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Title: Discussion on LP-WUS and LP-SS Design
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1. Introduction

In 3GPP wake-up signals (WUS) are specified in both LTE-M/NB-IoT as well as NR-Rel-17 under the name of paging early indication (PEI). The key difference between those WUS and a low-power (LP)-WUS is that the LP-WUS is received with a *low-power* wake-up receiver (WUR) *independent* of the main radio, i.e. the main radio can be turned off.

A SI [1] on low-power (LP) wake-up signal (WUS) and receiver for NR has been carried out in Rel-18 with the report available in [2]. In Rel-19, a WI [3] was agreed including the following objective related to LP-WUS and LP-SS design:

> Objectives:
>
> - To specify an LP-WUS design commonly applicable to both IDLE/INACTIVE and CONNECTED modes (RAN1, RAN4)
>   - Specify OOK (OOK-1 and/or OOK-4) based LP-WUS with overlaid OFDM sequence(s) over OOK symbol
>   - The LP-WUS design shall ensure that for IDLE/INACTIVE operation, the same information is delivered irrespective of LP-WUR type. The OFDM sequence can carry information.
>   - At least duty-cycled monitoring of LP-WUS is supported
> - For IDLE/INACTIVE modes
>   - Specify procedure and configuration of LP-WUS indicating paging monitoring triggered by LP-WUS, including at least configuration, sub-grouping and entry/exit condition for LP-WUS monitoring (RAN2, RAN1, RAN3, RAN4)
>   - Specify LP-SS with periodicity with Yms for LP-WUR, for synchronization and/or RRM for serving cell. (RAN1, RAN4)
>   - LP-SS is based on OOK-1 and/or OOK-4 waveform with or without overlaid OFDM sequences. Further down selection between with and without overlaid OFDM sequences is to be done within WI.
>   - Note: For LP-WUR that can receive existing PSS/SSS, existing PSS/SSS can be used for synchronization and RRM instead of LP-SS.
>   - Y will be decided within WI. 320ms is the start point.
>   - Specify further RRM relaxation of UE MR for both serving and neighbor cell measurements, and UE serving cell RRM measurement offloaded from MR to LP-WUR, including the necessary conditions (RAN4, RAN2)

This contribution focuses on LP-WUS design in RRC IDLE mode.

2. OOK Waveform Designs

Regarding the LP-WUS waveform design the following has been agreed in RAN#116-bis:

> Agreement:
>
> For OOK-4 with M >1, support M=2 & M=4 (working assumption) for LP-WUS.
>
> - FFS whether value of M depends on SCS
> - FFS M=1 for OOK-4

In this section, we review the OOK modulation and the 2 agreed OOK schemes, OOK-1 and OOK-4.

We denote N PRBs as the bandwidth of the LP-WUS including potential guard bands (GB). The actual number of used PRBs for the WUS and GB are referred to as N_{WUS} and N_{GB}, respectively, such that $N = N_{WUS} + N_{GB}$.

Moreover, we refer to the ON-signal $\boldsymbol{a}$ as the sequence of complex symbols allocated to the OOK symbol if the corresponding bit is one.

The overall DL transmission block diagram is depicted in Figure 1. The B information bits $\boldsymbol{b} = [b_0, b_1, \ldots, b_{B-1}]$ are encoded and the resulting C coded bits $\boldsymbol{c} = [c_0, c_1, \ldots, c_{C-1}]$ are modulated onto L consecutive OFDM symbols each carrying M bits. That is, M is the number of coded bits per OFDM symbol or the number of OOK symbols. Subsequently, the signal in frequency-domain $\boldsymbol{S}_m$ of message $m = 0,1, \ldots, 2^B - 1$ is mapped to the overall resources $\boldsymbol{X}_m$ of N sub-carriers and OFDM-modulated resulting in the time-domain signal $\boldsymbol{x}_m(t)$.

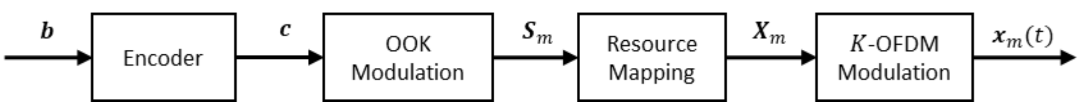

Figure 1: Overall transmission block-diagram per OFDM symbol.

Subsequently, we review OOK modulation as well as the specific OOK-1 and OOK-4 modulations in the WI objectives.

2.1. OOK Modulation

Denote the OOK modulated signal $\boldsymbol{s}_m$ in time-domain for message $m = 0,1, \ldots, 2^C - 1$ as

$$\boldsymbol{s}_m = [\boldsymbol{s}_0, \boldsymbol{s}_1, \ldots, \boldsymbol{s}_{C-1}]$$

where C is the number of coded bits transmitted per OFDM symbol l and $\boldsymbol{s}_i = [s_{i0}, s_{i1}, \ldots, s_{iN'_B-1}]$ with $N'_B = \lfloor N'/C \rfloor$ the number of samples for sequence $\boldsymbol{s}_i$, $i = 0,1, \ldots, C-1$. The OOK modulation consists of mapping an ON-signal or ON-sequence $\boldsymbol{a} = [a_0, a_1, \ldots, a_{N'_B-1}]$ to $\boldsymbol{s}_i$ whenever the corresponding bit is one, i.e.

$$\boldsymbol{s}_i = \begin{cases} \mathbf{0}, & c_i = 0 \\ \boldsymbol{a}, & c_i = 1 \end{cases}$$

Hereby, the ON-signal $\boldsymbol{a}$ can be *any complex sequence* and can be different for every $\boldsymbol{s}_i$.

In case of multiple ON-sequence, consider Q ON-sequences $\boldsymbol{a}_q$ able to encode $\mathrm{B}_2 = \log_2 Q$ bits.

2.2. OOK-1: Single-bit in 1 OFDM symbol

The simplest OOK scheme allocates the ON-signal $\boldsymbol{a}$ of length N_{WUS} to the corresponding WUS SCs if the bit is one and zeros otherwise (in baseband).

A block-diagram is shown in Figure 2.

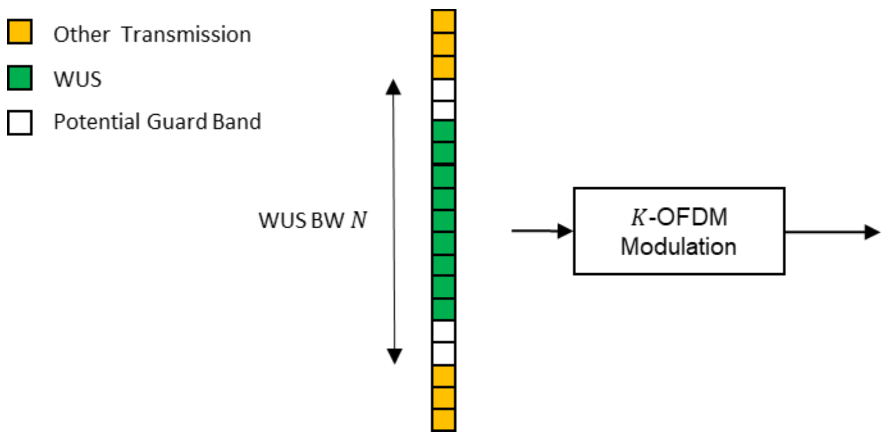

Figure 2: Block-diagram for OOK-1.

This transmission scheme can only transmit a single bit per OFDM symbol. Thus, the only means to increase the data rate is to shorten the OFDM symbol length by increasing the sub-carrier spacing (SCS).

