases, focusing on coverage enhancement, NES, and UE power saving.  **Proposal 5:** The study and evaluation of waveform enhancements should focus on CM characteristic of the waveform. |
| MediaTek | **Proposal 2:** With DFT as a pre-coder, DFT-s-OFDM should be supported within the 6G waveform framework.  **Proposal 3:** For enhancement and optimization of a given 6G usage scenario, the corresponding waveform enhancement should consist of a scenario-dependent pre-coder followed by CP-OFDM, or more broadly, a concatenation of scenario- dependent coded modulation and CP-OFDM.  **Proposal 4**: Under the pre-coded CP-OFDM framework described in Proposal 3, study the low PAPR pre-coder design for coverage enhancement. |
| Sony | **Proposal 1:** RAN1 should study OFDM and DFT-s-OFDM as baseline waveforms for 6GR as well as at least OTFS and AFDM as candidate waveforms. In this study, RAN1 should consider the following criteria for assessing the waveforms:   * Ease of multiplexing users (in time, frequency and spatially), reference and other signals * Time and frequency offset sensitivity * PAPR * DMRS overhead requirement * Ease of implementation in 6G using 5G as baseline * Flexibility – numerology * ISAC amenability * Latency * Modulation complexity * Channel estimation complexity   **Proposal 3:** RAN1 should study multi-layer transmission with high order modulation for DFT-s-OFDM in 6GR. |
| Rakuten | **Proposal 3:** 6GR should support optional pre-transformation techniques for peak-to-average power ratio (PAPR) reduction in uplink transmissions and also for downlink transmissions supported by space or airborne elements.   * For systems using the OFDM waveform, the legacy DFT-spread OFDM (DFT-s-OFDM) is proposed as a candidate. * If alternative waveforms are adopted for 6G, their PAPR characteristics must be thoroughly evaluated, and suitable pre-processing methods should be developed to achieve PAPR performance comparable to that of DFT-s-OFDM. |
| Sharp | **Proposal 2:** RAN1 should study DFT-s-OFDM for 6GR. |
| IITM | **Proposal 2:** 3GPP should consider the use of DFT-s-OFDM in DL/UL at least for NTN and FR2 use-cases. |
| CEWiT | **Proposal 1:** Investigate usage of DFT-s-OFDM in DL at least for NTN and FR2 usecases. |

### Questions

A large number of companies suggest DFT-s-OFDM to be adopted as a waveform for 6GR downlink at least for some use cases

Please add your company name in the list if you’d like to indicate support or no support for a particular question posed. Additional points can be added to the second and the third table.

|  |  |  |
| --- | --- | --- |
| **Question 2.5.1** | **Support: Yes** | **Support: No** |
| DFT-s-OFDM should be adopted for 6GR waveform for downlink at least for some use cases | Google, Xiaomi, Sony | QC, Nokia, OPPO, Samsung |
| If DFT-s-OFDM is adopted, should it be extended to support >1 layers? | Google, Sony | CMCC, InterDigital, Nokia, Samsung |

If you answered “Yes” to the above question, please elaborate on the target use case, e.g. “the only baseline waveform of 6G DL for all scenarios (CP-OFDM should be dropped)”, or “FR2 downlink for improved coverage as a complementary waveform to CP-OFDM”.

|  |  |
| --- | --- |
| **Question 2.5.2** | |
| **Company** | **Target use case for DFT-s-OFDM support for DL** |
| CMCC | The energy saving gain of DL DFT-s-OFDM waveform is unclear for TN BS. However, DFT-s-OFDM is expected to support better link budget by allowing higher DL Tx power for NTN. It may also be optimal to generate a certain waveform for sensing. Consequently, the issue is whether we need such dedicated optimization for some specific service and deployment scenario. |
| Xiaomi | Both CP and DFT-S-OFDM can be kept in DL. For NTN use case, DFT-S-OFDM can be useful for system and link level coverage fulfilment. |
| Sony | DFT-s-OFDM will be highly beneficial for NTN DL. |
| OPPO | For 6GR baseline waveform (only considering MBB and IoT), the link-level gain of DFT-s-OFDM DL is limited. And it brings restriction to DL scheduling, e.g., only TDM for multiplexing DFT-s-OFDM UEs and OFDM UEs in a cell, thus may bring capacity loss on system level.  We are open to discuss it for NTN. But it should be discussed in Agenda 11.12, not 11.3.1. |
| Lenovo | We believe that DFT-s-OFDM can be beneficial to enhance DL coverage and improve energy efficiency for some use-cases. NTN and IoT are example use-cases for which DFT-s-OFDM can be beneficial. |
| Rakuten | Same as other companies, we open for NTN DL use cases. |

Additional comments

|  |  |
| --- | --- |
| **Company** | **Comment** |
| Ofinno | Before we discuss whether DFT-s-OFDM is adopted in the DL or not, in our view RAN1 should first study/discuss use cases for DFT-s-OFDM in DL, and if there are any problems with existing 5G DL waveform (i.e., CP-OFDM). |
| CMCC | If DL DFT-s-OFDM waveform is introduced only for NTN and sensing, it may not be necessary to support >1 layer. |
| Xiaomi | Prefer not to have multi-rank given the use case for NTN is mainly coverage fulfilment instead of SE delivery. |
| QC | Multiplexing of channels/users likely to be an issue. Do not think DFT-S-OFDM is likely to bring any benefits even for NTN use case. |
| Samsung | It is better to focus on enhancing uplink coverage due to the Tx power difference. |

## Other waveforms

|  |  |
| --- | --- |
| NICT | **Proposal 1:** RAN1 to consider both PAPR and OOBE performances when evaluating candidate 6GR waveform(s).  **Proposal 2:** RAN1 to consider SP-DFT-s-OFDM as one of candidate waveforms for 6GR.  **Proposal 3:** RAN1 to consider SP-OFDM as one of candidate waveforms for 6GR |
| ZTE | **Proposal 5:** Enhanced CP-less DFT-s-OFDM can be considered for 6G waveform study.  **Proposal 6:** GFB-OFDM should be considered in 6G waveform study as a scheme to support wideband transmission and flexible subband configuration. |
| Cohere | **Proposal 1:** Zak-OTFS is considered as one of the 6G potential waveforms and is included in the 6G waveform study. |
| Tejas | **Proposal 4:** [FBMC?] has a significant drawback compared to the 5G-NR OFDM waveform. A 6GR waveform study that includes [FBMC?] as a candidate waveform should provide strong justification for further study.  **Proposal 5:** GFDM has a significant drawback compared to the 5G-NR OFDM waveform. A 6GR waveform study that includes GFDM as a candidate waveform should provide strong justification for further study.  **Proposal 6:** We support the study of AFDM as a potential candidate for 6G-R.  **Proposal 7:** We support the study of OTFS as a potential candidate for 6G-R, subject to the following conditions being demonstrated by proponents.   1. MIMO and Beamforming Support – The waveform must enable efficient multiantenna operation (including massive MIMO) and beamforming, with pilot overhead and receiver complexity kept at practical levels for deployment. OTFS’s MIMO scalability should be shown to be practically implementable, including for large-scale antenna systems. 2. Processing Latency – Any additional computational burden introduced by OTFS should be addressed through optimized algorithms and architectures, ensuring latency remains within acceptable limits without degrading performance. 3. Performance Gains and Benchmarking – OTFS performance should be thoroughly benchmarked against a baseline (e.g., CP-OFDM) under both low- and high-mobility scenarios. Gains in spectral efficiency, robustness, and throughput must be significant enough to justify adoption, and such gains should be achievable in practice. 4. Comparison to OFDM Alternatives – If equivalent or near-equivalent performance gains cannot be achieved through enhanced OFDM-based receiver schemes at similar or lower implementation complexity or where no such OFDMbased alternative exists, OTFS’s advantage should be explicitly established. |
| IITH | **Proposal 1.** Include OTFDM as a candidate waveform for UL and DL (a companion contribution discusses its applicability for DL) focusing on coverage, latency, and Doppler KPIs.  **Proposal 6.** Evaluate OTFDM usage in both DL and UL for coverage expansion |
| Panasonic | **Proposal 8:** RAN1 can access the need to introduce OTFS-based waveform targeting severe delay-Doppler scenario and/or sensing scenarios. |
| LG Electronics | **Proposal 4:** The potential and operation of spreading OFDM waveforms to enhance diversity gain should be studied for the 6GR system.  **Proposal 5:** RAN1 studies Doppler-robust waveforms for critical physical channels (e.g., synchronization signals, PRACH, DL/UL reference signals, etc.) for high-mobility/NTN scenarios. |
| ETRI | **Proposal 5.** RAN1 to consider AFDM as an additional waveform candidate for 6G radio. |
| Sony | **Proposal 1:** RAN1 should study OFDM and DFT-s-OFDM as baseline waveforms for 6GR as well as at least OTFS and AFDM as candidate waveforms. In this study, RAN1 should consider the following criteria for assessing the waveforms:   * Ease of multiplexing users (in time, frequency and spatially), reference and other signals * Time and frequency offset sensitivity * PAPR * DMRS overhead requirement * Ease of implementation in 6G using 5G as baseline * Flexibility – numerology * ISAC amenability * Latency * Modulation complexity * Channel estimation complexity   **Proposal 4:** RAN1 should include OTFS in its study of 6GR waveforms especially on aspects of signal multiplexing and its impact on spectral efficiency, as well as implementation complexity.  **Proposal 5:** RAN1 should include AFDM in its study of 6GR waveforms. |
| Rakuten | **Proposal 2:** For 6GR operating in the designated frequency ranges rather than FR1, any proposal involving a non-OFDM waveform must clearly justify the additional cost compared to OFDM and demonstrate ease of integration with multi-antenna technologies.  **Proposal 3:** 6GR should support optional pre-transformation techniques for peak-to-average power ratio (PAPR) reduction in uplink transmissions and also for downlink transmissions supported by space or airborne elements.   * For systems using the OFDM waveform, the legacy DFT-spread OFDM (DFT-s-OFDM) is proposed as a candidate. * If alternative waveforms are adopted for 6G, their PAPR characteristics must be thoroughly evaluated, and suitable pre-processing methods should be developed to achieve PAPR performance comparable to that of DFT-s-OFDM. |
| Qualcomm | **Proposal 4:** In 6GR study on waveforms, focus on enhancements to the DFT-S-OFDM family of waveforms.  **Proposal 10:** For 6GR waveform study, consider feasibility to enhance spectrum utilization for small channel bandwidths using spectrum confinement techniques (e.g. WOLA) of reasonable complexity. |
| Sharp | **Proposal 3:** RAN1 should study Interlace OFDM for 6GR. |
| IITM | **Proposal 3:** Study the use of single carrier TDMA bursts in the current frame structure for NTN |
| Anemone Technology | **Proposal 1:** To study the application of OSDM to 6GR. |
| CEWiT | **Proposal 2:** Support studying the performance of OFDM with phase modulation or LFM as a candidate waveform for sensing use cases.  **Proposal 3:** In 6GR, support OOK based waveforms at least for low end devices.  **Proposal 4:** Support multiplexing of waveforms based on criteria like time and frequency resource, physical channels, and physical signals. |
| Reliance Jio | **Proposal:** The new 6G Radio SI shall study possible new waveforms for multiple specific vertical use cases such as NTN, IoT, V2X, broadcast etc apart from eMBB. |

