3GPP TSG RAN WG1 Meeting #122bis R1-250xxxx
Prague, Czech
13th – 17th October 2025

**Agenda item: 11.4.2**

**Title: FL summary #1 on modulation, joint channel coding and modulation**

**Source: Modulator (Qualcomm Incorporated)**

**Document for: Discussion/Decision**

# Introduction

From [1], for Physical Layer structure for 6GR, we have the following objective

1. Physical Layer structure for 6GR,
	1. Waveforms (OFDM-based) and modulations. 5G NR Waveforms and modulation should be considered for 6GR and is also the benchmark for other potential proposals. [RAN1, RAN4]

The following email thread is assigned for the discussion

In this contribution, we summarize the contributions submitted to agenda item 11.4.2 on modulation, joint channel coding and modulation, and discussion during the meeting.

# Discussion

## Discussions on legacy uniform QAM constellations

According to SID [1], 5G NR modulation should be considered for 6GR. There are various proposals to further enhance modulation. The following tries to capture the discussion on the topic.

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| --- | --- |
| Company | Position |
| Nokia | * For 6GR DL, 5G NR uniform QPSK, 16QAM, 64QAM, 256QAM and 1024QAM are supported for data channel
* For 6GR UL, 5G NR uniform QPSK, 16QAM, 64QAM, and 256QAM are supported for CP-OFDM for data channel
* For 6GR UL, 5G NR pi/2 BPSK, uniform QPSK, 16QAM, 64QAM, and 256QAM are supported for DFT-s-OFDM for data channel
* FFS: Enhancements and other modulation schemes
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| Spreadtrum | * No need to introduce new modulation in 6GR day 1.
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| ZTE | * The maximum modulation order can be considered for 6GR UL is 1024QAM.
 |
| Xiaomi | * For 6GR DL, 5G NR uniform QPSK, 16QAM, 64QAM, 256QAM and 1024QAM are supported as basis for data channel
* For 6GR UL, 5G NR uniform QPSK, 16QAM, 64QAM, and 256QAM are supported as basis for CP-OFDM for data channel
* For 6GR UL, 5G NR pi/2 BPSK, uniform QPSK, 16QAM, 64QAM, and 256QAM are supported as basis for DFT-s-OFDM for data channel.
* For channels other than the data channel, RAN1 clarifies under which agenda item the discussion should proceed.
* For enhanced modulation schemes for PAPR reduction based on uniform modulation, RAN1 clarifies under which agenda item the discussion should proceed.
* Regarding the maximum modulation order, up to 1024QAM for DL and up to 256QAM for UL are the baseline for data channel for 6GR.
	+ Study the applicable frequency ranges for 1024QAM.
	+ For the study of 4096QAM for DL and 1024QAM for UL, need to consider performance, complexity, requirements, applicable scenarios, associated restrictions, and challenges and solutions.
 |
| HW | * Full study shall be performed before making decision on whether to introduce a higher modulation order for 6GR, at least on the following aspects:
	+ Feasibility, taking into account challenges like high requirement of EVM
	+ Achievable benefits and the associated applicable scenarios, taking into account aspects like interference impacts
 |
| CATT | * Observation 1: 4096-QAM offers significant spectral efficiency gains but suffers from high PAPR and increased sensitivity to frequency and phase noise, leading to greater implementation challenges.
* Proposal 1: 1024-QAM is recommended for downlink reuse, while uplink modulation should be limited to a maximum of 256-QAM due to UE transmit power constraints.
 |
| Oppo | * Observation 1: 4096QAM requires approximately -38 dB EVM, reflecting a 6 dB reduction compared to the NR 1024QAM EVM requirement. This stringent EVM requirement for 4096QAM would cause deployment barriers and further increase hardware cost.
* Observation 2: In both UMa and UMi scenarios, only a very limited subset of UEs’ link quality is enough to support 4096QAM. It can be expected that 4096QAM may bring marginal gains on the system throughput and cell average spectral efficiency.
* Proposal 1: For the study of high-order modulation, the implementation feasibility, such as EVM requirement and applicability in practical deployment scenarios shall be considered.
 |
| Ericsson | * Support 5G NR uniform QAM constellation as the basis modulation scheme for 6G.
* Support at least QPSK, 16 QAM, 64 QAM and 256 QAM for uplink.
* Support at least QPSK, 16 QAM, 64 QAM, 256 QAM and 1024 QAM for downlink.
* 6G devices with high capability for FWA use case may benefit from supporting higher order modulation and advanced modulation schemes under near-LoS propagation condition.
* Study modulation schemes for high power and high capability services to maximize spectrum efficiency.
* Performance of higher order modulation is sensitive to radio impairment such as EVM over the transmitting OFDM symbols.
* Realistic hardware impairment assumptions, including EVM requirement, shall be considered while evaluating modulation schemes, especially at higher order modulations.
* MPR or A-MPR value increases at higher modulation order and decreases at lower PAPR.
* Uplink evaluations shall consider the MPR/A-MPR range and the PAPR property of the waveform.
 |
| Lenovo | * Observation 1: Utilizing π/2-BPSK for DL narrowband transmissions could offer significant reductions in repetitions (e.g., ~27%-38% for 6RBs-12RBs) needed to achieve desirable target BLER (e.g., 10%) under extended coverage.
* Proposal 2: Study and evaluate benefits (e.g., BLER, EE gains) vs. caveats (e.g., SE losses) of utilizing π/2-BPSK modulation in 6GR for DL narrowband extended coverage applications.
* Proposal 3: Study for high throughput and high capabilities UEs (e.g., residential FWA) 4096QAM modulation for DL transmissions and characterize its realistic performance (incl. BLER, BER, LLR) and achievable spectral gains over existing 5G NR schemes.
 |
| WiSig, IITH | * P1. Uplink Baseline Choice (Normative Direction for 6G NR):
	+ Adopt π/2-BPSK DFT-s-OFDM as the MPR-0 baseline for UL in 6G NR. QPSK DFT-s-OFDM remains available for capacity-oriented cases, but π/2-BPSK is the default coverage-robust choice.
* P2. Expanded MCS Coverage for π/2-BPSK (Normative Direction):
	+ Introduce additional MCS entries for π/2-BPSK to create a smoother spectral-efficiency ladder at low SINR and minimize dependence on HARQ/time-domain repetitions. The scheduler can select among these entries based on instantaneous link quality.
* P3. Control and Initial Access (Normative Direction):
	+ Enable π/2-BPSK as a default option for initial access, early data, and post-handover re-attachment, especially useful for coverage-limited bands or configurations.
* P4. Downlink Study Item (Study Direction):
	+ Initiate a low-PAPR downlink waveform study (including near-constant-envelope options) to evaluate coverage and energy gains versus baseline CP-OFDM, with careful attention to spectral emissions, MIMO operation, mobility, and scheduler coexistence with capacity modes.
 |
| Apple | * Proposal 1: Study of 4KQAM for DL and 1KQAM for UL should include RF challenges with realistic RF modeling, EVM requirement, deployment scenarios, applicability in real-field deployment and benefits in practical scenarios.
	+ Early RAN4 involvement is essential for the study.
 |
| Qualcomm | * Observation 1: Further extension of 4096 QAM requires 30dB or more SNR, which limits its use cases.
* Proposal 1: Study use cases, and practical system design requirements and challenges for 4096 QAM in downlink and 1024 QAM in uplink.
 |
| AT&T | * Study the gains and challenges of supporting higher modulation orders in 6GR, including 4096-QAM and 1024-QAM for PDSCH and PUSCH, respectively.
 |
| Charter | * Observation 1: With improved SNR conditions along with intelligent beamforming, advanced RF front-ends and high spectral efficiency, the support of higher modulation orders in 6GR becomes highly desirable.
* Proposal 1: For 6GR, RAN1 to study the potential increase of the modulation orders in both DL and UL directions (e.g., modulation order of 1024 for UL and modulation order(s) 2048+ for DL) at least contingent on eligible device types.
* Proposal 3: RAN1 to involve RAN4 early in the discussions related to higher modulation orders and constellation shaping schemes beyond those existing in 5G NR. All new modulation orders and constellation designs should be studied and understood in the presence of practicable impairments such as EVM and I/Q imbalance, according to RAN4 inputs.
* Proposal 4: RAN1 to study the feasibility of more layers with higher modulation orders to support higher data rates and spectral efficiency requirements in 6GR, for eligible device types, such as CPEs.
* Proposal 5: RAN1 to study other necessary enhancements such as larger TBSs and buffer sizes and extended MCS indexing in order to support the increase in modulation orders in both DL and UL, for eligible device types, such as CPEs.
 |
| DCM | * Observation 8: Uniform QAM with higher modulation order is challenging at practical systems due to the extremely high SNR requirements and non-robustness over RF impairments.
 |
| Hanbat | * Proposal 1: RAN1 to support 4096QAM for DL data channels, but only as an optional modulation scheme which is restricted to very high SNR environments.
* Proposal 2: Considering stringent power conditions for UEs, RAN1 to support up to 256QAM for UL data channels.
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| CEWiT | * Observation 1: FWA devices are expected to support large data rates in a rank deficit channel
* Proposal 1: Support higher order modulation schemes (E.g., >1024 QAM) at least for FWA devices
	+ 4096 QAM in DL and 1024 QAM in UL
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|  |  |

