3GPP TSG RAN WG1 Meeting #120-bis **R1-2502586**
Wuhan, China, April 7th – 11th, 2025

Agenda Item: 9.4.1
Source: EURECOM
Title: Discussion on Physical Channel Modulation Aspects for Ambient-IoT
Document for: Discussion and Decision

1. Introduction

The WI item scope has been agreed in [1] with the RAN1 scope defined below:

RAN1 Scope: **RP-243326**

- PRDCH and PDRCH, which are the only physical channels in R2D and D2R, respectively.
- R2D and D2R signal(s)
- Multiplexing/multiple access in R2D is by only TDMA, and in D2R is by only TDMA and FDMA.
- R2D supports only OOK-4 modulation, one solution for CP handling. D2R backscattering supports only OOK and BPSK modulations.
- R2D transmission supports only the Manchester line code in TR 38.769
- D2R transmission supports:
    - Either the Manchester line code in TR 38.769 or no line code (one to be down-selected); and
    - A corresponding small frequency shift method according to the options in TR 38.769.
- R2D does not support FEC. D2R supports only convolutional code with generator polynomials as per TS 36.212 (unless RAN1 decides to use other generator polynomials by RAN1#120bis).
- PRDCH and PDRCH both support transmission without CRC, and with CRC as per the generator polynomials in TS 38.212 (unless RAN1 decides to use other generator polynomials by RAN1#120bis) for 6-bit CRC and 16-bit CRC. Cases to use which length of CRC, or no CRC, to be decided in RAN1.
- D2R supports physical layer repetition transmission. R2D does not support physical-layer repetition transmission.

This contribution focuses on modulation aspects and waveform design for the R2D (downlink) channel/signal.

In light of the few meetings available for normalization in Rel-19, we suggest to reuse existing sequence designs and modulation principles of OOK waveforms for R2D from the work on LP-WUS.

2. R2D Waveform

It has been agreed that "R2D supports only OOK-4 modulation" [1]. That is, the time domain OOK sequence is DFT precoded and mapped to the corresponding frequency resources.

In the previous meeting, the following agreement has been reached

> Agreement: **RAN1#120**
>
> For R2D transmission, from reader perspective, DFT-s-OFDM waveform is supported for OOK-4 modulation. For the details of DFT-s-OFDM waveform generation of OOK-4 modulation:
>
> - Certain specification of DFT-s-OFDM waveform generation for OOK-4 modulation is needed in RAN1.
>   - FFS: identify what potential details of 5 steps in section 4.4 of TR 38.769 needs to be specified.
> - This does not preclude RAN4 to discuss R2D waveform generation themselves when defining requirement(s), if needed.

The 5 steps in section 4.4 of TR 38.769 read

> Agreement: **TR 38.769 V2.0.0**
>
> With reference to the R2D waveform described in Clause 6.1.1.1, for evaluation purposes the waveform for DFT-s-OFDM is generated as follows:
>
> 1. The time domain OOK signal is the *M* chips of one OFDM symbol.
> 2. A chip is represented (e.g. upsampled) by *L* samples
>   - Companies to report *L*
> 3. An *N*'-points DFT is performed on the samples of one OFDM symbol to obtain the frequency domain signal.
>   - Companies to report *N*', e.g. *N*'=128 or equal to *X*
> 4. Map the frequency domain signal obtained by N'-points DFT to the *X* subcarriers of $B_{tx,R2D}$.
>   - Companies report how to map and report *X*
> 5. An *N*-points IDFT is performed to obtain the time domain signal.
>   - Companies to report *N*, and how value was selected
>
> Note: Companies report whether/how CP samples are added.

In our understanding, it is beneficial to specify the L time-domain samples in Step 2. More precisely, the choice of the ON-sequence impacts the spectral shape of the transmission. If the spectral shape is known, the device can optimize its receiver filter to improve signal reception. We therefore propose to specify the ON-sequence.

Proposal 1: Consider specifying time-domain sequence mapped to ON-chip in Step 2.

The choice of the ON-sequence should follow the LP-WUS design which agreed on the *cyclically extended Zadoff-Chu sequence* $s(n)$ of length L_{ZC}, already specified in the standard [TS 38.211, Section 5.2.2.1], generate as

$$s(n) = X_q(n \, mod \, B_{ZC})$$

with

$$X_q(m) = e^{-j\frac{\pi q m(m+1)}{B_{ZC}}}$$

where $m = 0,1, \dots, B_{ZC} - 1, n = 0,1, \dots, L_{ZC} - 1$, $B_{ZC} = PP(L_{ZC})$ with $PP(x)$ denoting the largest prime less or equal to x and q is the root.