### Questions

A range of candidates are presented as waveforms for 6GR to be studied within the study item:

* SP-DFT-s-OFDM (Spectral precoding DFT-s-OFDM)
* SP-OFDM (Spectral precoding OFDM)
* CP-less DFT-s-OFDM
* GFB-OFDM (Generalized filter-bank OFDM)
* AFDM (Affine Frequency Division Multiplexing)
* OTFS (Orthogonal Time Frequency Space)
* Zak-OTFS
* OTFDM (Orthogonal Time Division DFT-s-OFDM)
* Focus on enhacements to DFT-s-OFDM
* Single-carrier TDMA
* OSDM (Orthogonal Sequence Division Multiplexing)
* OOK-based waveforms

If you are a proponent of a waveform, please add a row per waveform supported for further study and elaborate on the target use case, e.g. “the baseline waveform of 6G DL for all scenarios”, or “FR2 downlink for improved coverage in addition to CP-OFDM”, or “a UL DFT-s-OFDM modification for PAPR reduction with lower modulation orders”

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| **Question 2.6** | | | |
| **Company** | **Waveform** | **DL, UL or both** | **Target use case** |
| CMCC | Focus on enhacements to DFT-s-OFDM | UL | Higher Tx power or energy efficiency for the uplink transmitter of UE |
| CEWiT | AFDM | DL | It can be useful from sensing perspective. |
| Sony | AFDM | Both | Very useful for ISAC and resilient to doppler for NTN and phase noise for high frequencies. |
| QC | Focus on enhacements to DFT-s-OFDM | UL | * Low PAPR waveforms for cell-edge Ues. * Better support for higher data rates, e.g., multi-layer DFT-S-OFDM * Improving scheduling flexibility * Better support for multi-antenna UEs   Flexible freq-domain mapping |
| Nokia | DFT-s-OFDM | UL |  |
| Samsung | Focus on enhancements to DFT-s-OFDM | UL | To improve coverage, PAPR reduction should be considered for DFT-s-OFDM. |

## PAPR reduction

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| Nokia | **Proposal 3:** Frequency Domain Spectrum shaping (FDSS) and FDSS with spectrum extension (FDSS-SE) are supported in 6G Radio. |
| CATT | **Proposal 4:** It is proposed to study FDSS but FDSS-SE is deprioritized for DFT-S-OFDM waveform in 6GR.  **Proposal 5:** It is proposed to study odd-order modulation (e.g. 32QAM) schemes for PAPR reduction for DFT-S-OFDM in 6GR  **Proposal 6:** It is proposed Selective Mapping (SLM) is deprioritized for CP-OFDM waveform in 6GR.  **Proposal 7:** It is proposed to study Tone Reservation (TR) for CP-OFDM waveform in 6GR. |
| Vivo | **Proposal 2:** Study waveform adjustments to achieve high UE power efficiency and UL coverage.  **Proposal 3:** Study techniques to further reduce PAPR/DCM, including CFR-SE/FDSS-SE/TR. |
| Xiaomi | **Proposal 3:** The UL coverage enhancement mechanism in Rel-18 including power domain solution and waveform switch related solution |
| ZTE | **Proposal 1:** Tone reservation can be considered in 6G waveform study as a low-complexity scheme to reduce PAPR, while maintaining compatibility with both UL and DL waveforms.  **Proposal 2:** Selected Mapping (SLM) can be considered in 6G waveform study as a low-complexity scheme to reduce PAPR, while maintaining compatibility with both UL and DL waveforms.  **Proposal 3:** FDSS can be considered in 6G waveform study. |
| Samsung | **Proposal 2:** Study PAPR reduction schemes over DFT-s-OFDM for better UL coverage than NR.  **Proposal 3:** To evaluate and compare PAPR reduction schemes, practical hardware impairments should be considered together.  **Proposal 4:** Study FDSS-SE for coverage enhancement in 6GR.  **Proposal 5:** Study PAPR reduction with AI/ML-based transform-precoding for 6GR. |
| IITH | **Proposal 2.** Define shaping options Pre-/post-DFT shaping (including “excess subcarrier” use to time limit the ISI channel and enable pre DFT DMRS inclusion) and/or post-IFFT filtering to confine spectrum mask to standardize PA-friendly spectra. |
| Panasonic | **Proposal 7:** RAN1 can assess the need to introduce PAPR/CM reduction techniques targeting coverage enhancement, especially for UL. |
| Intel | **Proposal 2:** For 6G waveform, at least for eMBB service: For UL transmissions, RAN1 to further study techniques to reduce PAPR/CM. Potential waveform choices may include frequency domain spectrum shaping with and without spectrum extension.  **Proposal 3:** For 6G, RAN1 to further study potential enhancement for DL waveform at least for eMBB service, considering aspects of UE multiplexing, CA, MIMO and PAPR/CM reduction. |
| Lenovo | **Proposal 2**: Study and evaluate CP-OFDM waveform enhancement techniques including PAPR/CM reduction techniques such as Selected Mapping (SLM) and Tone Reservation (TR) for coverage enhancement and energy efficiency improvement, and compare to implementation-based techniques in terms of complexity, signal distortion, and spectral efficiency.  **Proposal 3:** Study enhancing DFT-s-OFDM waveform by incorporating PAPR/CM reduction techniques such as FDSS, DFT precoder extension, etc. |
| InterDigital | **Proposal 4:** Study PAPR reduction techniques for uplink DFT-s-OFDM to support coverage enhancement for 6G  **Proposal 5:** The following KPIs relevant for communication should be evaluated when studying PAPR reduction techniques or a new waveform: Spectral efficiency (bps/Hz), BLER, Cubic metric, PAPR |
| Apple | **Proposal 2:** Study enhancement of Low PAPR Waveform for PUSCH and PUSCH-DMRS, such as FDSS (e.g. approximating GMSK) and BW extension, for achieving coverage enhancement in the DFTs-OFDM framework  **Proposal 3:** Study both spec. transparent and non-transparent methods for PAPR reduction. Consider the use of both baseline and advanced receivers  **Proposal 4:** Consider overall trade-offs between low PAPR and demod/decode performance, Rx complexity, RF requirement. Evaluation assumptions considering realistic channel estimation and realistic PA nonlinearity |
| Sony | **Proposal 2:** RAN1 should study PAPR reduction schemes for application to CP-OFDM 6GR. |
| Qualcomm | **Proposal 5:** For 6GR, study the family of low PAPR waveforms obtained using DFT-S-OFDM with Pi/2 BPSK and truncated mapping.  **Proposal 11:** For 6GR waveform study, consider waveforms and waveform shaping techniques that facilitate the support of high power uplink transmissions for higher power class UEs and further tightening the associated MPRs for different modulation orders |
| IITM | **Proposal 1:** 3GPP should study the option of enabling mechanisms for PAPR reduction techniques in CPOFDM. |

### Questions

A number of Tdocs suggest studying PAPR reduction techniques. Generally the PAPR reduction techniques are specific to transmit waveform and the solutions may also be specific to link direction. Given that it is difficult to discuss PAPR reduction techniques without having first an agreed waveform or waveforms to target the PAPR reduction to.

Please add your company name in the list if you’d like to indicate support or no support for a particular question posed. Additional points can be added to the second table.

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| **Question 2.7.1** | **Support: Yes** | **Support: No** |
| Postpone the PAPR reduction technique discussion until the waveform selection discussion has matured. | Ofinno, CMCC, Google, InterDigital, Sony, Nokia, OPPO, Rakuten |  |

If you answered “No” to the above question, please elaborate on the PAPR reduction technique you’d suggest to continue discussion on without further due”.

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| **Question 2.7.2** | **DL, UL  or both** | **PAPR reduction technique and the target waveform** |
| QC | UL | Pi/2 BPSK DFT-S-OFDM with truncated mapping. |
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Additional comments

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| **Company** | **Comment** |
| CMCC | In our mind, the only issue is whether DFT-s-OFDM waveform will be used for downlink communication. It can impact the purpose and target of PAPR reduction, which will further impact the justification of the candidate techniques. |
| InterDigital | Ok to wait to discuss PAPR reduction techniques but we need to set a deadline to agree on the waveforms to adopt. |
| Sony | OK to wait until waveform is decided |
| QC | Suggest we get started on this soon. We are expecting evaluations to take reasonable time and effort. Prefer to give companies enough time to implement and study some of the new proposals. We also anticipate significant involvement from RAN4. |
| Samsung | Non-transparent FDSS and FDSS-SE for Pi/2-BPSK should be investigated. |
| Lenovo | We think discussion on PAPR reduction techniques should be started alongside waveform discussion since the outcome of evaluating these techniques can help for better decision on waveform |

## Tx power for UL

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| Nokia | **Proposal 4:** High power class should be the baseline for 6G due to significant enhancement in coverage.  **Proposal 5:** Power boosting features should be part of the baseline for 6G. |
| IITH | **Proposal 4.** Set UE Tx power classes for handheld and FWA across legacy and new 6G bands; align with MPR referenced to π/2-BPSK. |
| Qualcomm | **Proposal 11:** For 6GR waveform study, consider waveforms and waveform shaping techniques that facilitate the support of high power uplink transmissions for higher power class UEs and further tightening the associated MPRs for different modulation orders |

### Questions

A few companies mention Tx power or power class and MPR. Power class and MPR definitions are generally considered to belong to RAN4. It maybe also difficult to discuss these techniques until the waveform and PAPR reduction techniques have matured further.

Please add your company name in the list if you’d like to indicate support or no support for a particular question posed. Additional points can be added to the second table.

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| --- | --- | --- |
| **Question 2.8** | **Support: Yes** | **Support: No** |
| Consult RAN4 on the power class | Ofinno, CMCC, Google, QC, Nokia, OPPO, Samsung |  |
| Continue power class discussion in RAN1 (regardless of whether RAN4 is consulted on the matter or not) |  | Ofinno, CMCC |
| Consult RAN4 on the MPR and power boosting | Ofinno, CMCC, Google, Xiaomi, QC, Nokia, OPPO, Samsung |  |
| Continue MPR and power boosting discussion in RAN1 (regardless of whether RAN4 is consulted on the matter or not) |  | Ofinno, CMCC |

Additional comments

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| **Company** | **Comment** |
| CMCC | The achievable coverage gain highly depends on whether/how much higher Tx power is supported for eMBB UE. RAN4 has to be involved for at least roughly determining the practical value for power class and Tx power boosting. |
| Xiaomi | Prefer to initiate such discuss pending RAN4 assessment on the RF characteristics. Also, diverse UE types including LPWA UE needs to be considered when we discuss these features. |
| QC | Agree that these topics need RAN4 input.  It will be good for RAN1 to be aware of (a) power classes of interest (b) PA models/architecture for the different power classes of interest.  RAN1 will also need guidance from RAN4 on PA models for evaluating low PAPR waveforms. |

## Waveform switching

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| Nokia | **Proposal 6:** Dynamic waveform switching is introduced to 6G in the first release. |
| Xiaomi | **Proposal 3:** The UL coverage enhancement mechanism in Rel-18 including power domain solution and waveform switch related solution |
| Ericsson | **Proposal 3:** RAN1 to study the benefits and relevance of waveform switching between CP-OFDM and DFT-S-OFDM in 6GR. |
| NEC | **Proposal 1:** CP-OFDM and DFT-s-OFDM in NR are baseline as 6GR uplink waveform. 6GR could study to support dynamic waveform switching during initial access. |
| InterDigital | **Proposal 3:** Support dynamic waveform switching for the uplink |

### Questions

A number of Tdocs suggest defining dynamic waveform switching. However, it seems premature to discuss waveform switching when that is only meaningful if at least two waveforms are defined.