2.3. OOK-4: Transform M-bit OOK in time domain

This scheme uses DFT-precoding to convert M OOK symbols in time-domain to frequency domain for allocation to N_{WUS} PRBs.

An example block-diagram is depicted in Figure 3. From the M (coded or physical) bits, a signal of length N' is generated where each bit is mapped to a sequence $\boldsymbol{s}_i$ of length N'_B, the sequence is 0 if the corresponding bit is zero and $\boldsymbol{s}_i = \boldsymbol{a}$ otherwise. The resulting sequence is DFT precoded and the output is mapped to the overall transmission bandwidth.

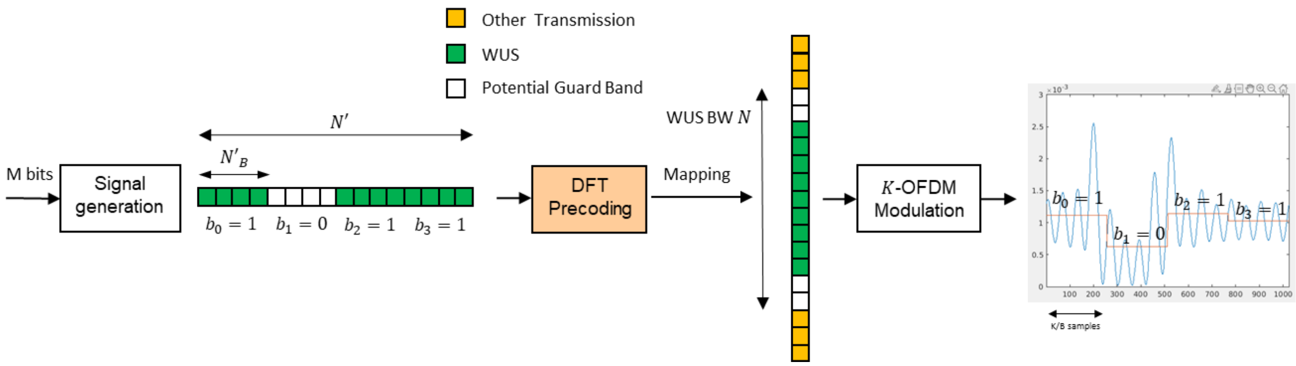

Figure 3: OOK-4, Block-diagram with $M=4$.

2.4. Waveform Generation

For the discussion on LP-WUS waveform generation, we borrow the block-diagram from the feature lead summary in Figure 4.

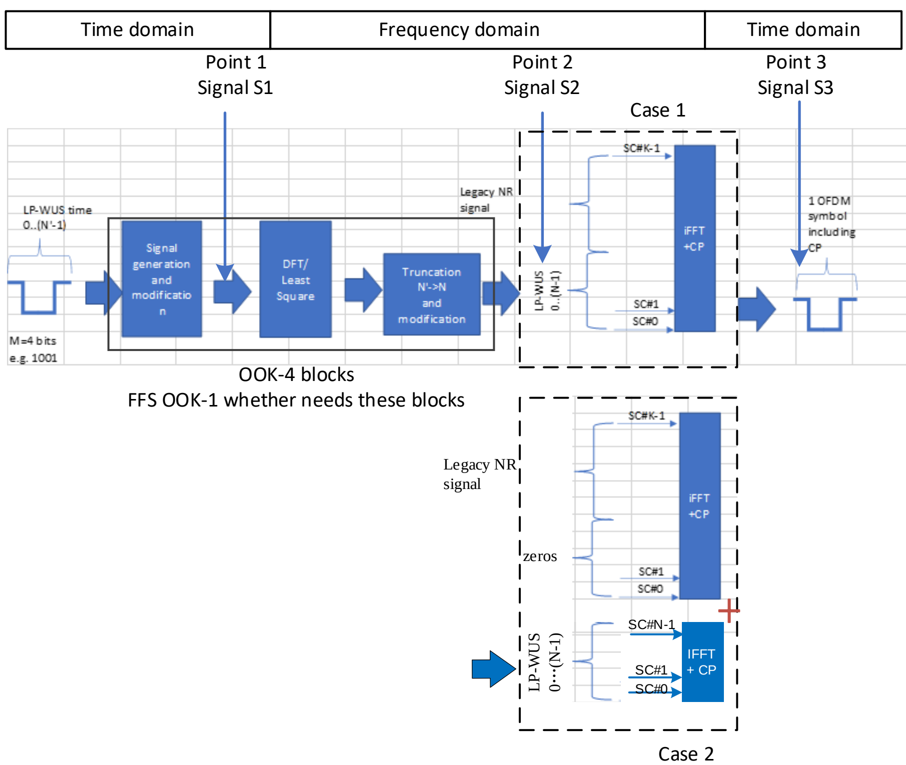

Figure 4: Block-diagram for LP-WUS waveform generation.

2.4.1. Pulse Shaping at S1

Pulse shaping should be considered together with the ON-sequence design. It has been shown that shorter pulses, or ON-sequences that concentrate the energy in the middle of the pulse, are more robust to timing errors. However, short pulses will capture less multi-path diversity and it is therefore necessary to ensure that the duration of the pulse is sufficiently long.

Moreover, a potential preamble and/or a receiver that applies time-windowing (sliding window), will mitigate the impact of timing inaccuracy. Hence, shortening the pulse might not be necessary/beneficial after all.

Proposal 1: Consider if pulse-shaping is required after sequence design and potential preamble are agreed.

2.4.2. DFT-Shift for Signal at S1

Given the generation of the OFDM waveform, a DFT-shift might be required to ensure that the LP-WUS spectrum integrates seamlessly into the overall NR spectrum.

For an energy detector, the DFT-shift has no impact on the detection performance. However, a coherent receiver needs to know if a DFT-shift has been applied or not. In general, the DFT shift can be applied at the gNB or at the receiver. We don’t have a strong preference but since the standard MR OFDM-based receiver compensates for shift, the same could be assumed for the LR.

Proposal 2: The DFT-shift is compensated at the LR.

3. Coding

The WUS coding procedure is shown in Figure 5. The payload $\boldsymbol{b}$ is channel encoded resulting in codeword $\bar{\boldsymbol{d}}$ which is then rate matched to the available resources. Subsequently, the rate matched coded bits $\boldsymbol{d}$ are encoded with a line code, e.g. Manchester coding or Pulse Position coding, resulting in the coded bits sequence $\boldsymbol{c}$ which is OOK modulated to a time-domain sequence $\boldsymbol{s}(t)$. This time domain sequence is converted to frequency-domain and mapped to the WUS bandwidth.

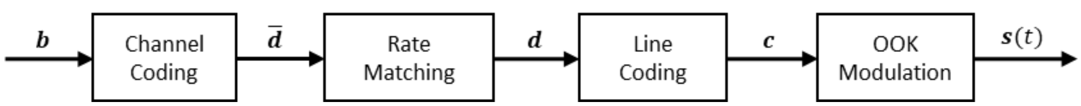

Figure 5: Block-diagram of WUS encoding procedure.

Agreement:	**RAN1#121**
From specification design perspective, for both RRC idle/inactive and RRC connected mode, support up to 5 information bits and up to 32 codepoints for a LP-WUS.	

3.1. Channel Coding and Rate Matching

To meet target requirements, it has been agreed to consider the following scheme:

Agreement:	RAN1#120

For LP-WUS information carried by OOK, select alt 1 for codepoint to meet FAR and MDR performance.