The length L_{ZC} depends on the chip duration of L samples (i.e., M and the configured $B_{tx,R2D}$), which itself may depend on the CP-handling mechanism.

3. R2D Modulation

The following has been agreed on the R2D bandwidth [2]:

Agreement: **TR 38.769 V19.0.0**

The study defines the following bandwidths for R2D:

- Transmission bandwidth, $B_{tx,R2D}$ from a reader perspective: The frequency resources used for transmitting R2D. For an OFDM-based waveform with subcarrier spacing of 15 kHz, $B_{tx,R2D} \leq$ twelve PRBs, and would be down-selected among:
- Alt 1: Including 180 kHz, 360 kHz
- Alt 2: Integer multiple(s) of 180 kHz
- Alt 3: Integer multiple(s) of the subcarrier spacing
- Occupied bandwidth, $B_{occ,R2D}$ from a reader perspective: The frequency resources used for transmitting R2D, and potential guard band.
- $B_{occ,R2D} \geq B_{tx,R2D}$.

The starting point for possible M-values defining the length of the ON-sequence are [2]:

Agreement: **TR 38.769 19.0.0**

Table 6.1.1.4-1 is a starting point for study of M values and the associated minimum $B_{\mathrm{tx,R2D}}$ value. The reader can use any transmission bandwidth greater than or equal to the minimum $B_{\mathrm{tx,R2D}}$ value.

Note: Depending on further study, the maximum value of M may be less than 32.

Note: The performance can be better when transmission bandwidth greater than the minimum $B_{\mathrm{tx,R2D}}$, depending on device processing and transmit power constraint.

Table 6.1.1.4-1: Starting point for M values and the associated minimum $B_{\mathrm{tx,R2D}}$ value

M	Minimum $B_{\mathrm{tx,R2D}}$ # of PRBs
1	1
2	1
4	1
6	1
8	2
12	2
16	2
24	3
32	4

During RAN1#120 it was agreed to not specify the exact BW $B_{tx,R2D}$

Agreement: **RAN1#120**

RAN1 does not specify the exact bandwidth a reader shall use for $B_{\mathrm{tx,R2D}}$.

- For R2D, specify the minimum $B_{\mathrm{tx,R2D}}$ # of PRBs associated to each M value.
- For R2D, whether to specify the maximum $B_{\mathrm{tx,R2D}}$ # of PRBs is up to RAN4
- Note: Reader can transmit any $B_{\mathrm{tx,R2D}}$ subject to this minimum $B_{\mathrm{tx,R2D}}$ and the agreed 15 kHz subcarrier spacing, and subject to other limitations that are up to RAN4.

Concerning the possible transmission BWs $B_{tx,R2D}$, it is important to note that more BW configurations will result in more ON-sequences that have to be potentially pre-computed and stored at the reader/device. Per BW, there are 2^M possible sequences per OFDM symbol if no coding is applied (and $2^{M/2}$ with Manchester coding).

With regards to the M values it was agreed that M is no less than 16.

Agreement: **RAN1#120**

For R2D, for the OOK-4 modulation for M-chip per OFDM symbol transmission:

- The maximum M value is no less than 16, and to be down-selected from 32, 24 or 16 at RAN1#120bis.

In the following we carry out link-level simulations for different combinations of M and $B_{tx,R2D}$. The simulation assumptions are summarized in Table 1. We assume no impairments, perfect synchronization and perfect CP removal at the device. Moreover, we use Manchester coding and a packet size of 20 bits. Thus, the duration of the transmission is 40 OFDM symbols (3 slots), 20 OFDM symbols (2 slots) and 10

OFDM symbols (1 slot) for $M = 1$, $M = 2$ and $M = 4$, respectively. The power, for one BW configuration, is normalized such that the total transmit power per packet is identical, e.g. factor 1/2 for $M = 1,2$ and 3/2 for $M = 6$ compared to $M = 4$.

The results are shown in Figure 1. In general, the TDL-A channel with 30ns delay spread is not very frequency selective and hence the performance difference between short OOK symbols (large M) and longer OOK symbols (small M) are not very pronounced as is the case for instance in a TDL-C channel with 300ns delay spread. Moreover, the spectral properties of the transmitted waveform are impacted when the OOK symbol is short because a shorter ON sequence (e.g. 2 or 3 samples) is unable to shape the spectrum such that most of the energy is contained its center. Thus, the receive filter captures less energy.