Please add your company name in the list if you’d like to indicate support or no support for a particular question posed. Additional points can be added to the second table.

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| **Question 2.9** | **Support: Yes** | **Support: No** |
| Postpone the waveform switching discussion until the waveform selection discussion has matured. | Ofinno, Google, Xiaomi, InterDigital, Sony, QC, Nokia, OPPO, Rakuten |  |

Additional comments

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| **Company** | **Comment** |
| QC | Agree to postpone. Can revisit after we make more progress on the waveform families that we support. |
| OPPO | Agree to postpone. And evaluation results should be shown to justify the gain. |
| Lenovo | This can be postponed after the decision on waveform is made for both DL and UL |

## Sensing

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| Spreadtrum | **Proposal 3:** Only 6GR communication waveform is used for ISAC waveform in day 1. New waveform which is more compatible with radar characteristics is not precluded (can be considered) in day 2 for ISAC. |
| Huawei | **Proposal 3:** 6GR should study OFDM based sensing waveform for ISAC use cases.  **Proposal 6:** Shared communication and sensing waveforms should be studied for low overhead and co-existence benefit, where both communication and sensing requirements should be considered. 4.2 Evaluation methodology  **Proposal 7:** Sensing function has different performance metrics from communication function, where AF, PSLR, ISLR, PAPR should be considered. |
| CATT | **Proposal 8:** Two waveforms for pulse wave (PW) with short power boosting duration can be considered: Option-1: OFDM-based PW with larger SCS (i.e. 960 kHz or 1920 kHz) Option-2: LFM (Linear Frequency Modulation) chirps -based PW.  **Proposal 9:** The OFDM-based CW and Orthogonal Chirp Division Multiplexing (OCDM)-based CW can be studied. |
| ZTE | **Proposal 7:** Study DFT-s-OFDM for downlink to generate pulse signals for large sensing coverage. |
| Ofinno | **Proposal 3:** Waveform related to ISAC is separately discussed from 6G waveform for 6GR Physical Layer structure. |
| LG Electronics | **Proposal 6**: A new waveform such as FMCW is studied for sensing as well as OFDM. |
| InterDigital | **Proposal 6:** Waveform for sensing is not covered in Agenda Item 11.3.1 and shall be studied separately in Agenda Item 11.14 |
| Qualcomm | **Proposal 1:** For 6G Radio waveform study, limit initial focus to waveform design for communication use cases. Waveforms for other use cases such as sensing to be discussed separately. |
| CEWiT | **Proposal 5:** Support multiplexing of OFDM for communication and phase modulation or LFM for sensing use case. |

### Questions

The placeholder agenda item 11.14 states: “*Including PHY functions and procedures for sensing technology (e.g., waveform. reference signals, measurement feedback, etc…), aspects of integration with communication services.”*. Several Tdocs mention this and suggest deferring the sensing waveform discussions to that agenda item, while a set of contributions initiate discussion on sensing waveform.

Please add your company name in the list if you’d like to indicate support or no support for a particular question posed. Additional points can be added to the second table.

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| **Question 2.10** | **Support: Yes** | **Support: No** |
| Should the sensing waveform discussion be deferred to Sensing agenda item 11.14? | Ofinno, CMCC, Google, Xiaomi, InterDigital, Fainity, QC, Nokia, OPPO | Sony |

Additional comments

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| --- | --- |
| **Company** | **Comment** |
| CMCC | The waveform design specifically for ISAC is preferred to be discussed in the agenda item of ISAC, as it involves too many sensing-specific requirements and technical details. This agenda can focus on the waveform design that can be used for both communication and sensing. |
| Fainity | We are open the corresponding waveform for communication and sensing could be different depends on the sensing scenarios. It may not be necessary to bundling them and take the integration into consideration from beginning. |
| Sony | We think a unified waveform study should include ISAC from the onset. |
| Lenovo | The discussion on sensing waveform can be carried out later alongside the discussion on PHY aspects of ISAC. |