- Alt 1: Coding with rate matching if any
  - For more than 2 information bits: RM coding as in section 5.3.3.3 of 38.212 (FFS: whether scrambling in the same section is applied or not)
  - 2 information bits (if supported): coding as in section 5.3.3.2 of 38.212 (FFS: whether scrambling in the same section is applied or not)
  - 1 information bit (if supported): repetition as in section 5.3.3.1 of 38.212 (FFS: whether scrambling in the same section is applied or not)
  - FFS: Code block length
  - FFS: Further repetition before or after Manchester coding

Working Assumption:	RAN1#120

Support 1 & 2 information bits for LP-WUS. No additional restriction is introduced on the supported number of subgroups/codepoints by LP-WUS.

- 2 information bits: coding is done as described in the first row in the table in section 5.3.3.2 of 38.212 (scrambling is not applied)
- 1 information bit: repetition is done as described in the first row in the table in section 5.3.3.1 of 38.212 (scrambling is not applied)

Proposal 3: Confirm working assumption on the support of 1 and 2 information bits for LP-WUS.

The remaining issue concern the code block lengths as well as repetition:

Agreement:	RAN1#121

For > 2 information bits with RM coding, support candidate code block (coded bits) length after rate matching within the below range:

- Alt 1a: code block (coded bits) length: [3,4]~[32,64]
  - FFS whether all or a subset of lengths is selected.
  - FFS whether same range applies to all M values
  - FFS: above lengths do not consider repetition (if supported) after rate matching

After rate-matching, the coded bits are Manchester coded and subsequently mapped to the available OOK symbols for LP-WUS. Assume there are $G = LM$ OOK symbols available, where L is the number of OFDM symbols for LP-WUS and M is the number of OOK symbols per OFDM symbol. Therefore, the number of coded bits after rate-matching is $E = G/2$, because of the $R = 1/2$ Manchester code. The code block length after RM coding is $N = 32$. Hence, a code block length $E = 64$ means that the RM codeword is repeated once, which mean $E = 64$ counts as repetition. If repetition is not considered, the maximum code block length should be $E = 32$.

Observation 1: For $B > 2$, without repetition, the maximum code word length is 32.

If repetition is supported, code block lengths $E > 32$ can be considered which would automatically repeat the bits according to the rate matching procedure. In our opinion repetition should be considered to ensure reliable reception. Note however, that it has been agreed in AI 9.2.2 that within an LO, every beam can contain multiple MOs which are supposedly also repetitions of the LP-WUS. So it is unclear to us how those 2 things fit together. Are we specifying both repetition within one MO and additionally repetition of MOs ?

Observation 2: Clarify how repetition of the LP-WUS relates to the potential repetitions of MOs within a beam.
Proposal 4: For $B > 2$, support repetition in the rate-matching procedure for LP-WUS.

Concerning the minimum code block length, if $B = 3$, $E = 3$ means there is no channel coding. Similarly, for $B = 4$ or $B = 5$, a code block length of $E = 3$ does not make sense. Hence, to support "no coding" we propose to set the minimum code block length after rate-matching to $E = B$.

Proposal 5: For $B > 2$, the minimum code block length is B.

The same range can apply to all M values as long as there are enough OOK symbols available to map the entire code block after Manchester coding. For instance, $B = 5$ requires at least $G = 10$ OOK symbols if there is no channel coding applied, i.e. $E = 5$, which means $10 = LM$ needs to be fulfilled.

Proposal 6: For $B > 2$, the code block lengths apply to all values of M.

We do not see a reason to constrain the range of possible code block lengths, which gives more flexibility to the length of the WUS. However, the length of the WUS (and thereby the code block length) should be identical for all MOs to ensure the same coverage for all beams and UEs.

Proposal 7: For $B > 2$, all of the code block lengths within the range are supported.

After channel coding, a line coding scheme is applied to facilitate data demodulation for ED receivers. Manchester Coding is the working, however for $M = 4$ Pulse Position Coding (PPC) is a viable alternative. PPC has *no additional resource overhead* but achieves a SNR gain of 3dB simply by pooling the available power to a single OOK symbol.

3.2. Line Coding: Discussion on Manchester Coding

The study on LP-WUS [2] suggests to utilize Manchester Coding, where one input bit is mapped to two coded bits. This coding technique is especially adapted to OOK with ED since it does not require threshold detection but a simple energy comparison of the two OOK symbols is sufficient for reliable decoding.

The following agreement has been made

Agreement:	**RAN1#118**
Support Manchester coding for LP-WUS • FFS other coding schemes.	

Subsequently, we address the FFS point on other coding schemes in the above agreement.

In case of $M = 4$, following the Manchester coding scheme, two of the four available OOK symbols per OFDM symbol will be ON. Hence, the available transmit power per OFDM symbol is divided among the two ON-symbols.

In the next section we discuss an alternative approach where two input bits are encoded in the position of a single ON symbol.

3.3. Line Coding: Pulse Position Coding for $M = 4$

The detection performance of Manchester Coding can be improved by jointly encoding multiple bits. More precisely, B input bits $\boldsymbol{b} = b_0, b_1, \dots, b_{B-1}$ are encoded to C output bits $\boldsymbol{c} = c_0, c_1, \dots, c_{C-1}$ according to

$$\bar{\boldsymbol{c}} = 2^m$$

where $m = 0,1, \dots, 2^B - 1$ is the message and $\bar{\boldsymbol{c}}$ is the *decimal* representation of codeword $\boldsymbol{c}$. For $B = 1$, we obtain the conventional Manchester code of rate $R = 1/2$ presented in Table 1.

Input Bits	**Coded Bits**
0	01
1	10

Table 1: Encoding for B=1 input bits and C=2 coded bits, rate R = ½.

Encoding $B = 2$ bits into $C = 4$ coded bits is given by Table 2.

Input Bits	**Coded Bits**
00	0001
01	0010
10	0100
11	1000

Table 2: Encoding for B=2 input bits and C=4 coded bits, rate R = ½.

As can be seen from Table 2, the input bits are encoded in the position of the one-bit, hence the name Pulse Position Coding (PPC), or Pulse Position Modulation.

Figure 6 shows an example of the transmitted waveform for the two encoding schemes without any co-scheduled transmissions. It can be observed that the pulse position coded data results in higher signal amplitudes, i.e. a power boost, compared to Manchester coding.

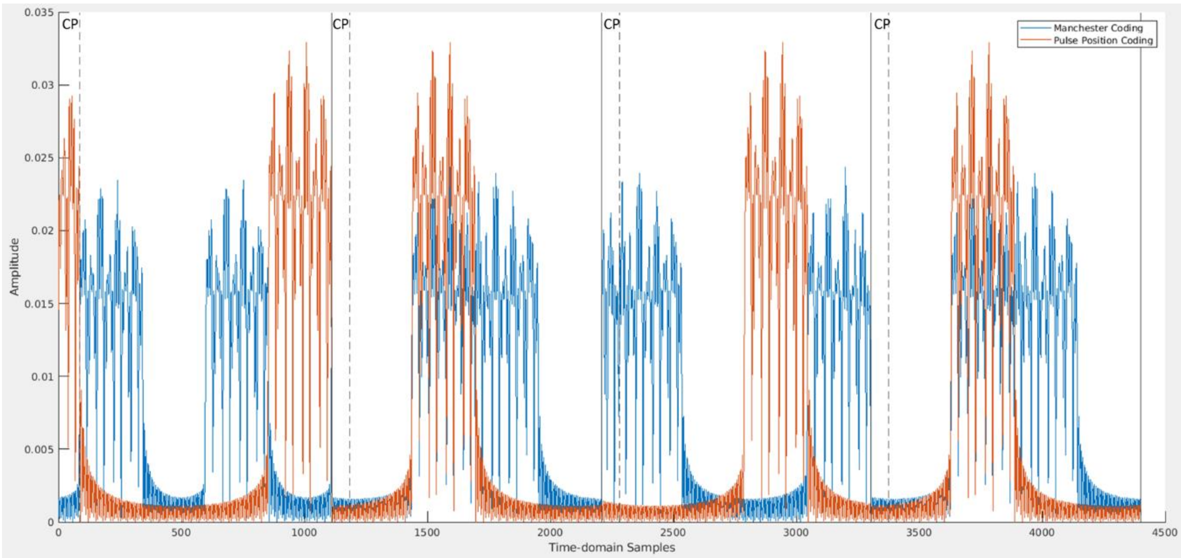

Figure 6: Transmit Signal for payload $\boldsymbol{b} = [1\ 1\ 0\ 1\ 1\ 0\ 0\ 1]$, $M = 4$, *4 OFDM symbols, no ACI.*