For a BW of 1 PRB and $M = 4$, the ON-sequence contains 3 samples. At the receiver with sampling rate of 1.92MHz, we obtain 128 samples per OFDM symbol (excluding CP) in base-band, i.e. 32 samples per OOK symbol. The BLER results for 1PRB BW are shown in Figure 1. It can be observed that there is no significant performance difference especially at high SNR. At low SNR, $M = 6$ performs best because the OOK symbol is short and hence the noise power per OOK symbol is lower which is an advantage when the noise power is high. We conclude, that larger values of M, e.g. $M = 6$, perform better and consume less transmission time/resources.

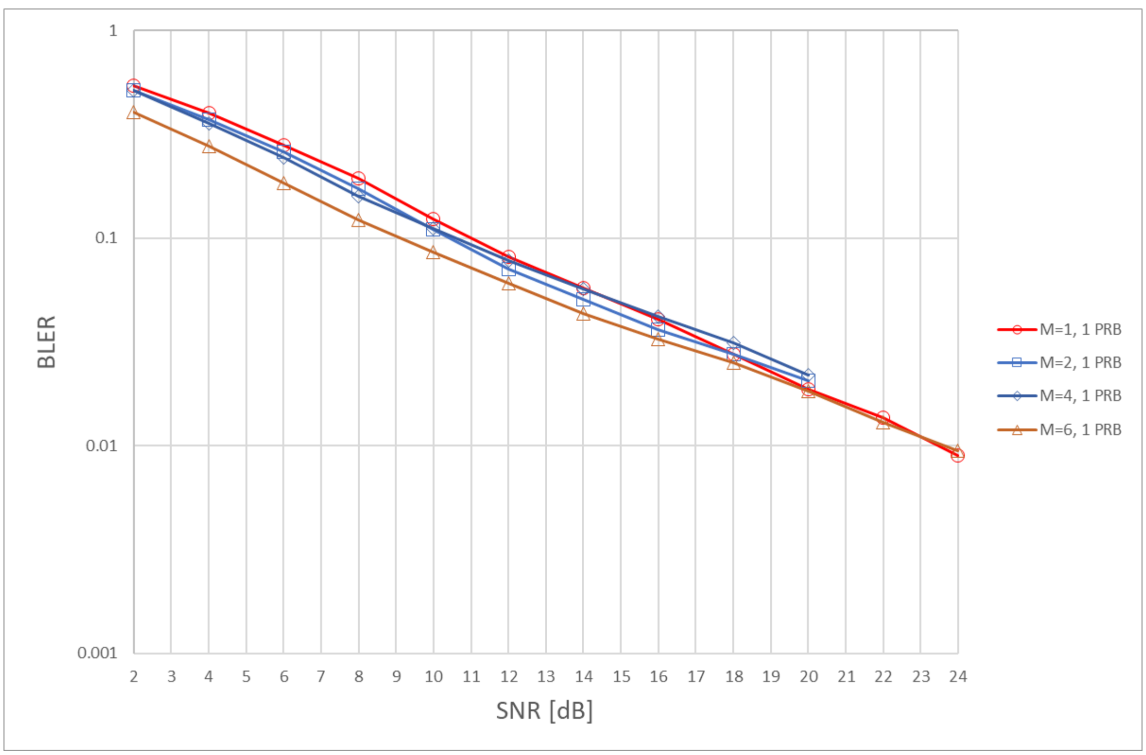

Figure 1: Performance for different values of M and BW of 1 PRB in TDL-A, 30ns.

The same conclusions hold true for a BW of 2 PRB as shown in Figure 2. $M = 12$ outpeforms both $M = 8$ and $M = 6$ by about 2dB.

Further increasing the BW shows a similar picture, depicted in Figure 3. For 4 PRB, $M = 24$ outperforms $M = 16$ by about ~2dB and the performance of $M = 36$ for 6 PRBs (we choose $M = 36$ rather than $M =$

32 so that M is a multiple of the number of REs) is somewhere in between. For comparison, we simulated the performance for 11 PRB, where we start to see some frequency diversity gain. Still, larger values of M perform better given the same total transmit power.

Observation 1: Given the same total transmit power, larger values of M outperform smaller M while minimizing both transmission resources and transmission time.