# Collection of proposals

|  |  |  |  |
| --- | --- | --- | --- |
|  | **Tdoc#** | **Title** | **Source** |
| [1] | [R1-2505127](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505127.zip) | Waveform for 6G Radio Air Interface | Nokia |
|  | **Proposal 1:** CP-OFDM is the waveform used for communication in 6G downlink  **Proposal 2:** CP-OFDM and DFT-s-OFDM are the baseline waveforms for 6G uplink  **Proposal 3:** Frequency Domain Spectrum shaping (FDSS) and FDSS with spectrum extension (FDSS-SE) are supported in 6G Radio.  **Proposal 4:** High power class should be the baseline for 6G due to significant enhancement in coverage.  **Proposal 5:** Power boosting features should be part of the baseline for 6G.  **Proposal 6:** Dynamic waveform switching is introduced to 6G in the first release. | | |
| [2] | [R1-2505156](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505156.zip) | Considerations for 6G Waveform | Kyocera Corporation |
|  | **Observation 1:** Without Doppler compensation, CP-OFDM performance deteriorates considerably at the high speeds envisioned by the IMT-2030 requirements and increasing SCS is the most effective means of mitigating performance degradation.  **Observation 2:** Increasing reference signal density (DMRS/PTRS) is much less effective than increasing SCS, and it entails loss in spectral efficiency due to increased RS overhead.  **Observation 3:** For normal CP, due to the fixed ratio between CP and useful OFDM symbol period in the 5G NR numerology, the SCS cannot be increased indefinitely without compromising performance due to the potential inability of a short CP in dealing with large Delay Spread scenarios.  **Proposal 1:** If 5G NR waveforms are to be reused for 6G, we need a description of the enhancements needed to meet 6G requirements (e.g., IMT-2030 targets) with their performance improvement in given scenarios and added complexity.  **Proposal 2:** If new waveforms are to be considered/adopted for some scenarios, describe the new waveforms and performance advantages in those scenarios as well as the additional complexity wrt to 5G waveforms addressing coexistence/backward compatibility issues. Any decision on waveform coexistence should consider how widespread very high mobility deployments are. | | |
| [3] | [R1-2505172](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505172.zip) | Discussion on waveform for 6GR | Spreadtrum, UNISOC |
|  | **Proposal 1:** 5G NR Waveform should be adopted for 6GR waveform, including DL/UL CP-OFDM and UL DFT-s-OFDM.  **Proposal 2:** DL DFT-s-OFDM waveform should be supported for 6GR in day 1.  **Proposal 3:** Only 6GR communication waveform is used for ISAC waveform in day 1. New waveform which is more compatible with radar characteristics is not precluded (can be considered) in day 2 for ISAC.  **Proposal 4:** New OFDM-based waveform other than CP-OFDM and DFT-s-OFDM for 6GR communication can be considered only if enough performance gain is justified together with comprehensive implementation evaluation, e.g., compatibility, complexity, and specification impact. | | |
| [4] | [R1-2505183](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505183.zip) | Waveform for 6GR air interface | Huawei, HiSilicon |
|  | **Observation 1:** Coverage enhancement is critical to improve user experience, especially for services requiring high data rate.  **Observation 2:** From UL and DL coverage perspective, lower PAPR DFT-s-OFDM waveform can be beneficial.  **Observation 3:** From UL spectral efficiency perspective, lower PAPR DFT-s-OFDM waveform and multilayer are beneficial.  **Observation 4:** From both network and device energy efficiency perspective, lower PAPR DFT-s-OFDM waveform can be beneficial.  **Proposal 1:** As a waveform base, CP-OFDM waveform should be supported in 6GR for both downlink and uplink and DFT-s-OFDM waveform is also supported for uplink.  **Proposal 2:** 6GR shall study lower PAPR DFT-s-OFDM waveform under different spectral efficiency for both downlink and uplink.  **Proposal 3:** 6GR should study OFDM based sensing waveform for ISAC use cases.  **Proposal 4:** In evaluation of low PAPR waveform, the coverage gain should comprise of both Tx power gain and the potential required SNR loss/gain under same data rate/spectral efficiency and same occupied T/F resources.  **Proposal 5:** The Tx power gain evaluation should be based on PA model(s) and RF requirements, where the polynomial PA model in [3] and 5G FR1 RF requirements could be considered as a start point before any update from RAN4, or reported by companies.  **Proposal 6:** Shared communication and sensing waveforms should be studied for low overhead and co-existence benefit, where both communication and sensing requirements should be considered. 4.2 Evaluation methodology  **Proposal 7:** Sensing function has different performance metrics from communication function, where AF, PSLR, ISLR, PAPR should be considered. | | |
| [5] | [R1-2505264](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505264.zip) | Waveform for 6GR Air Interface | Google |
|  | **Proposal 1:** The 6G waveform should be compatible with the CP-OFDM waveform with regard to MRSS.  **Proposal 2:** To maintain the same coverage for FR1 and FR3, low PAPR waveform for both DL and UL should be considered.  **Proposal 3:** Study DFT-s-OFDM waveform for both uplink and downlink transmission. | | |
| [6] | [R1-2505308](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505308.zip) | Discussions on waveform for 6GR | CATT |
|  | **Observation 1:** The PAPR is increasing with the increasing of DFT points e.g. 4096 to 8192.  **Observation 2:** To maintain the same coverage (i.e. same power spectral density), transmission power will be doubled with the doubled channel bandwidth.  **Observation 3:** The Pulse wave (PW) signal with short power boosting duration is beneficial for sensing, providing better coverage and being free from self-interference.  **Proposal 1:** Lower PAPR schemes shall be studied with considering following aspects in 6GR: Larger FFT size (e.g., from 4096 to 8192). Larger transmission channel bandwidth  **Proposal 2**: DFT-S-OFDM can be used on uplink channel, and the bandwidth of the uplink channel in terms of resource blocks should fulfill, where is a set of non-negative integers.  **Proposal 3:** The DFT-S-OFDM on RANK=2 transmission should be considered to reduce the PAPR in 6GR.  **Proposal 4:** It is proposed to study FDSS but FDSS-SE is deprioritized for DFT-S-OFDM waveform in 6GR.  **Proposal 5:** It is proposed to study odd-order modulation (e.g. 32QAM) schemes for PAPR reduction for DFT-S-OFDM in 6GR.  **Proposal 6:** It is proposed Selective Mapping (SLM) is deprioritized for CP-OFDM waveform in 6GR.  **Proposal 7:** It is proposed to study Tone Reservation (TR) for CP-OFDM waveform in 6GR.  **Proposal 8:** Two waveforms for pulse wave (PW) with short power boosting duration can be considered: Option-1: OFDM-based PW with larger SCS (i.e. 960 kHz or 1920 kHz) Option-2: LFM (Linear Frequency Modulation) chirps -based PW.  **Proposal 9:** The OFDM-based CW and Orthogonal Chirp Division Multiplexing (OCDM)-based CW can be studied. | | |
| [7] | [R1-2505416](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505416.zip) | Discussion on Waveform for 6GR air interface | vivo |
|  | **Proposal 1:** NR should be the baseline for general communication waveforms, i.e., DL: CP-OFDM UL: CP-OFDM, DFT-s-OFDM  **Proposal 2:** Study waveform adjustments to achieve high UE power efficiency and UL coverage.  **Proposal 3:** Study techniques to further reduce PAPR/DCM, including CFR-SE/FDSS-SE/TR.  **Proposal 4:** Support DCM as a metric to evaluate power domain performance of 6GR waveform.  **Observation 1:** DCM fits UE PA power back-off behavior better than PAPR and CM.  **Observation 2:** On power-domain metrics:   * CFR-SE achieves better PAPR than FDSS, FDSS-SE and TR for π/2-BPSK, QPSK and 16QAM. * CFR-SE achieves better DCM than FDSS, FDSS-SE and TR for QPSK and 16QAM. For π/2- BPSK, CFR-SE and FDSS-SE achieves almost the same DCM (about 0.2dB gap).   **Observation 3:** Considerable net gain can be achieved for CFR-SE: > 2dB for π/2-BPSK and QPSK，0.86 dB for 16QAM, compared with raw DFT-s-OFDM. Net gain of CFR-SE is higher than FDSS, FDSS-SE and TR for these modulations. | | |
| [8] | [R1-2505463](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505463.zip) | On 6GR waveform | Xiaomi |
|  | **Observation 1.** For improving spectral efficiency target, more justification is needed on the motivation of introducing OOBE mitigation-based waveform.  **Observation 2.** PARP is a key optimization target for power efficiency design target and RAN1 shall liaise with RAN4 if OBO assessment to identified power efficient waveform is needed.  **Proposal 1:** The following net gain evaluation metric is used for 6GR OFDM based waveform determination and RAN1 shall liaise with RAN4, if necessary, on RF dependent net gain assessment to identify the 6GR waveform that is coverage beneficial. *Net Gain =* Δ𝑆𝑁𝑅 + Δ𝑃𝐴𝑃𝑅  **Proposal 2:** To support the coverage performance for NTN DL, low-PAPR waveform such as DFTS-OFDM can be considered.  **Proposal 3:** The UL coverage enhancement mechanism in Rel-18 including power domain solution and waveform switch related solution | | |
| [9] | [R1-2505474](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505474.zip) | Waveform consideration for 6GR air interface | NICT |
|  | **Observation 1:** PAPR and OOBE are key performance indicators of waveforms that attribute to energy efficiency and spectral efficiency.  **Observation 2:** The SP does not cause any degradation of classical CP and FDE virtue like filtering and windowing techniques may do, nor does not give impact on PAPR characteristics of the original OFDM-based waveform.  **Observation 3:** The postdecoding process of the SP-applied signal is complete inverse of the generating procedure, resulting in ideal error rate characteristics equivalent to the original OFDM-based signal.  **Observation 4:** The SP can be implemented as orthogonal precoding without any degradation of CP, FDE and error rate property to effectively suppress OOBE when applied to both basic OFDM and DFT-s-OFDM.  **Observation 5:** The SP does not impact much on PAPR performance. So SP DFT-s-OFDM can benefit from the SP to show superior OOBE performance while keeping low PAPR performance property of DFT-s-OFDM.  **Proposal 1:** RAN1 to consider both PAPR and OOBE performances when evaluating candidate 6GR waveform(s).  **Proposal 2:** RAN1 to consider SP-DFT-s-OFDM as one of candidate waveforms for 6GR.  **Proposal 3:** RAN1 to consider SP-OFDM as one of candidate waveforms for 6GR | | |
| [10] | [R1-2505480](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505480.zip) | Discussion on waveform for 6GR air interface | TCL |
|  | **Observation 1:** The core design of the CP-OFDM and its Workarounds in NR is strained by the new requirements in multiple dimensions. The prudent path is to investigate new waveform paradigms that can natively handle these challenges.  **Observation 2:** The diversity of viable waveform candidates and approaches justifies a dedicated 3GPP study. RAN1 should evaluate these candidates systematically in the context of 6G use cases. | | |
| [11] | [R1-2505510](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505510.zip) | Views on the waveform for 6G | ZTE Corporation, Sanechips |