The main advantage of using $B = 2$ compared to $B = 1$, is that the total WUS transmit power per OFDM symbol is concentrated into a single ON-symbol and not divided among two ON-symbols. Hence, there is a 3dB SNR gain.

From results of the SI [2], it has been observed that the case $M = 4$ has the worst coverage compared to $M = 2$ and $M = 1$ with a loss of about 3dB for the reasons explained above. Thus, any coding scheme that can mitigate the coverage loss should be considered.

Observation 3: $M = 4$ with Manchester Coding has the worst coverage compared to $M = 1, 2$.

The proposed PPC results in a 3dB SNR gain compared to Manchester Coding and hence the required SNR is the same as for $M = 2$ but with double the data rate. Therefore, the WUS payload can be delivered twice as fast reducing the power consumption of the LR.

Proposal 8: For $M = 4$, consider jointly encoding multiple bits into ON pulse position to increase SNR by 3dB.

3.3.1. Decoding at the Receiver

At the receiver, one can distinguish two ways to decode a Manchester encoded payload, (i) per-codeword decoding and (ii) sequence decoding.

In case of per-codeword decoding, the Manchester codeword is decoded by accumulating the energy of the two corresponding OOK symbols and comparing their energy. The same strategy applies to PPC where the energy is computed for four OOK symbols and the symbol with the maximum energy determines the information bits.

For sequence-decoding, multiple codewords are decoded jointly by correlating with all possible coded sequences. Naturally, this is only feasible if the transmitted payload is small, otherwise the number of possible transmitted messages and hence the number of correlations increases exponentially. An important factor that needs to be accounted for is interference, which changes over time and can be significantly different at the start of the received sequence compared to the end of the sequence. This issue is usually addressed by taking the difference between the amplitudes of two adjacent OOK symbols which constitute a codeword under the assumption that the interference remains approximately constant within the codeword.
In case of PPC, the same paradigm applies but instead of subtracting the amplitude of the other OOK symbol, one has to subtract the *average* of the other *three* amplitudes because the codeword contains 4 OOK symbols. Again, the assumption here is that the interference is approximately constant over the codeword which, compared to the case of Manchester coding, is double the duration.

Discussion of Self-Clocking Aspect

Manchester coding has the advantage the there is always a transition from zero to one or one to zero in the codeword which allows for timing alignment, also referred to as self-clocking. One simple implementation to maintain timing alignment during the decoding process is an Early-Late architecture, where two parallel branches accumulate energy with one branch starting accumulation a few samples earlier (Early branch) and the other a few samples later (Late branch). By comparing the results of the two branches, one can determine if it is necessary to realign the OOK symbol timing.

With PPC, there is only one transition in the codeword but the same principle applies. The only difference is that the timing alignment is evaluated at the end of the codeword which takes four OOK symbols instead of two. However, unless the timing changes significantly within 4 OOK symbols, there is no impact on decoding performance.

Also note that timing determination, i.e. determining the rising or falling edges of the pulse, is improved in PPC since the SNR of the Pulse is higher.

3.3.2. Discussion on PAPR

It has been pointed out that PPC increases the PAPR of the resulting OFDM time-domain waveform which impacts existing base-station implementations, e.g. they may fail RAN4 requirements.

In this section, we analyze the impact of PPC on Peak-to-Average Power Ratio (PAPR) of the transmitted waveform. Unless stated otherwise, the simulation assumption in Table 6 are used. The transmission power of the WUS per OFDM symbol is kept constant. For an ON-sequence $\boldsymbol{a} = [a_0 a_1 \dots a_{N'_B-1}]$ of length N'_B, a *truncated* Zadoff-Chu sequence is used which is generate as

$$a_n = e^{\frac{-j\pi u n(n+1)}{N_{ZC}}}$$

where $n = 0,1,\dots,N'_B - 1$ and $N_{ZC} = NP(N'_B)$ with $NP(x)$ denoting the next prime greater or equal to x. In the simulations we use root $u = 1$.

From the encoding, it is expected that the PAPR of PPC is 3dB higher than with MC. However, the increase in PAPR is lower, for instance in Figure 6, the PAPR is 6.8dB and 9.3dB for MC and PPC, respectively. Hence the increase is only 2.5dB because of the CP. More precisely, if the last OOK pulse within the OFDM symbol is ON, the last samples of that symbol will be copied to the CP which increases the mean power of the signal and thus decreases the PAPR. The reduction in PAPR due to the CP is especially large in PPC because of the larger power in the ON symbol which results in a much lower PAPR for those payloads, overall resulting in a reduced average PAPR

With co-scheduled 64-QAM transmissions, the transmit signal looks quite different as depicted in Figure 7. The PAPR increases for MC and PPC to 9.3dB and 11.2dB, respectively.

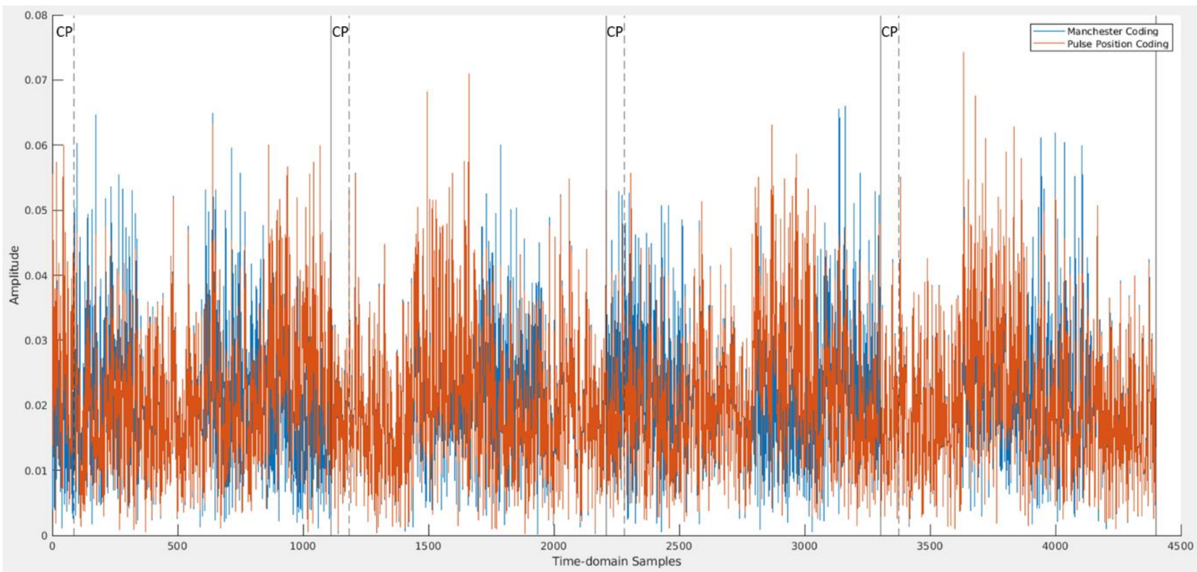

Figure 7: Transmit Signal for payload $\boldsymbol{b} = [11011001]$, M=4, 4 OFDM symbols, with 64-QAM ACI.