On legacy uniform QAM modulation, here is the summary on company positions

* Support 5G-NR uniform QPSK, 16QAM, 64QAM, 256QAM and 1024QAM for DL data channel
	+ Nokia, Xiaomi, Ericsson
* Support 5G-NR uniform QPSK, 16QAM, 64QAM, and 256QAM for UL data channel with CP-OFDM
	+ Nokia, Xiaomi, Ericsson
* Support 5G-NR pi/2 BPSK, uniform QPSK, 16QAM, 64QAM, 256QAM for UL data channel with DFT-s-OFDM
	+ Nokia, Xiaomi
* Support 5G-NR uniform QPSK, 16QAM, 64QAM, 256QAM for UL data channel with DFT-s-OFDM
	+ Ericsson
* Extend the use case for UL pi/2-BPSK (more MCS, default for UL IA and control transmission, defines MPR0)
	+ WiSig, IITH

On 4K QAM for DL and 1K QAM for UL, here is the summary on company positions

* Further study uniform 4K QAM for DL data channel
	+ Nokia, Xiaomi, HW, Ericsson, Lenovo, Apple, Qualcomm, AT&T, Charter, Hanbat, CEWiT
* Further study uniform 1K QAM for UL data channel
	+ Nokia, ZTE, Xiaomi, HW, Ericsson, Apple, Qualcomm, AT&T, Charter, CEWiT
* No need to introduce higher order modulation in the first release
	+ Spreadtrum, CATT
* UL no need to go beyond 256QAM
	+ Hanbat

Extending DFT-s-OFDM waveform or other low PAPR waveform to DL

* Study extending pi/2-BPSK to narrowband DL transmission
	+ Lenovo
* Initiate a low-PAPR downlink waveform study (including near-constant-envelope options) for DL
	+ WiSig, IITH

### Round 1 discussion

Discussion 2.1-1

For the study of uniform 4096QAM for DL and uniform 1024QAM for UL, need to consider performance, complexity, requirements, applicable scenarios (such as hot spot, FWA), associated restrictions (such as rank limitation), and challenges (such as EVM requirement, PAPR increase, MPR or A-MPR increase) and solutions.

* FFS: If and how to involve RAN4 early

Please provide your comments below.

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| --- | --- |
| Company | Comments |
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## Discussions on uniform constellation MCS table enhancements

We received the following proposals on uniform QAM MCS table enhancements

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| --- | --- |
| Company | Position |
| Nokia | * Study the possibility of allowing spectral efficiency operating points achievable with more than a single modulation order.
 |
| Xiaomi | * Observation 5: The selection of MCS tables in NR has become increasingly complex, especially for PUSCH in later releases.
* Study a new mechanism for defining and selecting MCS tables for 6GR.
 |
| HW | * Observation: For a given spectral efficiency (SE), the optimal MCS parameters (modulation and code rate) are different between AWGN and fading channels.
	+ An MCS table that is optimized for AWGN channels may suffer performance loss in fading channels, while an alternative MCS parameters with different modulation and code rate (with the same SE) could offer significant performance gain (e.g., up to 1.5dB).
* Study enhanced adaptive modulation and coding schemes to select the optimal MCS based on channel characteristics for performance improvement.
 |
| Oppo | * Observation 13: For the enhanced AMC supporting multiple combinations of modulation order and coding rate with the same spectral efficiency, the benefits of enhanced AMC may be marginal when integrating the UE CQI feedback procedure.
 |
| Rakuten | * Proposal 1: RAN1 studies the minimization of MCS tables for both PDSCH and PUSCH in 6GR to reduce system complexity while preserving configuration flexibility, considering the impact of modulation range, exploring mechanisms to maintain flexibility, and evaluating trade-offs using relevant KPIs.
 |
|  |  |

A summary of the proposals is provided below

* Enhance MCS tables to allow single SE point to be supported by multiple MCS entries with different modulation order
	+ Nokia, HW, Oppo
* Minimization of MCS table
	+ Rakuten
* Simplified mechanism to select MCS table
	+ Xiaomi

### Round 1 discussion

Discussion 2.2-1

Companies are encouraged to evaluate the proposal to allow a single spectrum efficiency point to be supported by multiple MCS entries with different modulation orders with uniform QAM. When providing results, companies are recommended to provide the following information

* Details on the overlapping MCS table design
* Performance benefit under different channel and rank assumptions
* MCS selection mechanism across multiple MCS corresponding to the same spectrum efficiency.
* Impact to UE CSI feedback

Please provide your comments below.

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| Company | Comments |
|  |  |

## Discussions on shaped constellations

For constellation shaping, we received the following proposals

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| --- | --- |
| Company | Position |
| Nokia | For GS* Geometric constellation shaping study should focus on constellations that can be generated using the uniform 1024QAM (or higher) constellation points in the downlink and uniform 256QAM (or higher) constellation points in the uplink. A geometrically shaped constellation shall retain at least the sign-symmetry. At most one geometrically shaped constellation per modulation order may be supported.
* Constellation shaping should focus on downlink data channel.

For PS* The PCS methods should be evaluated not only over the AWGN channel, but also over fading and 3GPP-compliant channels.
* The trade-off between the potential gain of PCS techniques and their corresponding impact on the processing chain w.r.t. latency, complexity, PAPR, (sub-)optimality for retransmission should be considered.
* The imperfect CSI should be considered in the performance evaluation both in both link as well as in system level.
 |
| Spreadtrum | * Don’t support non-uniform constellation in 6GR day1.
 |
| ZTE | * The following metrics should be evaluated for shaping modulation:
	+ BLER performance
	+ Throughput
	+ Complexity
* The following aspects for evaluation assumptions should be considered for shaping modulation:
	+ BLER performance for both initial transmission with varied TBS and spectrum efficiency
	+ Throughput performance with re-transmission and adaptive MCS assumption
	+ MIMO fading channel model
	+ Closed loop MIMO for MIMO precoder assumption
	+ MMSE receiver for MIMO receiver assumption

For GS:* Observation: NUC modulation is a mature technique and has been widely used in broadcast standards.
* Observation: Introducing NUC for 6GR does not affect the LDPC coding chain in 5G. The LDPC coding chain in 5G can be reused in 6GR.
* Observation: NUC modulation/demodulation is a full parallel process, and it is easier to achieve ultra-high throughput for 6GR.
* NUC modulation for 6GR can be studied and considered.