|  | **Observation 1:** TR-based OFDM achieves consistent PAPR reduction of approximately 2 dB at CCDF = 103 across QPSK, 16QAM, and 64QAM modulations, demonstrating its robustness and modulation-agnostic effectiveness.  **Observation 2:** With a properly chosen TR ratio, TR achieves effective PAPR reduction while preserving spectral efficiency.  **Observation 3:** The impacts of reserved tone has negligible effect on BLER performance across all modulation coding schemes.  **Observation 4:** SLM with different configurations have demonstrated noticeable gains on PAPR reduction, e.g., around 2dB and 1dB, across all modulation orders (QPSK, 16QAM, 64QAM), which indicates that the SLM scheme is robust and modulation-agnostic.  **Observation 5:** The SLM scheme has no effect on BLER performance across all modulation coding schemes under power-normalized transmission.  **Observation 6:** eDFT-s-OFDM can achieve lower PAPR than DFT-s-OFDM without FDSS, and similar PAPR performance as DFT-s-OFDM with FDSS.  **Observation 7:** Without CPE compensation or with ideal CPE compensation, eDFT-s-OFDM and DFT-s-OFDM exhibit identical BLER performance, indicating that phase noise affects both waveforms similarly.  **Observation 8:** With CPE compensation, CP-less eDFT-s-OFDM outperforms DFT-s-OFDM in BLER, as its head and tail sequences provide more reference elements than PTRS (20 vs. 8), enabling more effective phase noise mitigation.  **Observation 9:** eDFT-s-OFDM exhibits reduced OOB leakage compared to DFT-s-OFDM, primarily due to the use of identical head and tail sequences across symbols, which ensures time-domain continuity between adjacent OFDM symbols.  **Observation 10:** GFB-OFDM can decompose a large-size IFFT into multiple smaller-size IFFTs, enabling support for larger overall IFFT sizes while significantly reducing implementation complexity.  **Observation 11:** GFB-OFDM facilitates flexible subband configuration through a unified waveform generation method.  **Observation 12:** Compared to CP-OFDM, GFB-OFDM achiever lower OOBE with the implementation of polyphase filtering.  **Observation 13:** GFB-OFDM outperforms CP-OFDM in terms of performance, when using different subcarrier spacing or waveform type across subbands.  **Observation 14:** For sensing, a coverage of larger than 1 km is needed for one Tx/Rx pair, and hence a large transmission power, e.g., 58 dBm, is needed.  **Proposal-1:** For 6G waveform design, the following targets should be considered:   * OFDM-based waveform with better performance, e.g., improved coverage and throughput * Unified waveform design to support multiple scenarios and needs, e.g., ISAC and other scenarios (e.g., high-mobility scenarios)   **Proposal 1:** Tone reservation can be considered in 6G waveform study as a low-complexity scheme to reduce PAPR, while maintaining compatibility with both UL and DL waveforms.  **Proposal 2:** Selected Mapping(SLM) can be considered in 6G waveform study as a low-complexity scheme to reduce PAPR, while maintaining compatibility with both UL and DL waveforms.  **Proposal 3:** FDSS can be considered in 6G waveform study.  **Proposal 4:** DFT-s-OFDM with rank 2 for uplink transmission can be considered in 6G waveform study.  **Proposal 5:** Enhanced CP-less DFT-s-OFDM can be considered for 6G waveform study.  **Proposal 6:** GFB-OFDM should be considered in 6G waveform study as a scheme to support wideband transmission and flexible subband configuration.  **Proposal 7:** Study DFT-s-OFDM for downlink to generate pulse signals for large sensing coverage.  **Proposal 8:** The following aspects are recommented to be considered for the 6G waveform evaluation:   * Performance metrics: PAPR, BLER,OOBE; * The PA modelling with more realistic assumption | | |
| [12] | [R1-2505520](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505520.zip) | On 6G waveforms | Ericsson |
|  | **Observation 1** Sensing waveforms are included in upcoming discussions per the RAN1 meeting agenda; hence, they are beyond the scope of AI 11.3.1.  **Observation 2** Economies of scale mandate that the same waveform types to be specified for all frequency ranges, allowing for extensive hardware reuse.  **Observation 3** When considering waveforms and modulation techniques, the practical spectrum efficiency should include aspects such as inter-carrier guard bands, multiple access guard bands and periods, and self-interference.  **Observation 4** For initial deployment success of 6G in existing frequency bands, MRSS performance is key. MRSS efficiency will be maximized using OFDM as a 6G waveform and modulation technique.  **Observation 5** Uplink performance can be further improved, e.g., by further reducing the required power backoff and introducing multi-rank for DFT-S-OFDM.  **Observation 6** 5G NR Release-18 allows dynamic switching between CP-OFDM and DFT-S-OFDM waveforms in uplink that helps to dynamically adapt the uplink transmissions to changing channel conditions and to leverage the benefits of both waveforms.  **Observation 7** OFDM allows robust and low complexity receivers using efficient channel estimation, allowing for a wide range of device performance using the same waveform and modulation technique.  **Observation 8** OFDM allows for proven and efficient initial access and cell search.  **Observation 9** T/F resource partitioning allows for straightforward MIMO operation while maintaining simple receiver structures.  **Observation 10** Short transmissions with sub-1 ms latency are needed for sophisticated service levels.  **Observation 11** OFDM based multiple access efficiently handles interference, and ideally eliminates intra-cell interference, by means of allocating different users across orthogonal subcarriers.  **Observation 12** OFDMA meets the scheduling needs for today’s bursty traffic patterns and benefits from short scheduling horizons.  **Observation 13** OFDM is well-suited for low-latency communication due to its support for independent scheduling of low-latency and MBB services. The structured timefrequency grid, opportunity of mini-slot configuration and efficient FFT-based processing enable fast decoding.  **Observation 14** With appropriate compensation techniques introduced in 5G for high Doppler shifts due to satellite movement in NTN, OFDM based waveform is still suitable for NTN in 6G radio access.  **Proposal 1:** Support NR-based CP-OFDM for DL transmission for all ranks [and numerologies].  **Proposal 2:** Support NR-based CP-OFDM and NR-based DFT-S-OFDM for UL transmission for all ranks [and numerologies].  **Proposal 3:** RAN1 to study the benefits and relevance of waveform switching between CP-OFDM and DFT-S-OFDM in 6GR.  **Proposal 4:** Further study possible improvements to CP-OFDM and DFT-S-OFDM using 5G NR as a starting point. | | |
| [13] | [R1-2505584](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505584.zip) | Discussion on waveform for 6GR | Samsung |
|  | **Observation 1:** Applying FDSS-SE in a non-transparent manner can yield SNR gains compared to the transparent approach.  **Observation 2:** FDSS-SE with the well-designed filter enables achieving a PAPR of below 1 dB for π/2-BPSK.  **Observation 3:** The AI/ML-based transform precoding demonstrates PAPR reduction compared to conventional DFT spreading.  **Proposal 1:** OFDM shall be the baseline waveform for 6GR DL/UL with DFT-s-OFDM for the coverage-limited environments in UL.  **Proposal 2:** Study PAPR reduction schemes over DFT-s-OFDM for better UL coverage than NR.  **Proposal 3:** To evaluate and compare PAPR reduction schemes, practical hardware impairments should be considered together.  **Proposal 4:** Study FDSS-SE for coverage enhancement in 6GR.  **Proposal 5:** Study PAPR reduction with AI/ML-based transform-precoding for 6GR. | | |
| [14] | [R1-2505629](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505629.zip) | From Evolution to Revolution in 6G Waveforms using Zak-OTFS | Cohere Technologies |
|  | **Observation 1:** Zak-OTFS with the right choice of parameters becomes identical to the 5G CP-OFDM modulator. In other words, 5G CP-OFDM is a special case of Zak-OTFS.  **Observation 2:** Zak-OTFS with the right choice of parameters becomes filtered OFDM  **Observation 3:** Zak-OTFS implemented as a pre-processing step in front of the standard 5G CP-OFDM where the QAM symbols are allocated in the delay-Doppler domain and transferred to the time-frequency using IDFZT improves the performance significantly over the 5G CP-OFDM.  **Observation 4:** Fully optimized configuration of Zak-OTFS outperforms both 5G CP-OFDM and Zak-OTFS over 5G CP-OFDM  **Observation 5:** Zak-OTFS gives full flexibility in waveform selections with simple parameter settings and supports the evolution of the 6G waveform starting from the 5G CP-OFDM all the way to the fully optimized Zak-OTFS depending on gNB and UE readiness.  **Proposal 1:** Zak-OTFS is considered as one of the 6G potential waveforms and is included in the 6G waveform study. | | |
| [15] | [R1-2505633](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505633.zip) | Waveform design | Tejas Network Limited |
|  | **Observation 1:** The choice of waveform should support a wide range of applications and use cases, including immersive communication, massive connectivity, high-reliability lowlatency communication (HRLLC), integrated sensing and communication (ISAC), a unified waveform for NTN–TN operation, full-duplex transmission, and AI-native functionalities.  **Proposal 1:** Study various waveforms beyond OFDM to support the KPI and use cases defined for 6G-R.  **Observation 2:** To evaluate candidate waveforms for next-generation (6G) communication systems, it is essential to define Key evaluation metrics aligned with the functional requirements and KPI design targets for 6G radio access. The critical KPI’s for candidate waveforms can be PAPR, Pilot overhead, MRSS Compatibility, Computational complexity, Scalability along spatial dimensions (MIMO and diversity), Spectral efficiency, Robustness to multipath fading and doppler, OOB emissions, ISAC, and NTN feasibility.  **Proposal 2:** We propose to adopt the KPIs — PAPR, pilot overhead, MRSS compatibility, computational complexity (transmit and receive), MIMO scalability and spatial diversity, spectral efficiency, robustness to multipath and Doppler, and OOB emissions — for evaluating 6G-R waveforms, and to provide a qualitative assessment of candidate waveforms, namely OFDM, FBMC, GFDM, AFDM, and OTFS, for further study.  **Observation 3:** OFDM is a mature and widely adopted waveform. A focused attempt has been made to tackle key challenges like PAPR reduction, Constant Envelop OFDM (CEOFDM), Robustness to phase noise and CFO with Frequency modulated OFDM (FMOFDM), improving performance for high mobility scenarios with schemes like Block Scalable OFDM (BS-OFDM) [5].  **Proposal 3:** OFDM should be supported as a baseline, and its advanced variants (e.g., CEOFDM, FM-OFDM, enhanced DFT-s-OFDM, BS-OFDM) need to be considered for further study as waveform candidates for 6G-R.  **Observation 4:** FBMC has the following key advantages and disadvantages as a 6GR waveform  Advantages: Excellent spectral efficiency (no CP, tight subcarrier localization), very low out-of-band emissions, and potential resilience in asynchronous or spectrum-sharing scenarios.  Disadvantages: Higher complexity and signal processing cost. Not suitable for MIMO (especially massive MIMO precoding and channel estimation). Large filter and processing latency do not bode well for low-latency applications.  **Proposal 4:** GFDM has a significant drawback compared to the 5G-NR OFDM waveform. A 6GR waveform study that includes GFDM as a candidate waveform should provide strong justification for further study.  **Observation 5**: GFDM has the following key advantages and disadvantages as a 6GR waveform  Advantages: Improved spectral efficiency over CP-OFDM (due to lower CP overhead, tight subcarrier localization), very low out-of-band emissions, and potential resilience in asynchronous or spectrum-sharing scenarios.  Disadvantages: Higher complexity and signal processing cost. Large filter and processing latency do not bode well for low-latency applications.  **Proposal 5:** GFDM has a significant drawback compared to the 5G-NR OFDM waveform. A 6GR waveform study that includes GFDM as a candidate waveform should provide strong justification for further study.  **Observation 6:** AFDM is a generalized multicarrier waveform that uses an affine Fourier transform with chirp signals, retaining delay–Doppler orthogonality and achieving full diversity in doubly-dispersive channels, making it highly robust in high-mobility and high Doppler environments. It is backward-compatible with OFDM, enabling seamless coexistence with legacy systems and reuse of existing hardware and PAPR reduction techniques. AFDM delivers lower pilot and guard overhead through sparse delay–Doppler channel representation, enhancing spectral efficiency and reducing receiver complexity. It supports shorter guard intervals, non-orthogonal subcarrier packing, and extra modulation dimensions via chirp parameters. The nearly diagonal DAFT-domain channel allows simple equalization while advanced iterative solvers enable scalable MU-/Massive MIMO operation. AFDM is well-suited for NTN, ISAC, HRLLC, and high mobility use cases, combining communication and sensing capabilities with strong robustness to multipath and Doppler effects.  **Proposal 6:** We support the study of AFDM as a potential candidate for 6G-R.  **Observation 7:** Zak-OTFS retains the coexistence capability with OFDM by aligning to the same time-frequency grid, showing minimal performance impact on OFDM when proper guard spacing is applied. Compared to OFDM, Zak-OTFS offers clear advantages in highmobility and large-delay environments: lower PAPR, reduced pilot overhead, and much cleaner out-of-band emissions, enabling tighter spectrum packing and improved spectral efficiency in challenging conditions. In multipath- and Doppler-rich channels, Zak-OTFS demonstrates superior robustness, maintaining high link reliability and throughput where OFDM performance degrades. It scales well in spectral efficiency under mobility, often exceeding OFDM performance by large margins, but this comes at the cost of significantly higher computational complexity—especially in MIMO and multi-user scenarios—due to 2D transforms and joint equalization. While complexity can be mitigated using sparsityaware algorithms and parallelization, hardware demands remain higher than those of OFDM. Additionally, Zak-OTFS maps each information symbol across the entire TF grid and typically performs 2D equalization after the frame completes decoding, waits for a full frame, increasing processing latency.  **Proposal 7:** We support the study of OTFS as a potential candidate for 6G-R, subject to the following conditions being demonstrated by proponents.   1. MIMO and Beamforming Support – The waveform must enable efficient multiantenna operation (including massive MIMO) and beamforming, with pilot overhead and receiver complexity kept at practical levels for deployment. OTFS’s MIMO scalability should be shown to be practically implementable, including for large-scale antenna systems. 2. Processing Latency – Any additional computational burden introduced by OTFS should be addressed through optimized algorithms and architectures, ensuring latency remains within acceptable limits without degrading performance. 3. Performance Gains and Benchmarking – OTFS performance should be thoroughly benchmarked against a baseline (e.g., CP-OFDM) under both low- and high-mobility scenarios. Gains in spectral efficiency, robustness, and throughput must be significant enough to justify adoption, and such gains should be achievable in practice. 4. Comparison to OFDM Alternatives – If equivalent or near-equivalent performance gains cannot be achieved through enhanced OFDM-based receiver schemes at similar or lower implementation complexity or where no such OFDMbased alternative exists, OTFS’s advantage should be explicitly established. | | |