Figure 8 shows the CCDF of the PAPR for both coding schemes in the absence of ACI, i.e. LP-WUS is the only transmission in the 20 MHz BW. It can be observed that the mean PAPR is 6.74 dB and 9.37 dB for MC and PPC, respectively, i.e. PPC increase the mean PAPR by about 2.63 dB.

In both schemes, the difference between average PAPR and 1% outage PAPR is about 0.3dB. This means that only 1% of the time, the PAPR exceeds the average PAPR by 0.3dB.

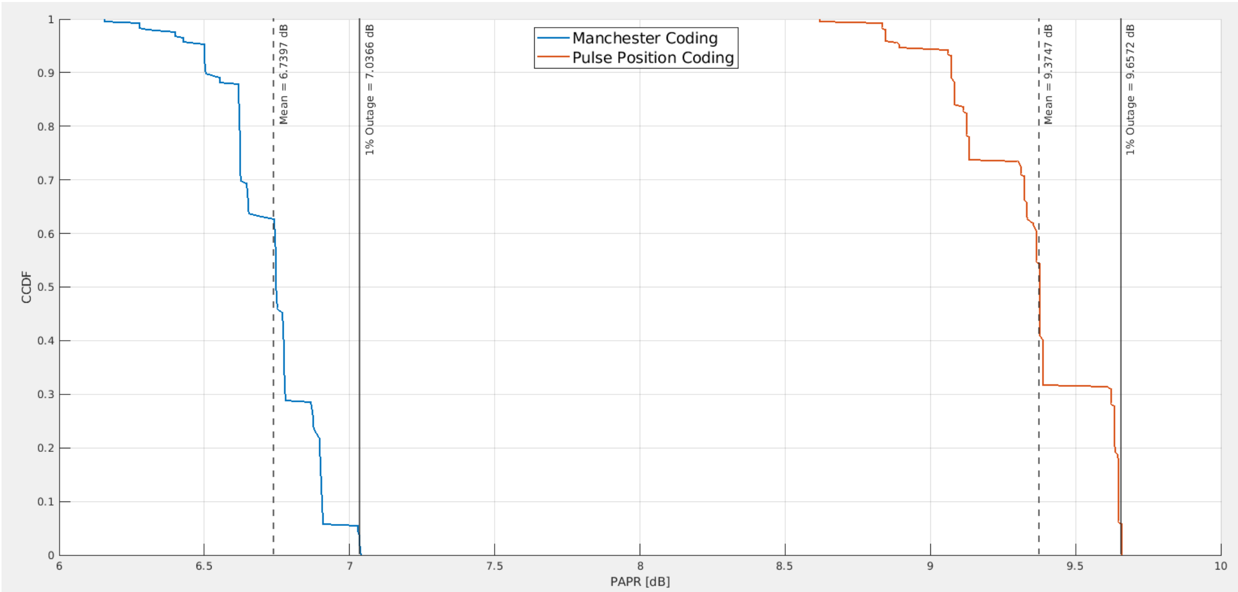

Figure 8: CCDF of PAPR, no ACI, 20MHz, 30kHz SCS, M=4, 8 bit payload, 4 OFDM symbols, average over 10k realizations.

Figure 9 shows the CCDF *with* co-scheduled 64-QAM transmissions. The mean PAPR is 9.52dB and 10dB for MC and PPC, respectively, i.e. a difference of about 0.5dB. As expected, the 64-QAM transmissions increase the average PAPR as well as the 1% outage PAPR. The transmission exceeds the average PAPR by about 1.6 dB for both schemes, 1% of the time.

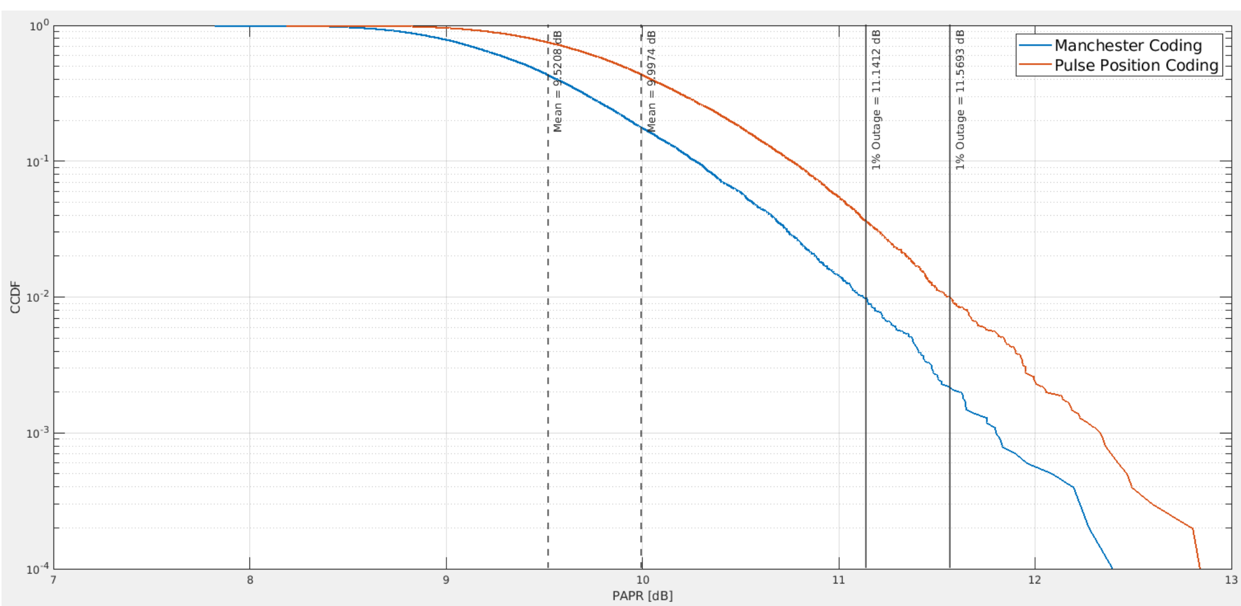

Figure 9: CCDF of PAPR, 64-QAM ACI, 1PRB GB, 20MHz, 30kHz SCS, M=4, 8 bit payload, 4 OFDM symbols, average over 10k realizations.

In summary, the impact of PPC on PAPR is manageable by the transmitter. With co-scheduled transmissions the average and 1% outage PAPR are only 0.5dB larger with PPC than MC. Without co-scheduled transmissions, the PAPR is lower for MC but still well within the acceptable range for PPC.

Table 3 provides simulation results for PAPR of various transmission schemes and system configurations.