For PS:* Observation: PAS modulation has impacts on coding chain in terms of:
	+ Additional procedures before or after channel coding
	+ Bit interleaving
* Observation: The following three aspects need to be considered for CCDM algorithm s:
	+ Precision mismatch between transmitter and receiver
	+ Serial process for encoding and decoding
	+ Performance loss in small TBSs
* Observation: PAS schemes with (A)ESS/shell mapping have an ultra-high memory requirement for encoding/decoding.
* Observation: IR-HARQ performance may degrade when PAS is used.
* The following issues for PAS can be studied and evaluated:
	+ Impact on channel coding chain
	+ Serial process and storage caused by DM algorithms
	+ Initial and retransmission performance
 |
| vivo | For GS:* Support to study AI/ML-based/optimized modulation, including constellation design and corresponding low complexity demodulation scheme.
* To minimize the potential signalling overhead and facilitate EVM requirements definition for transmitting/updating constellation, a low order AI optimized constellation can be selected from the high order QAM constellation points, e.g., from 4096QAM.
* Observations:
	+ AI optimized 2D-NUC and 1D-NUC can provide 0.45~0.8 dB and 0.15~0.6 dB gain respectively compared to legacy 256QAM.
	+ Observation 2: AI optimized constellations selected from 4096QAM can achieve similar performance gain compared to AI optimized constellations without constraint.

For PS:* Observation: Probabilistic shaping may have great impacts on the coding chain, such as the channel coding module, and some new building blocks are also needed. Large spec efforts could be needed. Further, scrambling after coding will defeat the potential gain of PAS as the adding of scrambling bits will change the probability of modulation symbols.
* Observation: Compared to legacy QAM modulation, both PAS with different DM structures and non-direct mapping-based PS have significantly higher computational complexity, and/or storage complexity, and/or processing latency.
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| Xiaomi | For GS:* Observation 1: The net gain of 1D-NUC and 2D-NUC depends on several factors, including the modulation order, shaping dimensions, channel conditions, and the extent of PAPR loss.
* Observation 2: 1D-NUC has demodulation complexity comparable to that of NR uniform modulation, but it yields a smaller performance gain compared to 2D-NUC.
* Observation 3: 2D-NUC can achieve a higher BLER-SNR gain, but at the cost of higher demodulation complexity.

For PS:* Observation 4: The net gain of PS depends on several factors, including the modulation order, complexity of distribution matcher, complexity of receiver, channel environment, and the extent of PAPR loss.
* Observation 5: PS can theoretically achieve a higher BLER-SNR gain, but at the cost of higher demodulation complexity and larger spec efforts.

For evaluation methodology:* Proposal 5: Support at least the following design metrics for evaluation of 6GR constellation shaping.
	+ BLER performance
	+ Throughput performance under fading channel (SISO, and MIMO with rank=1 and rank>1)
	+ Transmitter and receiver complexity, latency, parallelism implementation, and storage requirements,
	+ PAPR
	+ Expected spec impact
	+ PA efficiency, including EVM, MPR/A-MPR
* Proposal 6: Support at least the following simulation assumptions for 6GR constellation shaping.
	+ For MIMO channel evaluation, closed loop MIMO (with rank=1 and rank>1) is the baseline.
	+ For receiver type, MMSE receiver is the baseline.
	+ For evaluation channel, fading channel is the baseline, and AWGN channel is also considered.
	+ For TBS, a wide range of TBS should be assumed.
	+ For interference, either SLS or LLS with taking into different interference levels should be considered.
	+ For HARQ combing, both single transmission and re-transmission should be considered.
 |
| CMCC | For GS:* Observation 1: For geometric shaping, the constellation design should ensure universal performance across diverse channel conditions.
* Observation 2: Geometric shaping can reuse the 5G procedures for symbol mapping at the transmitter and symbol demapping at the receiver.
* Observation 3: For geometrically-shaped constellations, if the constellation map relies on a pre-defined lookup table, the memory and access overhead at the transmitter and the demapping complexity at the receiver should be considered, especially for 1024 and higher-order schemes.

For PS:* Observation 4: Probabilistic shaping can reuse the 5G constellation map.
* Observation 5: Probabilistic shaping requires a redesign of the channel coding and modulation chain.
* Observation 6: The core innovation of probabilistic shaping is the novel bit generation process, while the final step of mapping bits to a constellation point remains identical to legacy QAM.
* Proposal 1: Given that the bit-to-symbol mapping rule in probabilistic shaping is consistent with legacy QAM, we propose to address its design and evaluation under the channel coding agenda (10.4.1).

For evaluation: * Proposal 2: The following aspects should be carefully considered for the study of modulation schemes for 6GR:
	+ Universality over varying channel conditions
	+ Integration with channel coding
	+ Transmitter implementation complexity
	+ Receiver implementation complexity
	+ Feasibility validation via EVM-like metric with RAN4 involved
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| Lekha | * Observation 5: Constellation shaping enhances communication performance by optimizing either the geometry or probability distribution of modulation symbols, with recent machine learning methods enabling joint geometric and probabilistic shaping to maximize mutual information (I(X; Y)). This approach performs near channel capacity on AWGN channels, outperforms existing methods on various channels, and requires no prior knowledge or assumptions about the channel, making it suitable for unknown or non-differentiable channel models.
* Proposal 5: An adaptive scheme that selects between uniform modulation, probabilistic shaping, geometric shaping, or joint probabilistic and geometric shaping based on different SNR ranges can be implemented to achieve optimal performance.
 |
| Tejas | * Observation 1 :- The de-mapping complexity of 1D-NUC is comparable to that of a uniform constellation, as both require a similar number of operations for LLR computation.
* Observation 2 :- The de-mapping complexity of 2D-NUC is significantly higher than that of 1D-NUC due to the need for joint processing of in-phase and quadrature components.
* Proposal 1 :- RAN1 to Study the benefits and applicability of Non-Uniform Constellation (1D-NUC and 2D-NUC) for 6GR.
 |
| HW | For GS:* Observation: In geometric shaping, 2D-NUC may require a prohibitive demodulation complexity in high modulation order.
	+ The demodulation complexity of 2D-NUC is 14x for 1024QAM and 4x for 256QAM over LDPC decoding.
	+ Demodulation complexity of 1D-NUC is significantly lower than that of 2D-NUC.

For PS:* Observation: Compared to the existing 5G NR coding and modulation chain, supporting probabilistic shaping requires significant changes and extra complexity, necessitating a redesign of the 6G coding and modulation chain.
* Observation: In probabilistic shaping, the DM complexity grows with the modulation order, and different DM schemes incur different complexities:
	+ Complexity of CCDM is approximately 2x LDPC decoding for 1024QAM.
	+ Complexity of ESS is roughly 1/6 of LDPC decoding for 1024QAM. However, the storage of ESS is very high.
	+ Complexity of energy-based AC can reach 28.7x that of LDPC decoding for 1024QAM.
* Observation: The throughput of typical probabilistic shaping schemes is low:
	+ CCDM incurs ~10x processing delay over LDPC decoding.
	+ Even when the shaping block length is reduced (e.g., to 128), the processing delay still remains significant, approximately equivalent to 5 iterations of LDPC decoding.
* Observation: According to theoretical analysis, optimized modulation order and code rate combinations offers superior benefits (e.g., up to 1.5dB) compared to pure constellation shaping techniques (e.g., less than 0.2dB) under fading conditions.
* Observation: In the worst-case scenario, the computational complexity of sphere decoding (SD) is prohibitive (e.g., 3×108x over LDPC decoding).
* Observation: In precoded MIMO system equipped with sphere decoding, probabilistic shaping results in significant performance loss (~3dB) over uniform QAM.
* Observation: With probabilistic shaping, the computational complexity of reduced ML detection (i.e., using QRM-MLD) is 1~10x of that for LDPC decoding.
* Observation: With 2D-NUC, the computational complexity of reduced ML detection (i.e., using QRM-MLD) is 10~100 times of that for LDPC decoding.