| [16] | [R1-2505640](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505640.zip) | Discussion on 6G Waveform | NEC |
|  | **Proposal 1:** CP-OFDM and DFT-s-OFDM in NR are baseline as 6GR uplink waveform. 6GR could study to support dynamic waveform switching during initial access.  **Proposal 2:** 6GR strives for a unified waveform baseband generation and upconversion for all channels and signals including PRACH.  **Observation 1:** Key 6G requirements, like support for NTN and a strong focus on Network Energy Savings from Day-1, create an immediate need for a downlink waveform that offers better coverage and power efficiency than the 5G baseline.  **Proposal 3**: Study the support of low PAPR waveforms like DFT-s-OFDM for 6G downlink transmissions.  **Proposal 4**: Study the waveform configuration mechanism. This study should evaluate the trade-offs between a fixed configuration per cell and semi-static DL waveform switching.  **Proposal 5** Study multi-user scheduling techniques for downlink DFT-s-OFDM to balance throughput with low-PAPR properties. | | |
| [17] | [R1-2505649](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505649.zip) | Discussion on waveform for 6GR air interface | Pengcheng Laboratory |
|  | **Proposal 1**: Waveform design for 6GR should account for Inter-Symbol-and-Carrier Interference (ISCI) in high mobility scenarios to maintain reliable communication and sensing performance.  **Proposal 2**: A unified waveform design framework would be beneficial to simultaneously support communication and sensing functionalities (ranging/velocity estimation/imaging) in 6G systems. | | |
| [18] | [R1-2505675](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505675.zip) | Discussion on waveform for 6GR air interface | Ofinno |
|  | **Observation 1:** High spectral efficiency is achievable using OFDM based waveforms (CP-OFDM and DFT-s-OFDM) in 6G.  **Observation 2:** CP-OFDM and DFT-s-OFDM being associated with different levels of PAPR, can be used for uplink transmission in different cell coverage scenarios.  **Observation 3:** CP-OFDM and DFT-s-OFDM in 6G will greatly reduce implementation effort to support multi-RAT spectrum sharing (MRSS) between the 5G and 6G systems.  **Observation 4:** Advanced antenna techniques (e.g., increasing number of antenna elements) can be employed to enhance the coverage of 6G in 7GHz comparable to that of 5G in 3.5 GHz.  **Observation 5:** From the coverage point of view, in refarmed bands and in new spectrum (i.e., 7 GHz), CP-OFDM and DFT-s-OFDM are considered as baseline for the evaluation of the waveform in 6G.  **Observation 6:** CP-OFDM and DFT-s-OFDM are suitable for most practical radio environments in which 6G will be deployed.  Observation 7: The scalable nature of the numerologies in the OFDM-based waveform will allow easy implementation of CP-OFDM and DFT-s-OFDM over wide range of frequencies supported in 6G.  **Observation 8:** The existing 5G waveforms (CP-OFDM and DFT-s-OFDM) were considered feasible for NTN operation based on extensive studies in Rel-15 [TR 38.811].  **Observation 9:** The feasibility of sensing including the use cases and the waveform for sensing will be separately studied under Objective (9) of the 6G study item.  **Proposal 1:** Consider CP-OFDM for downlink transmission as baseline candidate for the evaluation of the waveform in 6GR.  **Proposal 2:** Consider CP-OFDM and DFT-s-OFDM uplink transmission as baseline candidates for the evaluation of the waveform in 6GR.  **Proposal 3:** Waveform related to ISAC is separately discussed from 6G waveform for 6GR Physical Layer structure. | | |
| [19] | [R1-2505679](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505679.zip) | Study on Waveform Enhancements | IITH and WiSig |
|  | **Proposal 1.** Include OTFDM as a candidate waveform for UL and DL (a companion contribution discusses its applicability for DL) focusing on coverage, latency, and Doppler KPIs.  **Proposal 2.** Define shaping options Pre-/post-DFT shaping (including “excess subcarrier” use to time limit the ISI channel and enable pre DFT DMRS inclusion) and/or post-IFFT filtering to confine spectrum mask to standardize PA-friendly spectra.  **Proposal 3.** Codify single-symbol operation: normative intra-symbol DMRS formats, CP options, and scheduler hooks for one-shot transmissions.  **Proposal 4.** Set UE Tx power classes for handheld and FWA across legacy and new 6G bands; align with MPR referenced to π/2-BPSK.  **Proposal 5.** Develop mobility benchmark with per-symbol DMRS to benchmark high-Doppler performance.  **Proposal 6.** Evaluate OTFDM usage in both DL and UL for coverage expansion | | |
| [20] | [R1-2505680](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505680.zip) | Uplink Control Channel Enhancements for 6G NR | IITH and WiSig |
|  | Not waveform related | | |
| [21] | [R1-2505702](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505702.zip) | Discussion on waveform for 6GR air interface | Panasonic |
|  | **Proposal 1:** 6GR should allow certain time / frequency resources can be different waveform for forward compatibility perspective and to support MRSS.  **Proposal 2:** For 6GR waveform design, time/frequency grid should be allowed to be aligned and orthogonal with NR boundary.  **Proposal 3:** OFDM-based waveform should be supported for 6GR. The definition of “OFDM-based” is to have subcarrier mapping and IFFT to generate time-domain signal.  **Proposal 4:** To have multiple waveforms should be considered to satisfy diverse requirements of 6GR.  **Proposal 5:** At least to support CP-OFDM for higher spectral efficiency (for both DL and UL) and DFT-s-OFDM for coverage enhancement (for UL) can be baseline.  **Proposal 6:** Any enhancements to CP-OFDM or DFT-s-OFDM and/or any newly introduced waveform must demonstrate clear and justified advantages over 5G waveform.  **Proposal 7:** RAN1 can assess the need to introduce PAPR/CM reduction techniques targeting coverage enhancement, especially for UL.  **Observation 1:** From system perspective, there are many challenges to support DFT-s-OFDM in DL, for example to multiplex SSB and other channel jointly, and the, the motivation of low PAPR waveform in DL is unclear.  **Proposal 8:** RAN1 can access the need to introduce OTFS-based waveform targeting severe delay-Doppler scenario and/or sensing scenarios. | | |
| [22] | [R1-2505757](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505757.zip) | Discussion on waveform and multiple access for 6G Radio | OPPO |
|  | **Proposal 1**: A unified 6GR baseline waveform is studied to fulfil the requirements of 6G MBB (Immersive Communication) and 6G IoT (Massive Communication). The baseline waveform is used for 6G HRLLC.  **Proposal 2**: Study waveforms to fulfil the requirement of 6G Sensing and 6G NTN (Ubiquitous Connectivity). Strive for reusing the 6GR baseline waveform for 6G Sensing and 6G NTN. An additional waveform can be considered if significant gain over the baseline waveform can be justified for a specific vertical scenario, but only supported by the vertical BS/UE.  **Proposal 3:** For studying the 6GR baseline waveform, evaluate waveform proposals using 5G NR waveform (i.e. CP-OFDM for DL and CP-OFDM/DFT-s-OFDM for UL) as the benchmark, with the consideration of following: Spectrum efficiency. Coverage. NW and UE side complexity. Compatibility and neutrality for proposals in other areas, i.e., no restriction to or bundling with specific proposals for 6G MIMO, modulation, channel coding, AI/ML enhancements, etc. Support flexible frequency-domain (e.g. RB-level) and time-domain (e.g. symbol-level) resource allocation. Support of efficient 5G/6G spectrum sharing.  **Proposal 4:** For studying the 6GR baseline waveform, support up to 2 waveforms in DL and up to 2 waveforms in UL, e.g., one optimized for spectrum efficiency, one optimized for coverage. At least 1 waveform in DL and 1 waveform in UL are mandatory supported for all device types, e.g. CP-OFDM in DL and DFT-s-OFDM in UL. The 2nd waveform can be considered for 6G MBB s which shares the processing units with the 1st waveform as much as possible.  **Proposal 5:** Study multiple access (MA), targeting a single MA scheme for each waveform, to fulfil the requirement of all 6G usage scenarios using this waveform.  **Proposal 6:** Orthogonal multiple access (OMA) is the baseline for 6GR. Evaluate OMA proposals using 5G NR as the benchmark, with the consideration of following: Spectrum efficiency. Coverage. NW and UE side complexity. Compatibility and neutrality for proposals in other areas, i.e., no restriction to or bundling with specific proposals for 6G MIMO, modulation, channel coding, AI/ML enhancements, etc. Support flexible frequency-domain (e.g. RB-level) and time-domain (e.g. symbol-level) resource allocation. Support of efficient 5G/6G spectrum sharing. | | |
| [23] | [R1-2505770](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505770.zip) | Discussions on waveform for 6G radio | Intel |
|  | **Observation 1:** For DFT-s-OFDM waveform with frequency domain spectrum shaping (FDSS): For π/2 BPSK, FDSS without spectrum extension can deliver better link level performance compared to FDSS with spectrum extension for different extension factors. For QPSK, FDSS with spectrum extension can perform better than FDSS without spectrum extension when extension factor 𝛼 = 3/8 is applied.  **Observation 2:** For DFT-s-OFDM waveform with frequency domain spectrum shaping (FDSS): When FDSS-SE with symmetric extension is applied for PUSCH transmission, PAPR and CM reduction can be observed compared to conventional DFT-s-OFDM waveform. For π/2 BPSK, FDSS with symmetric extension and FDSS without spectrum extension can provide better PAPR/CM reduction compared to FDSS with cyclic extension. For QPSK, FDSS with both symmetric and cyclic extension can provide better PAPR/CM reduction compared to FDSS without spectrum extension  **Proposal 1:** For 6G waveform, at least for eMBB service: For DL transmissions, RAN1 to consider CP-OFDM waveform as baseline. For UL transmissions, RAN1 to consider both CP-OFDM and DFT-s-OFDM waveform as baseline  **Proposal 2:** For 6G waveform, at least for eMBB service: For UL transmissions, RAN1 to further study techniques to reduce PAPR/CM. Potential waveform choices may include frequency domain spectrum shaping with and without spectrum extension.  **Proposal 3:** For 6G, RAN1 to further study potential enhancement for DL waveform at least for eMBB service, considering aspects of UE multiplexing, CA, MIMO and PAPR/CM reduction. | | |
| [24] | [R1-2505781](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505781.zip) | On Waveform Considerations for 6GR Air Interface | Lekha Wireless Solutions |
|  | **Observation 1:** As new spectrums are getting standardized for cellular and non-cellular deployments, the issues of PA efficiency, phase noise and high Doppler continue to plague the performance of traditional OFDM systems. This calls for the adoption of a new waveform that can counter the adversities suffered by OFDM, keeping OFDM performance as baseline.  **Observation 2:** There are a number of front runners in the list of possible 6G waveforms. Each one has its own set of use-cases and benefits. Hence, it is crucial to evaluate all the candidate waveforms in different scenarios and parameters to select the most suitable candidate.  **Proposal 1:** Standardization of new spectrums for cellular and non-cellular deployments adds to issues like PA efficiency, phase noise, and high Doppler in traditional OFDM systems. As such, new waveforms are being considered, each of which comes with unique use-cases and benefits, hence requiring evaluation in various scenarios, keeping OFDM as baseline. | | |