Scheme	**20MHz, SCS 30, 51PRBs, FFT=1024**	**20MHz, SCS 15, 106 PRBs, FFT=2048**	**10MHz, SCS 15, 52 PRBs, FFT=1024**	**100MHz, SCS 30, 273 PRBs, FFT=4096**	**20MHz, SCS 15, 106 PRBs, FFT=2048, WUS BW=2.5MHz**
64QAM	9.5/11.0	9.8/11.3	9.5/11.1	10.1/11.5	9.8/11.3
OOK-1, R=1/2	9.6/11.3	9.9/11.3	9.4/11.0	10.1/11.6	9.8/11.4
OOK-4, M=1, R=1/2	9.5/11.1	9.5/11.1	9.5/11.0	10.1/11.5	9.8/11.4
OOK-4, M=2, R=1/2	9.7/11.4	9.9/11.3	9.5/11.0	10.1/11.5	9.9/11.4
OOK-4, M=4, R=1/2	9.5/11.1	10.0/11.6	9.9/11.5	10.1/11.5	9.8/11.4
OOK-4, M=4, PPC R=1/2	10.0/11.6	10.7/12.2	11.3/12.7	10.2/11.6	10/11.6
OOK-4, M=4, PPC R=1/2, 64-QAM quantization	10.0/11.6	10.6/12.2	11.2/12.7	10.2/11.6	10/11.6

Table 3: Average PAPR [dB] / 1%Outage PAPR [dB], Simulation results for different encoding schemes and system configurations. WUS BW either 11 PRBs or 22 PRBs

The baseline "64QAM" assumes random 64-QAM symbols on all sub-carriers, i.e. no WUS. It can be observed that the impact on PAPR increases with larger WUS BW w.r.t. to the system BW. Moreover, up to $M = 2$, using OOK-1 or OOK-4 does *not* increase PAPR w.r.t. to the baseline. For $M = 4$ with Manchester coding R= $1/2$, there is only a very small increase of PAPR (0.4 dB) compared to the baseline.

For $M = 4$, the PAPR increase caused by PPC is about 0.5 dB and 0.7dB compared to MC if the WUS BW constitutes about 25% of the overall BW (5MHz out of 20MHz) for SCS 30kHz and 15kHz, respectively. For a 10MHz channel and 5MHz WUS the PAPR increase is about 1.4 dB. On the other hand, for a 100MHz channel and 5MHz WUS there is no increase in PAPR. Similarly, for a 20MHz channel with a 2.5MHz WUS the PAPR increase is only 0.2dB. In addition, quantizing the frequency-domain signal to 64-QAM constellation points does not impact the PAPR.

Observation 4: PAPR increase of Pulse Position Coding for $M = 4$ compared to Manchester encoding depends on the ratio of channel BW to WUS BW and is minor (~0.1dB) for many system configurations.

Figure 10 shows the performance for $M = 4$ (and for comparison $M = 2$ with 4 bit payload) with Manchester coding (MC) and Pulse Position Coding (PPC) for a 20MHz BW channel and a WUS BW of 5.04 MHz (24 PRB WUS + 2 PRB GB on each side), solid lines, and 2.52 MHz (12 PRB WUS + 1 PRB GB on each side), dashed lines. It can be observed that there is a 3dB SNR gain of PPC vs. MC in both system configurations. Moreover, in this setting (depending on RX filter design etc.), reducing the WUS BW by half, results in an SNR loss of about 3dB. The performance of MC with $M = 2$ is about the same as $M = 4$ with PPC but only delivering *half* the bit rate.

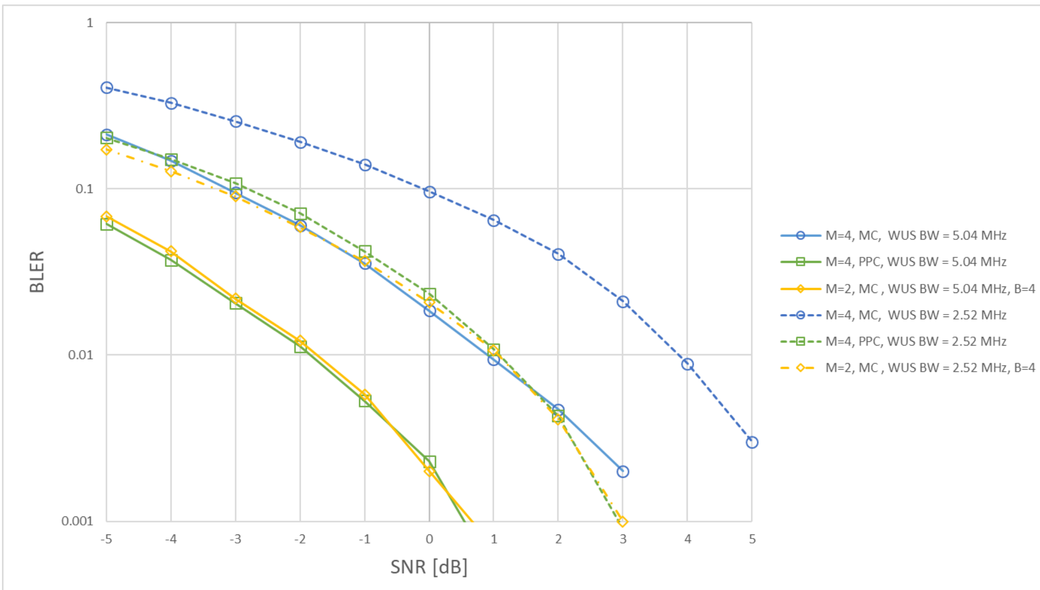

Figure 10: BLER vs. SNR, ED-WUR, 20 MHz (106 PRBs), SCS=15 kHz, M=4, 8 bit payload.

Therefore, with the *same* performance, a network operator can *save* 2.52 MHz of BW by configuring a WUS BW of 2.52 MHz with PPC as opposed to a WUS BW of 5.04 MHz with Manchester coding. The difference in PAPR is 0dB (10dB in both configurations) which is only 0.2dB above the baseline of 9.8dB.

Alternatively, the operator can use $M = 2$ but with half the bit rate.

In summary, we propose PPC for $M = 4$ to pool power in a single OOK symbol resulting in a 3dB gain. PPC is a simple line coding scheme. Other ways to achieve a 3dB gain is to increase the sequence length by more than factor 2 or by repetition. Both alternatives more than double the amount of transmission resources! Hence PPC is a real advantage and should be considered.

Proposal 9: Allow configuration of *Pulse Position Coding* for $M = 4$.

4. Overlaid OFDM Sequences

In this section, we discuss the aspects related to the sequence(s) utilized on the OOK ON-symbols.

4.1. Overlaid OFDM Sequence Design

Significant progress has been made in the last meeting to define the details of the overlaid OFDM sequence design.

Agreement: **RAN1#120-bis** For the root(s) used for overlaid OFDM sequences, gNB can configure any value from 1 ~ (B_{zc} -1), where Bzc is given by the largest prime number such that $B_{ZC} < L_{ZC}$, where L_{ZC} is the overlaid OFDM sequence length.

Working Assumption: **RAN1#120-bis** At least for FR1, support maximum 2 roots to be used for overlaid OFDM sequences for M=1/2/4 (max 2 for each M value). - Different roots can be picked for different M values.

Proposal 10: Confirm working assumption on the number of roots.

In the context of the sequence configuration, the following proposal is relevant for discussion

Proposal 3.3-5: For LP-WUS overlaid OFDM sequence configuration in a cell, - gNB configures number of sequences N1 (up to 16/8/4 for M=1/2/4), number of roots N2 and root index(s) (range:1 ~ Bzc-1）. - The number of CS is derived by N1/N2 - <u>N1 sequences are enumerated in increasing order of first increasing cyclic shift of first root sequence, and then in increasing order of the root sequence index in case of N2>1.</u>

We are fine with the proposal. Perhaps a clarification on the number of sequences $N1$, it seems that the common understanding is that $N1$ is a power of 2, so we suggest to add $N1 = 2^n$, with $n = 0,1, \dots, n_{max}$ and $n_{max} = 4,3,2$ for $M = 1,2,4$.