For a fixed M, increasing the bandwidth yields a significant performance gain. Moreover, a larger BW results in a longer OOK symbol duration (given fixed M) which influences the possible CP handling schemes.

Observation 2: Bandwidths larger than the minimum BW increase performance.

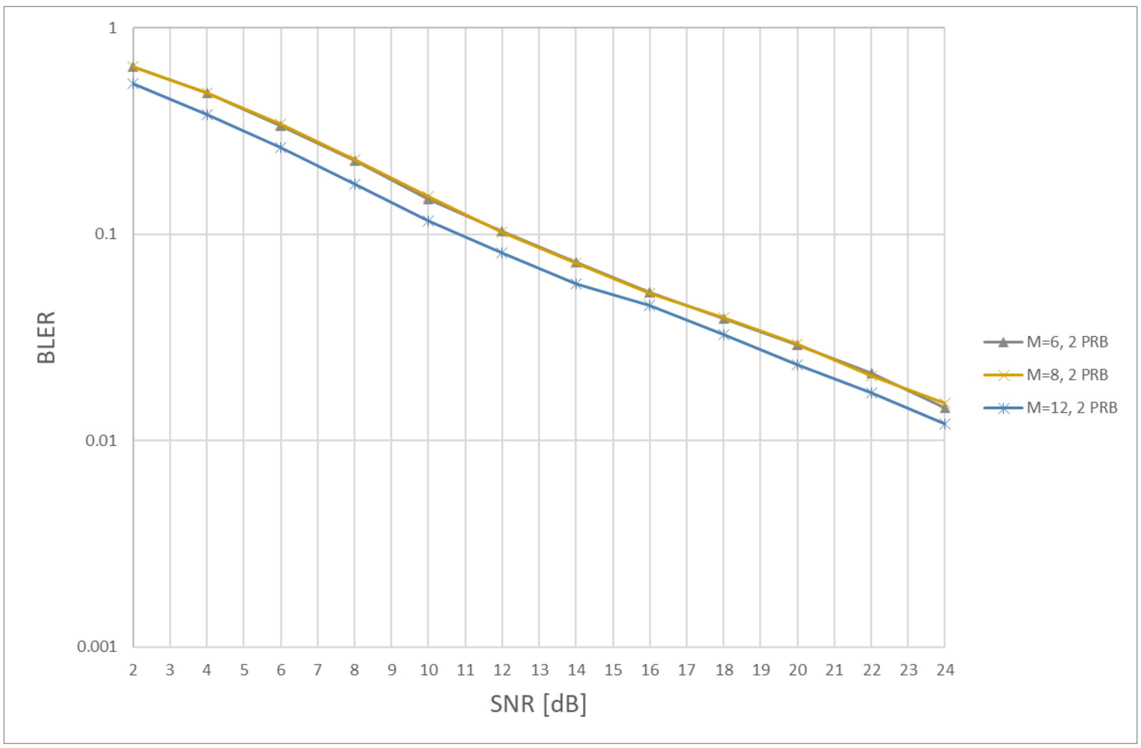

Figure 2: Performance for different values of M and BW of 2 PRB in TDL-A, 30ns.