| [25] | [R1-2505787](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505787.zip) | Discussion on waveform for 6GR | LG Electronics |
|  | **Proposal 1:** Following principles form the foundation for the waveform study in 6GR and guide the evaluation of both continuity with 5G NR and the exploration of new waveform candidates.   * To ensure smooth evolution and coexistence with legacy networks, waveform design must maintain compatibility with 5G NR wherever possible. * Minimize complexity and support diverse 6G services such as TN/NTN integration, joint communication and sensing, and massive IoT. * Future enhancements or new signal/channel structures should avoid significant increases in implementation complexity to ensure broad feasibility and scalability.   **Proposal 2:** CP-OFDM for both downlink and uplink, and DFT-s-OFDM for uplink should be adopted for 6GR as baseline waveforms.  **Proposal 3:** Low-PAPR waveform (e.g., DFT-s-OFDM) for DL transmission(s) can be studied as a candidate waveform in the 6GR study.  **Proposal 4:** The potential and operation of spreading OFDM waveforms to enhance diversity gain should be studied for the 6GR system.  **Proposal 5:** RAN1 studies Doppler-robust waveforms for critical physical channels (e.g., synchronization signals, PRACH, DL/UL reference signals, etc.) for high-mobility/NTN scenarios.  **Proposal 6**: A new waveform such as FMCW is studied for sensing as well as OFDM. | | |
| [26] | [R1-2505792](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505792.zip) | Discussion on 6GR Waveform | Lenovo |
|  | **Proposal 1:** Study waveform enhancement techniques targeting 6GR coverage enhancement, energy efficiency improvement and support of sensing while maintaining compatibility with current waveforms’ structures, complexity constraints, and support of MRSS.  **Observation 1:** With selected mapping scheme, the number of used sequences is important for PAPR/CM reduction, e.g., a gap of 0.5dB can be seen between 8 and 4 sequences.  **Proposal 2**: Study and evaluate CP-OFDM waveform enhancement techniques including PAPR/CM reduction techniques such as Selected Mapping (SLM) and Tone Reservation (TR) for coverage enhancement and energy efficiency improvement, and compare to implementation-based techniques in terms of complexity, signal distortion, and spectral efficiency.  **Observation 2:** FDSS using conventional filter methods (e., root-raised cosine, Hamming, Hanning, etc.) can give a good reduction in PAPR, however, the reduction of CM can be minor in some cases.  **Proposal 3:** Study enhancing DFT-s-OFDM waveform by incorporating PAPR/CM reduction techniques such as FDSS, DFT precoder extension, etc.  **Observation 3:** Sub-band/group based DFT scheme achieves approximately a 2.75 dB cubic metric (CM) gain compared to the CP-OFDM waveform, and a 1.31–2.68 dB gain over per UE DFT-S-OFDM which translates into reductions of more than 30% in the number of repetitions required to achieve a 10% BLER.  **Proposal 4:** Evaluate the feasibility of DFT-s-OFDM in DL for NTN and IoT use cases, focusing on coverage enhancement, NES, and UE power saving.  **Proposal 5:** The study and evaluation of waveform enhancements should focus on CM characteristic of the waveform. | | |
| [27] | [R1-2505827](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505827.zip) | Waveform for 6GR air interface | InterDigital, Inc. |
|  | **Observation 1:** For 6G communication, similar requirements compared to 5G can be applied to waveforms; coverage extension and high throughput  **Proposal 1:** CP-OFDM is the baseline downlink waveform for 6GR; support additional waveforms including a new waveform only if strong justifications can be demonstrated  **Proposal 2:** DFT-s-OFDM and CP-OFDM are the baseline uplink waveforms for 6GR; support additional waveforms including a new waveform only if strong justifications can be demonstrated  **Proposal 3:** Support dynamic waveform switching for the uplink  **Observation 2:** During Release 18 coverage enhancement study, performance gains in terms of PAPR reduction for the uplink DFT-s-OFDM were observed using techniques such as tone reservation or FDSS-SE  **Observation 3:** Coverage enhancing features shall be supported from Day 1 in 6G  **Proposal 4:** Study PAPR reduction techniques for uplink DFT-s-OFDM to support coverage enhancement for 6G  **Proposal 5:** The following KPIs relevant for communication should be evaluated when studying PAPR reduction techniques or a new waveform: Spectral efficiency (bps/Hz), BLER, Cubic metric, PAPR  **Proposal 6:** Waveform for sensing is not covered in Agenda Item 11.3.1 and shall be studied separately in Agenda Item 11.14 | | |
| [28] | [R1-2505913](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2505913.zip) | Waveforms for 6GR air interface | Apple |
|  | **Observation 1:** Low PAPR Waveform provides benefit in coverage (allows a higher output power without waveform saturation) and energy efficiency (depends on PA type and operating mode)  **Proposal 1:** future low PAPR waveform evaluations should adopt a multi-dimensional metric framework centered on Net Gain, spectral compliance, and realistic RF and receiver assumptions.  **Observation 2:** Optimization over FDSS (beyond 3-tap) achieves ~1.3-1.4dB PAPR using legacy 5G-NR pi/2-BPSK DFTs + FDSS. However, due to possible variation of gNodeB receiver implementation, UE may have to choose a relatively conservative FDSS per RAN4’s equalizer flatness guidance, resulting in high PAPR (3-4dB) instead of a constant envelop waveform  **Observation 3:** Using the 3-tap filters that approximate GMSK pulse shaping filter achieves the lowest PAPR among the nominal 5G-NR pi/2-BPSK + FDSS, but leave a gap to the ideal 0dB PAPR of a true constant-envelope waveform.  **Observation 4:** The introduction of non-transparent methods such as the FDSS-SE results in a further reduction in PAPR. This may be further reduced in the case that the FDSS is known by the receiver and an advanced receiver is used  **Proposal 2:** Study enhancement of Low PAPR Waveform for PUSCH and PUSCH-DMRS, such as FDSS (e.g. approximating GMSK) and BW extension, for achieving coverage enhancement in the DFTs-OFDM framework  **Proposal 3:** Study both spec. transparent and non-transparent methods for PAPR reduction. Consider the use of both baseline and advanced receivers  **Proposal 4:** Consider overall trade-offs between low PAPR and demod/decode performance, Rx complexity, RF requirement. Evaluation assumptions considering realistic channel estimation and realistic PA nonlinearity | | |
| [29] | [R1-2506020](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2506020.zip) | Waveform for 6GR air interface | MediaTek Inc. |
|  | **Observation 1:** The development of a configurable waveform framework is paramount, allowing for the dynamic optimization of waveforms for each specific usage scenario.  **Observation 2:** A holistic consideration and joint design of waveform, modulation, and coding schemes are crucial to unlock key enhancements in 6G.  **Observation 3**: 6G waveform needs to be configurable, legacy-compatible, and upgradable.  **Proposal 1:** CP-OFDM to serve as the baseline waveform configuration within the 6G waveform framework.  **Proposal 2:** With DFT as a pre-coder, DFT-s-OFDM should be supported within the 6G waveform framework.  **Proposal 3:** For enhancement and optimization of a given 6G usage scenario, the corresponding waveform enhancement should consist of a scenario-dependent pre-coder followed by CP-OFDM, or more broadly, a concatenation of scenario- dependent coded modulation and CP-OFDM.  **Proposal 4**: Under the pre-coded CP-OFDM framework described in Proposal 3, study the low PAPR pre-coder design for coverage enhancement. | | |
| [30] | [R1-2506065](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2506065.zip) | Discussion on 6GR waveform | ETRI, University of Surrey |
|  | **Proposal 1.** OFDM-based waveforms should be maintained as the baseline waveform candidate for 6G radio due to their maturity, ecosystem readiness, and easy migration from 5G  **Proposal 2.** RAN1 to investigate at least one additional waveform candidate alongside OFDM with the 6G Study Item.  **Proposal 3.** Any additional waveform considered should be closely related to OFDM waveform in structure and implementation, enabling smooth migration from existing NR designs and reuse of legacy HW.  **Proposal 4.** RAN1 to consider the following criteria for 6GR waveform evaluation:   * Extensibility from OFDM waveform for ease of migration from 5G NR * Enough level of performance benefits for selected target use cases * Implementation complexity and power efficiency * Support for diverse deployment scenarios * Feasibility within 6G SI timeline   **Observation 1.** The favorable properties and compatibility of AFDM with OFDM-based systems make it a valuable candidate for further study during the 6G waveform evaluation phase.  **Proposal 5.** RAN1 to consider AFDM as an additional waveform candidate for 6G radio. | | |
| [31] | [R1-2506097](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2506097.zip) | Discussion on the waveform design for 6G radio | CMCC |
|  | **Observation 1.** For improved data rate and spectrum efficiency of immersive communication, the key waveform design considerations include:   * Support efficient spectrum utilization considering the potential complicated multiplexing scheme. * Support efficient and convenient combination with massive MIMO scheme. * Support efficient implementation of signal processing in the case of 200 MHz or 400 MHz channel bandwidth.   **Observation 2.** For optimized energy efficiency and energy saving of immersive communication, the key waveform design considerations include:   * Potentially support PAPR reduction for lower OPEX of network and longer battery life of UE. * Potentially support non-coherent detector for downlink LP-WUS.   **Observation 3.** For efficient 5G-6G Multi-RAT spectrum sharing, the key waveform design considerations include: Support good intra-band coexistence between 5G and 6G RAN, with small frequency guard interval.  **Observation 4.** For massive communication, the key waveform design considerations include: Low PAPR waveform for uplink transmission, which can benefit both coverage enhancement and low UE power consumption.  **Observation 5.** For ISAC, the key waveform design considerations include: Potentially support long-range sensing by e.g. sufficient CP length for OFDM-based sensing signal or specific pulse waveform.  **Observation 6.** For NTN, the key waveform design considerations include: Potentially support PAPR reduction to increase maximum transmit power in both downlink and uplink.  **Proposal 1.** A compatible waveform design suitable for a wide range or even full-range of target use cases is preferred, while the necessity of a specific design for some individual use case has to be carefully justified.  **Proposal 2.** The following aspects need to be considered for the justification of PAPR reduction design:   * The PAPR reduction gain, for which PAPR, MPR, or other new metric (e.g., cubic metric) can be used. * Impact on signal quality, for which the degradation of e.g., EVM and/or link performance can be used. * Overhead, which can be represented as the percentage of the decreased data rate comparing to the case without the proposed PAPR reduction method. * Impacts on implementation, which is to identify the potential significantly increased complexity or big change to the conventional OFDM scheme.   **Proposal 3.** CP-OFDM is the baseline for the downlink waveform of 6G radio.  **Proposal 4.** Both CP-OFDM and DFT-s-OFDM waveform are the baseline for the uplink waveform of 6G radio. | | |
| [32] | [R1-2506117](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2506117.zip) | Considerations for 6GR waveform | Sony |
|  | **Proposal 1:** RAN1 should study OFDM and DFT-s-OFDM as baseline waveforms for 6GR as well as at least OTFS and AFDM as candidate waveforms. In this study, RAN1 should consider the following criteria for assessing the waveforms:   * Ease of multiplexing users (in time, frequency and spatially), reference and other signals * Time and frequency offset sensitivity * PAPR * DMRS overhead requirement * Ease of implementation in 6G using 5G as baseline * Flexibility – numerology * ISAC amenability * Latency * Modulation complexity * Channel estimation complexity   **Proposal 2:** RAN1 should study PAPR reduction schemes for application to CP-OFDM 6GR.  **Proposal 3:** RAN1 should study multi-layer transmission with high order modulation for DFT-s-OFDM in 6GR.  **Proposal 4:** RAN1 should include OTFS in its study of 6GR waveforms especially on aspects of signal multiplexing and its impact on spectral efficiency, as well as implementation complexity.  **Proposal 5:** RAN1 should include AFDM in its study of 6GR waveforms. | | |