For evaluation:* The following aspects need to be studied for evaluation of modulation enhancements for 6GR:
	+ BLER performance evaluated under various fading channels (SISO, and MIMO with rank-1 and rank>1), and closed loop MIMO with MMSE is used as baseline for MIMO channel;
		- For a fair comparison, evaluation shall be thoroughly investigated on different combinations of QAM modulation orders and code rates, using the optimal combination to target the best possible BLER performance;
	+ Throughput performance under fading channel
		- For throughput evaluation, needs to provide assumptions on link adaptation (e.g., target BLER for 1st transmission, maximum # of retransmissions)
	+ Complexity of any proposed scheme, at least including:
		- Computational complexity;
		- Storage complexity;
	+ Hardware throughput and latency
		- Considering algorithm parallelism and quantization effects.
	+ Standardization efforts and specification impact
	+ Realistic factors
		- PAPR
		- EVM
	+ System-level simulation results:
		- SU-MIMO and MU-MIMO;

For PAPR:* Observation: For DFT-s-OFDM waveform, both geometric shaping and probabilistic shaping increases the PAPR, and such an increase is particularly pronounced in probabilistic shaping.
 |
| CATT | For PS* Proposal 2: It is recommended that constellation shaping is considered when the spectral efficiency is above 3 bits per two dimensions (bits/2D), or the constellation size is not less than 64.
* Observation 2: For probabilistic shaping implemented by enumerative sphere shaping, the number of operations required by the decoding progress of the distribution matcher is about 5% of that required by demapping.
* Observation 3: For probabilistic shaping implemented by enumerative sphere shaping, the distribution matcher requires storages to implement encoding and decoding. The storage sizes shown by Table 3 are up to 1.388 Mbits.
 |
| Oppo | For GS:* Observation 5: Uniform QAM and 1D-NUC require similar demapping complexity.
* Observation 6: Compared with 2D-NUC, lower demodulation complexity could be achieved with 1D-NUC with slight performance degradation.

For PS:* Observation 10: For PS-based modulation, the introduction of DM may lead to serial processing latency and/or storage overhead.
* Observation 11: PS-based modulation may have massive impact on Tx/Rx chain, including code rate design, interleaving, scrambling, and redundancy version (RV) design, etc.

For evaluation:* Proposal 2: Support to study GS and PS constellation shaping for 6GR modulation scheme.
* Proposal 3: For study of constellation shaping, the following aspects shall be considered:
	+ Performance evaluation including spectral efficiency and BLER,
	+ PAPR of CP-OFDM and DFT-s-OFDM waveforms
	+ Complexity at transmitter and receiver, including computational complexity, storage, processing latency of modulation/demodulation module and additional hardware
	+ The difficulties of co-design of channel coding, modulation/demodulation, and introduction of potential additional hardware
	+ Impact on Tx/Rx chain, including interleaving, scrambling, and HARQ procedure
 |
| Samsung | For GS:* Observation 4: 1D-NUC does not bring significant PAPR increase compared to uniform QAM.
* Observation 5: 1D-NUC and uniform-QAM exhibit similar complexity for the sphere decoding based ML receiver within the SNR range of interest, while 1D-NUC outperforms uniform-QAM consistently.
* Proposal 1: Consider geometrically shaped 1D non-uniform constellation as a candidate modulation scheme for 6GR.

For PS:* Observation 6: Distribution matching for probabilistic shaping increases LDPC coding rate.
* Proposal 2: In the evaluation of probabilistic shaping, LDPC coding rate should be determined considering the distribution matching operation.
* Proposal 3: Explore probabilistic shaping in a way that keeps the 5G BICM structure as simple and unchanged as possible.
 |
| LG | For GS:* Observation 1: Non-Uniform Constellation provides capacity or BLER performance gain w/o additional transmission resources
* Proposal 1: RAN1 should study the use of Non-Uniform Constellation for 6G
* Proposal 2: Study the applicability of the constellation shaping for modulation orders supported in 5G NR (e.g., from 64 QAM up to 1024 QAM).
 |
| Ericsson | For evaluation:* Modulation schemes based on constellation shaping shows different performances under different evaluation setups, thorough evaluation considering realistic channels, transceiver impairments, and hardware settings are needed.
* It is essential to involve RAN4 early in discussions related to a new modulation scheme beyond the 5G scheme. RAN1 cannot unilaterally select a new modulation scheme without checking the practical considerations with RAN4.
* Use NR MCS table as starting point to evaluate constellation shaping schemes.
	+ Simulation based on optimized MCS can be provided optionally
* Include both SISO and MIMO scenarios for evaluation.
* Apply closed loop MIMO based precoder as evaluation baseline.
* Use at least MMSE receiver as baseline receiver for evaluation in both uplink and downlink.
* Include at least 32/64 ports and 4/8 ports antenna setup for network side transceiver assumptions, include at least 2T4R and 1T1R antenna setup for device side transceiver assumptions.
* Follow AI 11.2 as much as possible for the evaluation assumptions by reflecting realistic models and traffic patterns.
* Both link-level and system-level evaluations should be done for proposed new modulation schemes, e.g., NUC and PSCM.
* Implementation complexity and processing latency shall be analysed and compared with 5G modulation in the evaluation.
	+ FFS: How to quantify the complexity and latency.
 |
| IDC | For PS:* Observation 2: PCS can be easily integrated with NR shared channel processing, reusing LDPC encoding and decoding schemes
* Proposal 1: Study PCS as candidates for 6G joint coding and modulation with uniform QAM of NR as the baseline.
 |
| Lenovo | For GS:* Observation 2: The non-paired constellation framework retains legacy QAM demapping at the receiver, while only the transmitter uses NUC, specifically designed for this non-paired framework, i.e., NP-NUC, for mapping. Thus, receiver updates are not necessary to realize geometric shaping gains.
* Proposal 4: Study a non-paired constellation approach, e.g., NP-NUC at the transmitter and legacy QAM demapping at the receiver, which tailors geometric shaping to realistic wireless system constraints, such as low-complexity UE receivers in downlink.

For PS:* Proposal 5: Study probabilistic shaping to further improve the performance gains in 6G, while considering implementation/operational complexity.
* Observation 5: For link adaptation in PS systems, jointly optimizing modulation order, FEC code rate, and the shaping parameter at a given channel quality metric (e.g., SNR) is nontrivial and computationally intensive, while satisfying a target BLER constraint.
* Proposal 6: Study optimizing link adaptation for PS systems by targeting maximum data rate subject to a BLER constraint at a given channel quality (e.g., SNR). Evaluate various solution candidates to maximize the probabilistic shaping gain.
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| ETRI | For GS:* Observation 1: Geometric shaping provides BLER performance gains compared to uniform constellations when 5G NR LDPC codes are used. These gains become more significant when short code lengths are used and observed at low error rates.
* Proposal 1: RAN1 to study and evaluate geometric shaping (non-uniform constellation) schemes as one of the candidates for 6G modulation. The following details may be considered for comprehensive evaluations:
	+ BLER performance at low error rates (e.g., 10-4 ~ 10-5)
	+ BICM capacity analysis
	+ Complexity analysis (1D/2D-GS, comparison with uniform constellations)
	+ Channels: AWGN, fading, power limiter channels
	+ Choices of constellation sets depending on code rate/length
	+ Memory requirements for constellation sets (gNB, UE)
	+ MIMO considerations
	+ PAPR consideration (UL DFT-s-OFDM)
	+ For AI/ML approaches, use only resulting constellations to evaluate

For PS:* Proposal 2: RAN1 to study and evaluate probabilistic shaping schemes as one of the candidates for 6G modulation. The following details may be considered for comprehensive evaluations:
	+ BLER performance at low error rates (e.g., 10-4 ~ 10-5)
	+ BICM capacity analysis
	+ Complexity analysis (compared to uniform constellations, 1D/2D-GS)
	+ Bit interleaver/Scrambler considerations
	+ Additional latency issue
	+ Channels: AWGN, fading, power limiter channels
	+ Choices of distribution sets depending on code rate/length
	+ Memory requirements for distribution sets (gNB, UE)
	+ MIMO considerations
 |
| Rakuten | * Proposal 2: RAN1 studies joint channel coding and modulation (JCCM) schemes for 6GR, including geometric and probabilistic shaping, with the objective of enhancing spectral efficiency, considering the trade-off with receiver complexity.
 |
| Sony | GS for PAPR:* Observation 5: For DFT-s-OFDM, the PAPR behaviour may be improved by constellation shaping
* Proposal 5: RAN1 should study constellation shaping for PAPR reduction of DFT-s OFDM
* Proposal 6: RAN1 should study constellation shaping to simultaneously improve PAPR behaviour and spectral efficiency
 |
| MTK | For GS:* Observation 1: Geometric shaping is less complex from transmitter’s perspective and can provide a decent shaping gain.
* Observation 2: Geometrically shaped constellations can be either optimized for specific SNR/channel conditions or over a range of SNR/channel conditions.
* Proposal 2: RAN1 to study geometric shaping for higher-order modulations, taking into consideration the operation over a range of SNR and channel conditions.