Proposal 11: Add clarification that the number of configured overlaid OFDM sequences is a power of 2.

4.2. How to carry information by OFDM Sequences

On the issue of how to carry information bits by OFDM sequences, it has been agreed to map the raw information bits directly to the sequences:

Agreement:	RAN1#120-bis

For WUS information carried by the overlaid OFDM sequence(s), down-select between Alt 1 and Alt2:

- Alt 1: Raw information bits are mapped to sequence(s)
  - N raw information bits are divided into K segments from MSB to LSB, where K= ceil ($N/\log_2 L$), L is the number of candidate overlaid OFDM sequences for one OOK ON chip.
  - In one OOK ON chip, a segment of information bits is mapped to one sequence sequentially, e.g., for a segment of 2 information bits, 00 is mapped to sequence #1, 01 is mapped to seq #2.
  - In case $N/\log_2 L$ is not an integer, Bit 0 as MSB is used for padding

The remaining issues concern, if repetition is supported and how the sequences are mapped to the OOK on symbols.

Concerning repetition of the overlaid OFDM sequence(s). We think that all OOK ON symbols for LP-WUS should contain overlaid OFDM sequences. Hence the overlaid OFDM sequences are repeated until the last OOK ON symbol. If the detection performance of the ED receiver is not impacted by the overlaid sequences (which it isn't), we do not see why the overlaying should suddenly stop. Hence, there is also no need to make the repetitions configurable.

Proposal 12: Support repetition of the overlaid OFDM sequence(s) over the entire LP-WUS. No need to make the repetitions configurable.

With regards to the information bit order carried by the overlaid OFDM sequences. In our understanding, the order not only impacts the potential capability of early-termination but also impacts the correlation performance of the correlation receiver. In general, it is undesirable to transmit the same information in the Manchester coded bit as in the ON sequence.

Consider the example in Table 4, where 16 subgroups are mapped to 8 codepoints, i.e. a payload size of $B = 3$ bits.

Subgroups	Mapping to payload/codepoint $\boldsymbol{b}$	Output of Channel Coding $\overline{\boldsymbol{d}}$ (no scrambling)
1	{0,0,0}	{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0}
2,3	{0,0,1}	{0,1,0,1,1,0,1,0,0,1,1,1,0,0,0,0,1,0,0,0,1,0,0,1,1,0,1,1,1,1,1,0}
4	{0,1,0}	{1,1,0,0,1,1,0,0,1,0,0,1,0,1,0,1,1,0,1,0,0,1,0,1,1,1,0,1,0,0,1,0}
5,6,7	{0,1,1}	{1,0,0,1,0,1,1,0,1,1,1,0,0,1,0,1,0,0,1,0,1,1,0,0,0,1,1,0,1,1,0,0}
8,9	{1,0,0}	{1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1}
10,11,12,13	{1,0,1}	{1,0,1,0,0,1,0,1,1,0,0,0,1,1,1,1,0,1,1,1,0,1,1,0,0,1,0,0,0,0,0,1}
14,15,16	{1,1,0}	{0,0,1,1,0,0,1,1,0,1,1,0,1,0,1,0,0,1,0,1,1,0,1,0,0,0,1,0,1,1,0,1}
1-15	{1,1,1}	{0,1,1,0,1,0,0,1,0,0,0,1,1,0,1,0,1,1,0,1,0,0,1,1,1,0,0,1,0,0,1,1}

Table 4: Example of subgroup to codepoint/payload mapping for 16 subgroups and payload of B=3 bits.

We assume that there is no rate-matching, i.e. $\overline{\boldsymbol{d}} = \boldsymbol{d}$. Notice that the first 3 coded bits uniquely signal the codepoints. First consider $Q = 2$ available sequences per OOK ON symbol with possible mappings in Table 5. “OOK” indicates the bits modulated with OOK and transmitted on a single Manchester coded (MC) symbol, containing one OFF and one ON symbol. Here the output of the rate-matched codeword is transmitted. Alt1 $(Q = 1)$ maps one bit of the payload $\boldsymbol{b}$ to the sequences. The MC symbol $\bar{d}_1$ already contains information about the codepoint, i.e. it's either codepoints 0,1,6,7 or codepoints 2,3,4,5, which means that b_1 and b_2 are dependent, i.e. if $b_1 = 0$ then $b_2 = 1$ and vice versa. Hence, transmitting b_1 on the first ON symbol and b_2 on the second ON symbol will not give the correlation receiver more information. Therefore, it is best to transmit b_3 in one of the first 2 ON symbols. This enables the correlation receiver to determine the codeword after only 2 ON symbols. The same logic applies for $Q = 4$. Hence, propose to reverse the information bit order when encoding sequences to the ON symbols.

ON Symbol Index	1	2	3	4	5	6	7	8	9	…
OOK	$\bar{d}_1$	$\bar{d}_2$	$\bar{d}_3$	$\bar{d}_4$	$\bar{d}_5$	$\bar{d}_6$	$\bar{d}_7$	$\bar{d}_8$	$\bar{d}_9$	…
Alt1 $(Q = 2)$	b_3	b_2	b_1	b_3	b_2	b_1	b_3	b_2	b_1	…
Alt1 $(Q = 4)$	$b_3 b_2$	$b_1 b_3$	$b_2 b_1$	$b_3 b_2$	$b_1 b_3$	$b_2 b_1$	$b_3 b_2$	$b_1 b_3$	$b_2 b_1$	…

Table 5: Example of mapping to multiple OFDM overlay sequences with previous example of mapping for 16 subgroups and payload of B=3 bits.

Proposal 13: Reverse the information bit order for overlaid OFDM sequences.

5. LP-SS Design

It has been agreed to only support LP-SS without an additional sync signal for $M = 1$ and $M = 2$.

> Agreement: **RAN1#120-bis**
>
> Regarding whether to support additional sync signal to LP-SS, support the following for LP-WUS with M=1, M=2:
>
> - Option 1A: No additional sync signal, LP-SS periodicity =320ms
>   - Additionally support LP-SS periodicity of 160ms

The remaining question is how to support LP-WUS with $M = 4$. Given the time constraint, we prefer not to introduce an additional sync signal. As stated by other companies, $M = 4$ can be supported with LP-SS periodicity of 160ms. Detection reliability can also be enhanced by configuring more resources for LP-WUS which is more efficient than decreasing the LP-SS periodicity to 80ms for instance.

Proposal 14: Support $M = 4$ with LP-SS periodicity of 160ms and do not introduce additional sync signal.

Concerning the configuration of the OOK pulse duration for LP-SS and LP-WUS, it has been agreed that LP-WUS cannot be configured with smaller pulses than LP-SS to ensure accurate synchronization from LP-SS to decode LP-WUS.

Agreement: **RAN1#120-bis**

For the M value for LP-WUS and LP-SS, supports:

- Alt2: The M values for LP-WUS and LP-SS can be configured to be same or different. M value for LP-WUS cannot be larger than that of LP-SS.
  - At least for M values larger than 1 (applies to both LP-WUS and LP-SS)
  - FFS: If M=1 is configured for either of LP-WUS or LP-SS, M=1 is configured for both

The remaining issue concerns $M = 1$. It is obvious that if LP-SS is configured with $M = 1$, LP-WUS cannot be configured with $M > 2$ to ensure sufficient timing accuracy. We do not see any problem to configure LP-SS with $M > 1$ if LP-WUS uses $M = 1$.