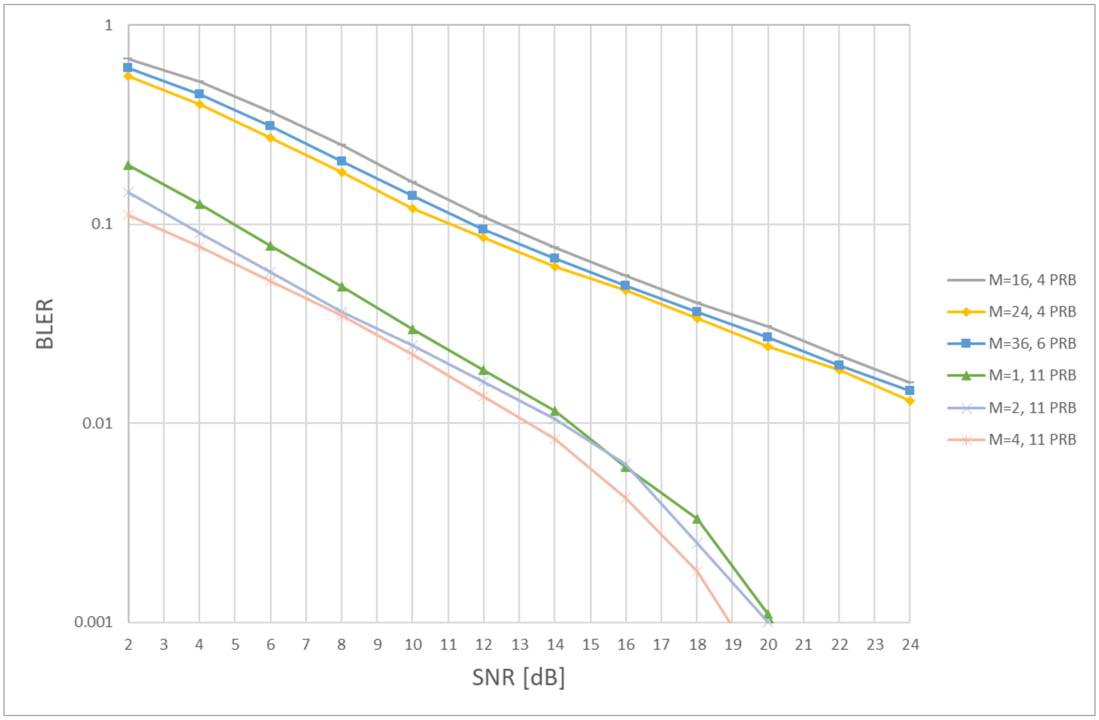

Figure 3: Performance for different values of M and BW of 4,6 PRB and 11 PRB in TDL-A, 30ns.

Proposal 2: Allow a maximum M value of 32 to achieve higher data rate than RFID.
Proposal 3: Support a selected number of M values, e.g. 1, 2, 4, 8, 16, 24 and 32.
Proposal 4: The minimum transmission BW $B_{tx,R2D}$ for $M = 32$ should be increased to ensure sufficient performance.

4. R2D Chip Duration

In our view, the chip duration C should be defined independently of the CP as $C = \frac{1}{SCS}\frac{1}{M}$. If a potential CP-handling method modifies C this can be captured as $C' = f(C)$, i.e. some function $f()$ that modifies the original chip duration C.

Proposal 5: Define chip duration as $C = \frac{1}{SCS}\frac{1}{M}$.

5. Conclusion

In this contribution, the following proposals and observations have been made:

Proposal 1: Consider specifying time-domain sequence mapped to ON-chip in Step 2.

Observation 1: Given the same total transmit power, larger values of M outperform smaller M while minimizing both transmission resources and transmission time.

Observation 2: Bandwidths larger than the minimum BW increase performance.

Proposal 2: Allow a maximum M value of 32 to achieve higher data rate than RFID.

Proposal 3: Support a selected number of M values, e.g. 1, 2, 4, 8, 16, 24 and 32.

Proposal 4: The minimum transmission BW $Btx, R2D$ for $M = 32$ should be increased to ensure sufficient performance.

Proposal 5: Define chip duration as $C = \frac{1}{SCS}\frac{1}{M}$.

6. References

[1] RP-243326, "New Work Item: Solutions for Ambient IoT (Internet of Things) in NR", RAN1 Vice-chair (Huawei), RAN#106, Dec 2024

[2] TR 38.769, "Study on solutions for ambient IoT (Internet of Things)", V19.0.0, Dec 2024.

7. Appendix

7.1. Link-Level Simulation Assumptions

The R2D link level simulation assumptions are summarized in

Parameter	Value
Carrier Frequency	900 MHz
Waveform	OOK waveform generated by OFDM modulator
SCS	15 kHz
Modulation	OOK-4 ON-Sequence = Cyclically Extended Zadoff-Chu
Code Scheme	Manchester Coding
Message size	20 bits
BS Channel BW (In-band deployment)	20MHz (106 PRBs @ 15kHz SCS)
Transmission BW	180 kHz
Channel Model	TDL-A with 30ns Delay Spread
Number of Tx/Rx chains for Ambient IoT device	1
Number of Tx/Rx chains at BS	2
Device Velocity	3 km/h
Adjacent Sub-carrier Interference (ACI)	none
Timing Error	none
CFO	none
Receiver	ED
BB Low-Pass Filter	3rd order Butterworth (X=3) with 4.32 MHz BW
ADC bit-width	4-bit
Sampling Frequency	7.68 MHz / 1.92 MHz
Sampling Frequency Offset (SFO) Fe	none

Table 1: General Link-Level Simulation Assumptions.