| [33] | [R1-2506140](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2506140.zip) | Discussion on Waveforms of 6GR Air Interface | Rakuten Mobile, Inc |
|  | **Observation 1:** When sharing a frequency band within FR1, if an existing RAT, either LTE or NR, is configured to use part of the band, and another wireless technology uses the remaining portion with the same OFDM waveform and subcarrier spacing, mutual interference between the systems can be avoided. The absence of interference allows all subcarriers across the band to be fully utilized by either system, ensuring optimal use of the available radio resources.  **Observation 2:** When sharing a frequency band within FR1, if an existing RAT, either LTE or NR, is configured to use part of the band, and another wireless technology uses the remaining portion with the same OFDM waveform but a subcarrier spacing that is either a multiple or a fraction of the other, mutual interference is minimal. In such cases, only a few subcarriers of the system of smaller subcarrier spacing near the boundary between the two systems may be affected. The radio resources across the band can still be utilized effectively.  **Proposal 1:** For 6GR operating in FR1, the OFDM is only one the waveform adopted, with subcarrier spacing options supported by 5G NR. Restrict the selection of subcarrier spacing configurations within each FR1 band to a limited set suitable for deployment to prevent undue complexity in the specifications.  **Proposal 2:** For 6GR operating in the designated frequency ranges rather than FR1, any proposal involving a non-OFDM waveform must clearly justify the additional cost compared to OFDM and demonstrate ease of integration with multi-antenna technologies.  **Proposal 3:** 6GR should support optional pre-transformation techniques for peak-to-average power ratio (PAPR) reduction in uplink transmissions and also for downlink transmissions supported by space or airborne elements.   * For systems using the OFDM waveform, the legacy DFT-spread OFDM (DFT-s-OFDM) is proposed as a candidate. * If alternative waveforms are adopted for 6G, their PAPR characteristics must be thoroughly evaluated, and suitable pre-processing methods should be developed to achieve PAPR performance comparable to that of DFT-s-OFDM. | | |
| [34] | [R1-2506218](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2506218.zip) | Waveforms for 6GR | Qualcomm Incorporated |
|  | **Proposal 1:** For 6G Radio waveform study, limit initial focus to waveform design for communication use cases. Waveforms for other use cases such as sensing to be discussed separately.  **Observation 1:** CP-OFDM and DFT-S-OFDM waveforms have performed well and met the needs of a varied set of 5G use cases and bands.  O**bservation 2:** Potential areas of focus for 6G waveforms include:   * Waveforms for cell-edge UEs * Waveforms for multi-layer transmissions in uplink * Better spectrum utilization * Enabling higher power uplink transmission * More flexibility in scheduling, waveform usage and spectrum usage in uplink   **Proposal 2:** Design considerations for 6G waveform study for communication purposes to include:   * new spectrum bands and associated requirements, e.g large BW * needs for new deployment scenarios, e.g. suburban macro, FWA, etc. * duplex operation, e.g., subband full duplex * enhancing coverage, e.g. design of low PAPR waveforms * Support for high power transmissions in uplink, e.g., higher power classes, MPR optimizations * integration with use cases such as sensing and positioning * Co-channel and adjacent channel requirements * Support for spatial multiplexing, beamforming, multiple access * Transceiver complexity associated with synthesis and reception; processing latency * Energy/power efficiency * Considerations on backward compatibility and coexistence with 5G * Scheduling flexibility and agility   **Proposal 3:** With backward compatibility, scalability, and flexibility in mind, and to leverage technologies and solutions developed for 5G, it is suggested that the 6G waveform study focus on the CP-OFDM and the DFT-S-OFDM family of waveforms. Potential enhancements or new waveform families must be compatible with the CP-OFDM framework, i.e., support time & frequency multiplexing with baseline waveforms & facilitate hardware reuse.  **Proposal 4:** In 6GR study on waveforms, focus on enhancements to the DFT-S-OFDM family of waveforms.  **Observation 3:** DFT-S-OFDM waveforms with Pi/2 BPSK modulation satisfy the following frequency domain property: , where are the frequency domain samples and L is the DFT size.  **Proposal 5:** For 6GR, study the family of low PAPR waveforms obtained using DFT-S-OFDM with Pi/2 BPSK and truncated mapping.  **Proposal 6:** For 6G Radio, support multi-layer DFT-S-OFDM transmissions in uplink.  **Proposal 7:** For 6GR waveform study, for DFT-S-OFDM waveforms, decouple the size of allocation from the DFT size. Define any DFT size that is a product of powers of 2, 3 and 5 as a valid DFT size. For any given allocation, determine the actual DFT size to use as the nearest valid DFT size smaller than the size of allocation.  **Proposal 8:** For 6GR waveform study, when considering DFT-S-OFDM waveforms, consider flexible frequency-domain mapping of the DFT output to the spectrum allocation.  **Proposal 9:** For 6GR waveform study, consider multi-tx enhancements for DFT-S-OFDM where different transmit ports transmit over different frequency domain allocations.  **Proposal 10:** For 6GR waveform study, consider feasibility to enhance spectrum utilization for small channel bandwidths using spectrum confinement techniques (e.g. WOLA) of reasonable complexity.  **Proposal 11:** For 6GR waveform study, consider waveforms and waveform shaping techniques that facilitate the support of high power uplink transmissions for higher power class UEs and further tightening the associated MPRs for different modulation orders. | | |
| [35] | [R1-2506239](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2506239.zip) | Requirements for 6GR Waveform Design | AT&T |
|  | **Proposal 1** The full capability of 6GR is realized with radio refresh in existing bands or in new greenfield bands while 6G deployment with existing open radios in legacy bands leveraging efficient 5G-6G MRSS is also possible.  **Proposal 2** After network attach, through RRC (re)configuration, novel air interface designs can be considered, as long as coexistence with the OFDM time-frequency grid as specified in 5G NR is ensured and the enhancement over 5G NR addresses an urgent, real-world need in a particular deployment or scenario. | | |
| [36] | [R1-2506268](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2506268.zip) | Study on waveform for 6GR | Sharp |
|  | **Proposal 1:** RAN1 should study CP-OFDM for 6GR.  **Proposal 2:** RAN1 should study DFT-s-OFDM for 6GR.  **Proposal 3:** RAN1 should study Interlace OFDM for 6GR.  **Proposal 4: To** avoid excessive configurations, excessive UE capabilities and UE capabilities reporting, 6G waveforms should be applied to diverse use cases/device types.  **Proposal 5:** RAN1 should study nonlinear PA effects.  **Proposal 6:** For FR2, RAN1 should study the phase noise effects.  **Proposal 7:** RAN1 should study phase noise effects under multiple phase noise models for diverse devices.  **Proposal 8:** RAN1 should study the doppler shift effects.  **Observation 1:** Interlace OFDM has the following advantages:   * (1) Power boosting * (2) Mitigation of frequency offset and phase noise effects * (3) OFDM symbol repetition * (4) BWP-level multiplexing   **Observation 2:** Regarding BER performance under attenuation-only channel without PA and without phase noise, Interlace OFDM with M = 2 has 3dB SNR gain compared to CP-OFDM.  **Observation 3:** Regarding PAPR performance, DFT-s-OFDM outperforms Interlace OFDM with M = 2, 6 and CP-OFDM.  **Observation 4:** Regarding BER performance for attenuation-only channel without PA and with phase noise, the phase noise effect is negligible when a carrier frequency is 3.5GHz and the subcarrier spacing is 30kHz.  **Observation 5:** Regarding BER performance for attenuation-only channel without PA and with phase noise, the phase noise effect of Interlace OFDM is smaller than | | |
| [37] | [R1-2506306](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2506306.zip) | Discussion on Waveform | NTT DOCOMO, INC. |
|  | **Observation 1:** Wider coverage may be needed for 6G. For 6GR waveform, PAPR performance improvement for better coverage, especially for uplink, may benecessary for 6GR. It should be noted that there are several other aspects that should be considered together with PAPR performance, such as use cases, achievable link budget, system-wise performance when it is deployed  **Observation 2:** DFT-s-OFDM enhancement with SE, including FDSS-SE and FDSS-CE, can reduce PAPR performance to achieve better coverage, which can be considered the waveform candidates for 6G uplink  **Observation 3:** FDSS-CE requires lower implementation complexity than FDSS-SE based on the serial implementation method for asymmetric SE  **Observation 4:** FDSS-SE, FDSS-CE can achieve a larger PAPR gain than DFT-s-OFDM under a larger SE factor  **Observation 5:** Under the same SE factor, FDSS-CE achieves a larger PAPR gain than FDSS-SE  **Observation 6:** FDSS-SE, FDSS-CE can achieve PAPR gain for any bandwidth; Under the same bandwidth, FDSS-CE achieves a larger PAPR gain than FDSS-SE  **Observation 7:** FDSS-SE, FDSS-CE can achieve a better link budget than DFT-s-OFDM; Under the same SE factor, FDSS-CE achieves a better link budget than FDSS-SE  **Observation 8:** Under the same payload, FDSS-SE, FDSS-CE will result in spectrum efficiency loss compared to DFT-s-OFDM  **Observation 9:** FDSS-SE, FDSS-CE result in larger spectrum efficiency loss than DFT-s-OFDM under a larger SE factor  **Proposal 1:** For 6GR study on waveform,   * Only OFDM-based waveform(s) should be considered (as described in the SID) * Any new waveform(s), even for OFDM-based, should be justified by clear gain * Unified design across scenarios/use cases is strongly preferred * Following the above, RAN1 can carefully assess the need in 6GR to introduce waveform(s) beyond 5G NR, targeting, e.g., PAPR performance improvement for better site coverage, especially for UL | | |
| [38] | [R1-2506320](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2506320.zip) | Discussion on Waveform for 6GR Air Interface | Indian Institute of Tech (M), IIT Kanpur, CEWiT |
|  | **Observation 1:** Waveforms with better PAPR are required to ensure energy efficiency and to support higher frequencies and NTN systems.  **Proposal 1:** 3GPP should study the option of enabling mechanisms for PAPR reduction techniques in CPOFDM.  **Proposal 2:** 3GPP should consider the use of DFT-s-OFDM in DL/UL at least for NTN and FR2 use-cases.  **Proposal 3:** Study the use of single carrier TDMA bursts in the current frame structure for NTN.  **Proposal 4:** 3GPP should support multiplexing of waveforms as required. | | |
| [39] | [R1-2506333](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2506333.zip) | Orthogonal Sequence Division Multiplexing for 6GR | Anemone Technology |
|  | **Observation 1:** At an SNR of 35 dBs the throughput of OSDM is 85% higher than OFDM with 16QAM in the 3GPP TDL-C channel with an RMS delay spread of 1148 ns and Doppler shift of 25 Hz.  **Observation 2:** At an SNR of 35 dBs the throughput of OSDM is 92% higher than OFDM with 1024QAM in the 3GPP TDL-C channel with an RMS delay spread of 383 ns and Doppler shift of 10 Hz.  **Proposal 1:** To study the application of OSDM to 6GR. | | |
| [40] | [R1-2506359](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2506359.zip) | Waveform design for 6G | CEWiT, IITM, Tejas, IITK |
|  | **Observation 1:** Waveform with better energy efficiency is required to ensure sustainability, support higher frequencies and NTN systems.  **Proposal 1:** Investigate usage of DFT-s-OFDM in DL at least for NTN and FR2 usecases.  **Proposal 2:** Support studying the performance of OFDM with phase modulation or LFM as a candidate waveform for sensing use cases.  **Proposal 3:** In 6GR, support OOK based waveforms atleast for low end devices.  **Proposal 4:** Support multiplexing of waveforms based on criteria like time and frequency resource, physical channels, and physical signals.  **Proposal 5:** Support multiplexing of OFDM for communication and phase modulation or LFM for sensing use case. | | |
| [41] | [R1-2506383](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_122/Docs/R1-2506383.zip) | 6G Waveform Study considerations | Reliance Jio |
|  | **Proposal:** The new 6G Radio SI shall study possible new waveforms for multiple specific vertical use cases such as NTN, IoT, V2X, broadcast etc apart from eMBB. | | |