For PS:* Observation 3: Probabilistic constellation shaping (PCS) has been extensively studied in the past few decades, and promising performance gain can be obtained using various PCS techniques.
* Proposal 3: RAN1 to study probabilistic constellation shaping for higher-order modulations.

For evaluation:* Proposal 4: For constellation shaping, evaluate the shaping gain for various NR SE settings and shaper block sizes.
* Proposal 5: For constellation shaping, evaluate the shaping gain under both AWGN and MIMO fading channel conditions, using the AWGN channel evaluation as the initial baseline.
* Proposal 6: For constellation shaping, evaluate its complexity impacts on the transmitter, the receiver, and MIMO operations.
 |
| Apple | For evaluation:* Proposal 2: For modulation shaping evaluation, adopt the following evaluation assumption:
	+ Throughput performance at 90% throughput point with TDL-A channel model
		- Max 4 HARQ transmissions
	+ Receiver assumption:
		- rML for DL
		- MMSE for UL
	+ For MIMO channel evaluation,
		- For close loop MIMO, 32 gNB antenna ports and 4/6 UE antenna configuration, SU MIMO with ideal precoding, with Rank =2 and Rank = 4
		- For open loop MIMO, 4x4 and 4x6 with Rank = 2 and Rank = 4
	+ For probability shaping, company to provide details of distribution matcher and sequence length.
	+ Channel estimation: genie and MMSE channel estimation.
	+ Transmitter and receiver complexity, latency, parallelism implementation, and storage requirements are reported
	+ PAPR for UL DFT-s-OFDM based waveform
	+ Expected spec impact
* Proposal 3: For modulation shaping evaluation, consider SLS evaluation with potential simplification.
 |
| Qualcomm | For PS:* Observation 2: A typical AC encoding implementation of CCDM is serial in the output sequence length, with encoding operations including addition, subtraction, comparison, multiplication, and division arithmetic.
* Observation 3: A typical ESS encoding implementation requires fixed storage, and is serial in the output sequence length, with encoding operations including addition, subtraction, comparison arithmetic, and table lookups.
* Observation 4: ESS generally has smaller rate loss than CCDM for a given output sequence length.
* Proposal 2: RAN1 to study DM schemes to achieve optimized performance/rateloss and complexity/latency trade-off.
* Observation 5: Manageable computation, storage complexity and latency for distribution matcher can be realized for implementation.
* Observation 6: Probabilistic shaping can re-use systematic bits priority mapping for unshaped bit levels in bit collection and interleaving.
* Observation 7: Scrambling of unshaped bits, including parity bits, is compatible with probabilistic shaping.

For GS:* Proposal 3: Company should share their preferred GS scheme (i.e. constellation points and bit labelling) for performance comparison.

For evaluation:* Proposal 4: Link level simulation should be conducted and prioritized for performance evaluations for 6G modulation study.
* Proposal 5: AWGN performance evaluation should be conducted at minimum for calibration purposes.
* Proposal 6: Detailed configuration parameters for MIMO fading channel evaluation should be provided.
* Observation 8: Enhancements for probabilistic shaping targeting different spectral efficiency levels can be achieved through optimized coding rates and constellation probability distributions.
* Observation 9: Enhancements for geometric shaping can be realized by optimizing constellation point locations for specific spectral efficiency targets.
* Proposal 7: The spectral efficiency targets defined in the NR MCS table should be used as a baseline for evaluating 6G modulation enhancements.

On PAPR:* Observation 16: Both PS and GS have similar PAPR as uniform QAM when CP-OFDM waveform is used.
* Observation 17: For DFT-S-OFDM waveform, PS with properly selected probability distributions (in particular, different from Maxwell-Boltzmann distribution) may provide similar PAPR to uniform QAM, while still providing meaningful shaping gain.
* Proposal 8: Study probabilistic shaping design for DFT-S-OFDM waveform to achieve a good trade-off between PAPR reduction and link level performance gain.

On complexity:* Observation 20: PS incurs limited complexity on the demodulation for both linear and non-linear demodulator.
* Observation 21: The demodulation complexity for (unstructured) GS can be prohibitive due to irregular constellation point locations, especially for large modulation order and high rank MIMO.
 |
| AT&T | * Study the performance of non-uniform constellations based on geometric shaping and/or probabilistic shaping for 6GR air interface, focusing on high-order modulation values.
* For 6GR proposals on non-uniform constellation and probabilistic shaping, prioritize designs that leverage the existing NR modulation architecture at both the transmit and receive chains.
* For 6GR proposals on non-uniform constellation, further emphasis is needed on the scalability of the constellation to include different values of constellation points, in addition to the underlying MCS selection procedure needed at the receiver side.

On evaluation:* For 6GR proposals on non-uniform constellation and probabilistic shaping, evaluation is needed for scenarios including SU-MIMO.
 |
| Charter | * Proposal 2: RAN1 to study new constellation designs for 6GR such as Probabilistic Shaping and Geometric Shaping with constellations larger than 256-QAM in the UL direction, e.g., 1024-QAM for eligible device types, such as CPEs.
 |
| DCM | * Observation 6: GCS optimized for various channel condition requires storage at both transmitter and receiver side. The performance gain of GCS over QAM increase with the modulation order, at the cost of increasing computation complexity at receiver side due to the complex-valued LLR computation.
* Observation 7: Probabilistic Constellation Shaping (PCS) will increase the implementation complexity over QAM and have large specification impacts.

GS for PAPR reduction:* Observation 5: By limiting the constellation points and bit labelling as a subset of high-order QAM constellation points, QAM-based constellation shaping (QAM-CS) could provide lower PAPR than QAM and lower implementation complexity than Geometric Constellation Shaping (GCS) and could be considered as a candidate of 6G modulation schemes.
* Proposal 1: Study QPSK Rotation and Constellation Shaping for PAPR reduction. Performance gain over UE/gNB complexity should be assessed.
 |
| Hanbat | * Proposal 3: For 6GR, RAN1 is encouraged to continue to study GCS and PCS as additional constellation techniques.
 |
| Google | On evaluation:* Proposal 1: For evaluating the performance of a PS-based modulation, companies should report the complexity based on the applied bit width of the DM function, and in different code block sizes (e.g., small, median, and large); and report whether the DM function applied serial or parallel process for latency evaluation.
* Proposal 2: For evaluating the performance of a GS-based modulation, companies should report the complexity of the demodulation in different code block sizes (e.g., small, median, and large); and the required memory for constellation mapping LUT (e.g., bit width for a non-uniformed constellation).
* Proposal 3: For evaluating new modulation method (e.g., PS, GS, or other shaping constellations methods), throughput analysis in SLS is required.
* Proposal 4: For the transmitter and receiver complexity and storage requirement in multiple-carriers CA structure should also be addressed, in case some of components can be shared among CA structures.
 |
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Multiple companies provided evaluation results for constellation shaping as well:

|  |  |
| --- | --- |
| Company | Evaluations provided |
| ZTE | NUC for AWGN channel* Observation: According to our simulation results, NUC can have shaping gain from 0.15 dB to 0.75 dB, where shaping gain of NUC increases as the modulation order increases.
	+ Shaping gain from 0.15dB to 0.75dB where shaping gain of NUC increases as the modulation order increases
	+ ~0.27dB shaping gain for MCS level 18 in NR 256QAM table at BLER = 0.1 in the CDL-A 1T1R channel.
	+ ~0.5 dB shaping gain for MCS level 18 in NR 256QAM table at BLER = 0.1 in the CDL-A 4T4R channel.
 |
| vivo | NUC from AI/ML for fading channel 1T1R |
| Tejas | NUC for AWGN 1T1R* Observation 3 :- Initial investigation using 5G-NR PDSCH BICM chain for a target BLER of 1% using MCS table 2 shows shaping gains of up to 0.7dB for 1D-NUC and up to 0.8dB for 2D-NUC.
* Observation 4 :- Higher-order modulation schemes achieve greater shaping gain.
 |
| HW | 1D-NUC and PS over AWGN and fading, compared with non-optimized MCS and optimized MCS, fixed MCS* For evaluation of constellation shaping, the actual shaping gain needs to be identified by fair comparison between shaping schemes and non-shaping schemes, so that the AMC gain from optimized MCS selection is not mixed into the observed gains.
* Observation 12: In AWGN channels, probabilistic shaping and NUC achieve shaping gains of 1.0 dB and 0.6 dB, respectively. Conversely, in fading channel scenarios, these gains experience a marked decrease with identical constellation configurations. Notably, AMC utilizing higher modulation orders deliver substantial performance enhancements in these fading scenarios

PS throughput performance with link adaptation and HARQ* Under link adaptation and HARQ retransmission, probabilistic shaping shows similar or slightly lower throughput performance over uniform QAM.
 |
| CATT | PS under AWGN* For 16-QAM, the performance gain of probabilistic shaping compared to uniform BICM at 2.5 bits/2D is about 0.4 dB;
* For 64-QAM, the performance gain of probabilistic shaping compared to uniform BICM at 3.0~4.5 bits/2D is about 0.8~1.0 dB;
* For 256-QAM, the performance gain of probabilistic shaping compared to uniform BICM at 5.0~6.5 bits/2D is about 0.8~1.4 dB;
* For 1024-QAM, the performance gain of probabilistic shaping compared to uniform BICM at 7.0~8.5 bits/2D is about 0.8~1.7 dB.

GS under AWGN* The performance gain of 16-NU-QAM compared to 16-QAM is very small.
* The performance gain of 64-NU-QAM compared to 64-QAM is about 0.2 dB.
* The performance gain of 256-NU-QAM compared to 256-QAM is 0.4~0.6 dB at 4.0~5.0 bits/2D. For the transmission rate of 6.5 bits/2D, there is no gain.
* The performance gain of 1024-NU-QAM compared to 1024-QAM is 0.6~0.8 dB at 5.0~7.0 bits/2D. For the transmission rate of 8.0 bits/2D, there is no gain.
 |
| Oppo | 1D/2D-NUC for AWGN and Rayleigh fading channel* Observation 3: In AWGN and Rayleigh fading channels, 2D-NUC could achieve 0.7 dB and 0.4 dB gain compared with uniform QAM, respectively.
* Observation 4: In AWGN and Rayleigh fading channels, 1D-NUC has less than 0.2 dB performance degradation compared with 2D-NUC.

PS for AWGN and Rayleigh fading* Observation 7: Ideal-DM-based PS could achieve about 1.2 dB performance gain compared with uniform QAM. But the rate loss issue of practical DM may significantly degrade the performance gain of PS.
* Observation 8: In i.i.d. Rayleigh fading channel, the performance gain of PS significantly declines, and CCDM-based PS has even worse performance (0.8dB loss) than uniform QAM.
* Observation 9: The performance gain of PS reduces as the code block length decreases. With small code block length, performance of CCDM-based PS would be worse than that of the uniform QAM.
 |
| Samsung | 1D-NUC for fading channel and MIMO channel:* Observation 1: 1-D NUC outperforms uniform QAM over a wide range of operating Es/No points, channel model parameters, and antenna configurations.
* Observation 2: The performance gain of 1-D NUC over uniform QAM increases with the modulation order.
* Observation 3: 1D-NUC outperforms uniform QAM for the sphere decoding based ML receiver.
 |
| Ericsson | PSCM/ATSC for AWGN and TDL-A SISO* Preliminary SISO evaluation shows constellation shaping schemes having performance loss over 5G QAM for large PRB allocations in TDL-A channel while having performance gain over 5G QAM in AWGN channel and small PRB allocations.
 |
| IDC | PS in AWGN fixed MCS* Observation 3: Initial simulation results for PCS show performance gains (e.g., 0.7-0.8 dB) over uniform QAM.
* Observation 4: Simulation results for PCS show potential 0.5% – 0.7% EVM requirement s relaxation over uniform QAM.
 |
| Lenovo | NP-NUC and NUC for AWGN, Rayleigh SISO, MIMO 2x2* compared to conventional QAM. Under the simulation setup considered, the observed gains are 0.2dB - 0.45dB on AWGN channels, 0.05dB - 0.25dB on Rayleigh fading channels, and 0.1dB - 0.3dB on TDL-A/B channels.

PS for TDL SISO, MIMO 2x2* Observation 4: In OFDM SISO and MIMO systems, for TDL channels, probabilistic shaping offers the SNR gains of 0.9dB – 1.4dB, compared to uniform QAM, under considered simulation setups.
 |
| MTK | PS fixed MCS for AWGN |
| Apple | PS with MIMO static channel and TDL fading channel, 4x4 and 4x6, rML, fixed MCS |
| Qualcomm | GS/PS fixed MCS, AWGN* Observation 10: PS achieves significant gain over uniform QAM baseline in AWGN channel.
* Observation 11: PS achieves 04~0.7 dB gain over GS in AWGN channel.
* Observation 12: With maximum 512 block length for PS with CCDM, the performance loss is less than 0.1dB.

PS MIMO fading channel, accurate beamforming, fixed MCS* Observation 13: With accurate beamforming at the transmitter, similar shaping gains as in AWGN channel is observed over MIMO fading channels, with LMMSE receiver.

PS MIMO fading channel, open and closed loop precoding, fixed MCS* Observation 14: PS may provide more than 1.53 dB performance gain in MIMO scenarios due to interference shaping, for both open-loop precoding, as well as closed-loop precoding with realistic SRS sounding periodicity.

PS MIMO fading channel, closed loop precoding with SRS, outer loop link adaptation* Observation 15: With closed-loop precoding and outer-loop link adaptation, PS may provide 5~16% throughput gains across wide range of SNR values and mobility conditions.

System sim:* Observation 18: rML receiver is widely adopted in UE implementation. For 5G uniform QAM, it offers significant system-level throughput gains over LMMSE receiver.
* Observation 19: Probabilistic shaping yield ~10% mean throughput gain with rML receiver in the system level evaluations.
 |
|  |  |

Both probabilistic shaping and geometric shaping receive strong support for study from the contributions. An evaluation campaign will be needed before we can make any decision. In this meeting, the moderator plans to focus on the discussion on how to study, instead of drawing any conclusions.