Proposal 15: Support larger $\boldsymbol{M}$ value for LP-SS if LP-WUS is configured with $\boldsymbol{M = 1}$.

6. Conclusion

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

Proposal 1: Consider if pulse-shaping is required after sequence design and potential preamble are agreed.

Proposal 2: The DFT-shift is compensated at the LR.

Proposal 3: Confirm working assumption on the support of 1 and 2 information bits for LP-WUS.

Observation 1: For $\boldsymbol{B > 2}$, without repetition, the maximum code word length is 32.

Observation 2: Clarify how repetition of the LP-WUS relates to the potential repetitions of MOs within a beam.

Proposal 4: For $\boldsymbol{B > 2}$, support repetition in the rate-matching procedure for LP-WUS.

Proposal 5: For $\boldsymbol{B > 2}$, the minimum code block length is $\boldsymbol{B}$.

Proposal 6: For $\boldsymbol{B > 2}$, the code block lengths apply to all values of $\boldsymbol{M}$.

Proposal 7: For $\boldsymbol{B > 2}$, all of the code block lengths within the range are supported.

Observation 3: $\boldsymbol{M = 4}$ with Manchester Coding has the worst coverage compared to $\boldsymbol{M = 1, 2}$.

Proposal 8: For $\boldsymbol{M = 4}$, consider jointly encoding multiple bits into ON pulse position to increase SNR by 3dB.

Observation 4: PAPR increase of Pulse Position Coding for $\boldsymbol{M = 4}$ compared to Manchester encoding depends on the ratio of channel BW to WUS BW and is minor (~0.1dB) for many system configurations.

Proposal 9: Allow configuration of *Pulse Position Coding* for $\boldsymbol{M = 4}$.

Proposal 10: Confirm working assumption on the number of roots.

7. References

[1] RP-213645, “New SID: Study on low-power Wake-up Signal and Receiver for NR”, vivo, RAN#94e

[2] TR-38.869, “Study on low-power Wake-up Signal and Receiver for NR”, V.18.0.0, 3GPP, 2023

[3] RP-234056, “New WID: Low-power wake-up signal and receiver for NR (LP-WUS/WUR)”, CMCC (moderator, RAN VC), RAN#102, Edinburgh, GB, December 11-15, 2023

[4] R1-2405708, “Summary # 5 of discussions on LP-WUS and LP-SS design”, Moderator (vivo), RAN1#117

8. Appendix

8.1 Receiver Algorithms

6.1.1. Envelop/Energy Detection in Base-band

The received signal $y(t)$ is first passed through a band-pass filter to extract the WUS frequencies. Subsequently, $y(t)$ is converted into base-band using a sampling frequency $f_{S,WUS}$ resulting in a sampling rate reduction of $r = f_{S,OFDM}/f_{S,WUS}$. Therefore, with K denoting the FFT size of the OFDM transmission, we obtain $N = K/r$ WUS samples per OFDM symbol in time-domain at the receiver base-band. Denote $\boldsymbol{y}_l \in \mathbb{C}^N$ the discrete received signal in base-band of OFDM symbol l. With M the number of OOK symbols per OFDM symbol we have $\boldsymbol{y}_l = [\boldsymbol{y}_{l,1,}\boldsymbol{y}_{l,2} \dots \boldsymbol{y}_{l,M}]$ with $\boldsymbol{y}_{l,i} \in \mathbb{C}^{N_M}$ the $N_M = N/M$ samples per OOK symbol. The energy $e_{i,l}$ of OOK symbol i in OFDM symbol l is then given by

$$e_{i,l} = \sum_{n=1}^{N_M} \left|y_{l,i,n}\right|^2 = \boldsymbol{y}_{l,i}^H \boldsymbol{y}_{l,i}$$

The energy is then compared to a threshold or if Manchester coding is used, the energy values are compared, e.g. for Manchester code $R = 1/2$

$$b_{j,l} = \begin{cases} 0, & if\ e_{i,l} < e_{i+1,l} \\ 1, & if\ e_{i,l} \geq e_{i+1,l} \end{cases}$$

Where $b_{j,l}$ is bit j encoded in 2 consecutive OOK symbols i and $i+1$ of OFDM symbol l.

6.1.2. Correlation detection in Base-band in Time-Domain

If the ON-sequence $\boldsymbol{a}$ is known the receiver can carry out correlations with all possible transmitted sequences $\boldsymbol{s}_m = [\boldsymbol{s}_{m1}\boldsymbol{s}_{m2} \dots \boldsymbol{s}_{mL}] \in \mathbb{C}^{NL}$. After OFDM demodulation, the WUS signal (sub-carriers) is transformed back into time-domain via Inverse-DFT precoding. We assume that channel estimates are not available, hence a we use a RAKE demodulator for square-law combination of orthogonal signals [Proakis, Figure 14-5-7].

6.1.2.1. Correlation per OOK Symbol

If the correlation is carried out per OOK symbol (referred to as COR-WUR-OOK), the resulting time-domain signal $\boldsymbol{y}_{l,i}$ of the i^{th} OOK symbol is correlated with $\boldsymbol{a}$ and the N_P peaks of the correlator output are combined to exploit frequency-diversity in fading channels i.e.

$$e_{i,l} = \sum_{n=1}^{N_P} \max_{N_P} \left|(\boldsymbol{y}_{l,i} \star \boldsymbol{a})[n]\right|^2$$

where $\max_{N_P}|f(x)|^2$ returns the N_P largest absolute values squared of $f(x)$ and the linear cross-correlation function $(f \star g)[n]$is defined as

$$(f \star g)[n] = \sum_{m=-N}^{N} f^*[m]\, g[m+n]$$

6.1.2.2. Correlation per WUS

If the correlation is carried out over the entire WUS to achieve the largest processing gain (referred to as COR-WUR), the message $m, m = 0,1, \dots, 2^B - 1$, for payload of B bits WUS is decoded as

$$\hat{m} = \underset{m}{\operatorname{argmax}} \sum_{n=1}^{N_P} \max_{N_P} |(\boldsymbol{y} \star \boldsymbol{s}_m)[n]|^2$$

where $\boldsymbol{y}$ is the time-domain WUS and $\boldsymbol{s}_m$ is the known WUS for message m.

6.2. Simulation Assumptions

Unless otherwise stated, the link-level simulation assumption in Table 6 are used.

Parameter	**Value**
Carrier Frequency	2.6 GHz (FDD)
Waveform	OOK-4
Channel Structure	Option 3: Payload only (no CRC)
SCS	30 kHz
WUS payload	8 bits
Configuration of LP-WUS Signal	OOK-4: M=4 ON-Sequence = Zadoff-Chu Multiple Sequences are obtained via different cyclic shifts
WUS Duration	4 OFDM symbols
Code Scheme	Manchester Code R=1/2 with transmission of encoded bits
Channel BW	20MHz (51 PRBs @ 30kHz SCS)
LP-WUS BW	5 MHz (14 PRBs = 168 SCs) 148 SCs for WUS (4.44 MHz) + 10 SCs GB on each side
Filter	3rd order Butterworth with 4.32 MHz BW
Adjacent Sub-carrier Interference (ACI)	Random 64-QAM symbols with 0dB
WUS Sampling Rate	7.68 MHz
ADC bit-width	inf
Channel Model	TDL-C, 300ns Delay Spread
Timing Error	0

Frequency Error	0
Antenna configuration	1Tx, 1Rx
UE speed	0 km/h
Receiver	Energy Detector, Correlation Detector (Energy of 5 highest peaks is combined)

Table 6: Link-level simulation assumptions.