### Round 1 discussion

Discussion 2.3-1

For 6GR constellation shaping evaluation for CP-OFDM, (Geometric shaping and probabilistic shaping with optimized MCS), the proposed scheme will be compared with non-shaping with NR MCS table. The evaluation and comparison should consider at least the following:

* BLER performance under AWGN channel (at least for performance calibration)
	+ 1st transmission as priority
	+ FFS HARQ re-transmission
* BLER performance under fading channel (SISO, SIMO, and MIMO with rank=1 and rank>1) with fixed MCS
* Throughput performance with link adaptation under fading channel (SIMO, MIMO with rank=1 and rank>1)
	+ Needs to provide assumptions on rate adaptation (e.g., target BLER for 1st transmission, maximum # of retransmissions)
* Transmitter and receiver complexity, latency, parallelism implementation, and storage requirements,
* Other KPI not excluded, such as PAPR, EVM, MPR/A-MPR
* Expected spec impact

Please provide your comments below.

|  |  |
| --- | --- |
| Company | Comments |
|  |  |

Discussion 2.3-2

For link level simulation evaluation, follow EVM agenda item for default values, and the proponent companies are encouraged to evaluate the following and should report the exact scheme evaluated.

* MIMO channel configuration, including Channel profiles (TDL, CDL, delay spread, and Doppler), Tx/RX antenna settings
* MIMO scenario:
	+ SU-MIMO
	+ FFS MU-MIMO
* Precoder assumption
	+ Close loop MIMO (reciprocal beamforming (e.g., SVD, SLR/RZF, etc.), codebook based)
		- Realistic CSI/SRS periodicity and SRS chanEst assumptions
	+ Open loop MIMO
* Receiver assumption (for MIMO): LMMSE (baseline) for UL, rML or LMMSE for DL
* LLR demapper: Max-log (baseline) or Log-MAP
* Channel estimation: Realistic (baseline) or Genie
* Other assumptions: Channel coding NR-LDPC (baseline), PxSCH bandwidth 24RBs (baseline), SCS 30KHz (baseline), FD interleaver used or not

FFS: System level simulations

Please provide your comments below.

|  |  |
| --- | --- |
| Company | Comments |
|  |  |

Discussion 2.3-3

For 6GR constellation shaping study, proponent is encouraged to provide details for the PS/GS schemes considered for evaluation and comparison, including at least the following

* Probabilistic shaping for CP-OFDM (and DFT-s-OFDM)
	+ Use the list of spectrum efficiencies in NR MCS table as starting point, and provide constellation (including normalization), coding rate and target probabilistic distribution for each SE
	+ Relationship between shaping and FEC, codeword to symbol mapping, and other modules (such as scrambling), in transmit and receive chains
	+ PS algorithm details (for example, source coding based, channel coding based, etc) and parameters (such as block length, rate loss)
* Geometric shaping for CP-OFDM (and DFT-s-OFDM)
	+ Use the list of spectrum efficiencies in NR MCS table as starting point, and provide target constellation shapes (including normalization) (1D-NUC, 2D-NUC, QAM-CS, etc) for each SE
	+ GS mapping details, such as bit to constellation point mapping
	+ Note: AI/ML can be used to generate the constellation, but for evaluation purposes, only the resulting constellation needs to be provided.

Please provide your comments below.

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| --- | --- |
| Company | Comments |
|  |  |

Discussion 2.3-4

For 6GR constellation shaping evaluation for DFT-s-OFDM (Geometric shaping and probabilistic shaping with optimized MCS), the proposed scheme will be compared with non-shaping with NR MCS table. The evaluation and comparison should consider at least the following:

* PAPR/CM of the resulting waveform
* BLER performance under AWGN channel (at least for performance calibration)
	+ 1st transmission as priority
	+ FFS HARQ re-transmission
* BLER performance under fading channel (SIMO) with fixed MCS
* Throughput performance with link adaptation under fading channel (SIMO)
	+ Needs to provide assumptions on rate adaptation (e.g., target BLER for 1st transmission, maximum # of retransmissions)
* Transmitter and receiver complexity, latency, parallelism implementation, and storage requirements
* Expected spec impact

Please provide your comments below.

|  |  |
| --- | --- |
| Company | Comments |
|  |  |

## Discussions on new modulations for PAPR reduction

|  |  |
| --- | --- |
| Company | Position |
| ZTE | * Non-transparent PAPR reduction schemes should be studied in 6GR.
* I-π/2-BPSK modulation scheme should be considered to further reduce PAPR for DFT-s-OFDM.
* Observations
	+ By inserting the normalized sum of two adjacent π/2-BPSK symbols between them, I-π/2-BPSK can reduce the phase difference between consecutive symbols from π/2 to π/4.
	+ Due to interpolation process, I-π/2-BPSK occupies twice the bandwidth of the original π/2-BPSK signal, which is equivalent to spectrum extension.
	+ Frequency-domain truncation with a truncation factor F (F<1) can be applied for I-π/2-BPSK to adapt to different spectrum efficiency requirements.
	+ Compared to π/2-BPSK without FDSS, I-π/2-BPSK with FDSS provides PAPR reduction of approximately 2.8 dB and 2.3 dB for 3/5 and 1/2 truncation, respectively, at 1% CCDF.
	+ Compared to π/2-BPSK with FDSS, I-π/2-BPSK with FDSS achieves approximately 1 dB and 0.6 dB lower PAPR for 3/5 and 1/2 truncation, respectively, at 1% CCDF.
	+ I-π/2-BPSK with FDSS achieves better BLER performance than π/2-BPSK with FDSS under the same spectral efficiency.
	+ I-π/2-BPSK with FDSS shows only a slight performance loss of 0.1~0.2 dB for 1/2 truncation and 0.2~0.3 dB for 3/5 truncation, at 1% BLER, compared to π/2-BPSK without FDSS under the same spectral efficiency.
	+ When the net gain is defined by the sum of PAPR and BLER gain, I-π/2-BPSK with FDSS (1/2 truncation) provides approximately 2.1 dB net gain over π/2-BPSK without FDSS, and approximately 0.9 dB net gain over π/2-BPSK with FDSS.
	+ When the net gain is defined by the sum of PAPR and BLER gain, I-π/2-BPSK with FDSS (3/5 truncation) provides approximately 2.5 dB net gain over π/2-BPSK without FDSS, and approximately 1.1 dB net gain over π/2-BPSK with FDSS.
 |
| Lekha | * Observation 3: SOQPSK is a constant-envelope modulation scheme designed for power-efficient communication, particularly in bandwidth-constrained environments. It minimizes spectral sidelobes and offers excellent spectral efficiency.
* Proposal 3: Shaped Offset Quadrature Phase Shift Keying based Orthogonal Frequency Division Multiplexing (SOQPSK-OFDM) is proposed for 6G to provide bandwidth efficiency, reduced spectral leakage, and Bit Error Rate (BER).
 |
| Panasonic | * Proposal 2: In addition to 5G NR pi/2-BPSK modulation, RAN1 can assess the need to introduce MPR / PAPR reduction technique such as phase rotated QPKS targeting coverage enhancement, especially for UL.
* Proposal 3: For MPR / PAPR analysis, how relationship with ACLR, SEM, EVM, spurious emissions, and occupied bandwidth progress will require discussion in RAN1 as PAPR only does not determine the amount of UE Tx power.
 |
| Ericsson | * Observation 5 6G use cases with power constraints such as energy efficiency and energy saving, enhanced coverage, LPWA devices, require moderate modulation order, low complexity, and low PAPR design.
* Proposal 11 6G modulation scheme shall support power constrained services with moderate modulation order and low complexity.
* Proposal 12 Modulation schemes with Low PAPR property can be studied.
 |
| MTK | * Proposal 1: For DFT-s-OFDM, support O-QPSK for coverage enhancement.
 |
| DCM | * Observation 1: pi/2-BPSK has been used in DFT-s-OFDM waveform in NR to reduce the PAPR for coverage limitation scenarios.
* Observation 2: QPSK rotation can reduce the PAPR of the DFT-s-OFDM waveform while achieving a higher data rate than pi/2-BPSK.
* Observation 3: QPSK rotation can be combined with DFT-s-OFDM, DFT-s-OFDM with FDSS and/or spectrum extension enhancement for further PAPR reduction.
* Observation 4: When QPSK rotation is combined with DFT-s-OFDM with asymmetric spectrum extension enhancement, i.e., FDSS-CE, the optimal phase rotation angle should depend on the spectrum extension factor.
 |
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The list of proposed schemes includes:

* Interpolated pi/2-BPSK with frequency domain truncation and FDSS – ZTE
* QPSK enhancements
	+ Offset-QPSK: Lekha (SOQPSK), MTK (OQPSK)
	+ Rotated-QPSK: Panasonic (pi/4-QPSK), DCM (QPSK with more general rotation)

### Round 1 discussion

Discussion 2.4-1

Companies are encouraged to evaluate the proposed schemes, including interpolated pi/2-BPSK, Offset-QPSK, and rotated-QPSK, and also encouraged to propose other schemes. However, given limited online/offline time and limited information provided, the moderator does not plan to discuss these topics before more information becomes available. It is also noted that similar proposals have been submitted to waveform agenda item. We need to decide in which agenda to continue study this topic.

If you have other suggestions, please provide below.

|  |  |
| --- | --- |
| Company | Suggestions |
|  |  |

## Discussions on joint channel coding and modulation

Multiple proposals received in the contributions submitted to 11.4.1, as summarized in the table below. In this section, we will treat proposals on joint channel coding and modulation only.

|  |  |
| --- | --- |
| Company | Position |
| Spreadtrum | * Don’t support joint channel coding and modulation in 6GR.
	+ Note: it is not precluded to discuss “joint channel coding and modulation” use case in 6G AI.
 |
| Vivo | * The imbalance between different bits in QAM symbols should be considered in the mapping between coded bits and modulated symbols, for example, in the form of a better bit interleaver design.
* Compared with NR design, the cross-codeblock interleaver design, e.g., MGCM can better leverage the unequal sub-channel capacity of QAM modulated symbols, by jointly modulating multiple different (e.g., coding rates/schemes) coded blocks.
* Observation: In the scenario of UCI multiplexed with UL-SCH, the cross-codeblock interleaver design, e.g., MGCM, can greatly simplify the RE allocation pattern, and meanwhile achieve greater throughput (larger than 10% in some simulated scenarios) for UL-SCH or deliver more UCI payload compared to NR baseline.
* Further study the cross-codeblock interleaver design, e.g., MGCM, as a solution for joint coding and modulation, considering at least the following two use cases:
	+ Two SCH data blocks coded by LDPC using different coding rates
	+ Multiplexed UCI and UL-SCH data blocks, respectively coded by Polar and LDPC
 |
| Xiaomi | * Reuse the 5G NR BICM framework in 6GR for coding-modulation concatenation.
 |
| Lekha | * Observation 4: Joint channel coding and modulation can optimize the overall communication system. For instance, it can adapt the modulation scheme based on the channel conditions and the coding strategy, leading to better performance in varying environments.
* Proposal 4: Learning based joint channel coding and modulation are crucial for 6G systems, where low latency and high data rates are essential. Several applications including semantic communications are found to benefit from the joint modulation and coding scheme.
 |
| HW | * Considers
	+ LDPC codes optimization for constellation shaping
	+ Polar codes optimization for constellation shaping
	+ Multi-level coding
	+ Delayed BICM
 |
| Oppo | * Observation 12: To address the issue of unbalanced bit-level reliability for QAM constellation, the interleaver may have to be customized for every possible individual combination of code block length and modulation order. That would lead to additional implementation difficulties.
 |
| Samsung | * QC-block interleaving
 |
| Rakuten | * Proposal 3: RAN1 studies the optimization of modulation labelling rules for 6GR, considering their impact on performance in joint demodulation and decoding scenarios, especially when non-capacity-achieving channel codes are used.
 |
| Sony | * Observation 1: DBICM requires a non-Gray bit-mapping.
* Observation 2: NR’s bit-mapping minimizes ID gains.
* Proposal 1: RAN1 should study bit-mappings for DBICM to be used in combination with DBICM and/or BICM-ID.
* Observation 3: TB-DBICM is a special case of interleaving the coded bits from N code blocks.
* Proposal 2: RAN1 should study the benefits of DBICM and CBI-BICM over BICM
* Proposal 3: RAN1 should investigate in which scenarios CBI-BICM is superior to TB-DBICM
* Proposal 4: RAN1 should establish benchmark receiver architectures for CBI-BICM
* Observation 4: CBI-BICM improves about 0.3 dB over BICM at BLER 10% for the considered setup.
 |
|  |  |

To summarize, we have the following opinions or proposals on joint channel coding and modulation collected from the contributions:

* Reuse 5G-NR BICM design and no changes needed - Xiaomi
* MGCM with cross codebook interleaving– vivo
* QC-block interleaving – Samsung
* DBICM and its variations – Sony, HW

### Round 1 discussion

Discussion 2.5-1

Companies are encouraged to evaluate the proposed schemes, including DBICM and its enhancements, MLC, MGCM with cross codebook interleaving, QC-block interleaving, and also encouraged to propose other schemes. However, given limited online/offline time and limited information provided, the moderator does not plan to discuss these topics before more information becomes available.

If you have other suggestions, please provide below.

|  |  |
| --- | --- |
| Company | Suggestions |
|  |  |

## Miscellaneous discussions

|  |  |
| --- | --- |
| Company | Proposals |
| Lekha | * Observation 1: Machine learning-aided modulation enables real-time adaptation of modulation schemes by leveraging channel conditions, mobility, and QoS requirements, leading to improved efficiency and robustness.
* Proposal 1: It is proposed to use machine learning-aided modulation for real-time adaptation of modulation schemes by leveraging channel conditions, user mobility, and QoS requirements to enhance efficiency and robustness.
* Observation 2: In 6G, modulation schemes are expected to be tailored for specific use cases to maximize performance based on diverse and evolving requirements.Proposal 2: In 6G, modulation schemes are expected to be tailored to specific use cases to meet diverse performance requirements. Higher-order QAM supports eMBB, ML-aided modulation enhances URLLC, and low-complexity schemes like OOK, BPSK, and QPSK are ideal for mMTC and VLC. Advanced applications such as holographic communication can use AI based adaptive modulation, RIS uses RIS modulated QAM, and phase shift keying schemes are preferred for satellite links .
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| LG | * Observation 2: Mixed modulation can achieve finer granularity in spectral efficiency and improved reliability
* Proposal 3: RAN1 should study the use of mixed modulation for 6G
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| Panasonic | * Proposal 4: RAN1 can assess the need to introduce sequence-based DMRS-less transmission for small information block length such as PUCCH with UCI bits up to 11 bits.
* 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 and modulation in DL is unclear.
* Proposal 7: Resource-specific modulation order assignment should be studied at least with carrier / BWP granularity.
	+ FFS: Finer granularity such as PBG / RB is further considered.
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| Ericsson | * 6G deployments such as MIMO, Multi-TRP, NTN, require robust modulation scheme to achieve good performance under varying propagation channels, and the evaluation shall consider the assumption of receiver algorithms.
* 6G modulation schemes shall support services with varying propagation channels and provide robust performance.
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| CEWiT | * Observation 2: Two-stage DCI approach provides significant advantages to:
	+ Address coverage requirements of different scenarios like NTN, large-cell deployments
	+ Enhance robustness of the control channels
	+ Improve energy efficiency at UE side by simplifying the blind decoding
* Observation 3: QPSK outperforms BPSK at lower aggregation levels (e.g., AL = 1 and AL = 2). As aggregation level increases, the performance of BPSK and QPSK becomes nearly same since the coding rate of BPSK and QPSK are comparable.
* Proposal 2: In 6GR, to have a robust control channel coverage, QPSK modulation for the PDCCH carrying first stage DCI should be considered, and the link adaption should be considered for second stage DCI.
	+ FFS: the BPSK for stage 1 DCI based on the channel coding and waveform adopted for PDCCH chain.
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