RAN1 studied robustness of OOK-1, OOK-2, OOK-3, OOK-4, FSK-1, FSK-2 and OFDMA waveform to time and frequency offset in Sections X.Y, and X.Z resp. and observed the following:

* OOK/FSK waveform with longer time segment and with a single or multiple frequency segments is comparable (0 us) or more robust (by 4us) to timing error than waveform with shorter time segment.
* One source shows that without sliding window, OFDMA tolerates up to 4us timing error, when SCS <=30kHz, and receiver did not perform FFT.
* Tolerance to timing error varies with sliding window size assumed by a receiver and was shown to tolerate timing error up to 4us if proper sliding window size is assumed by a receiver.
* *Single frequency segment OOK (except OOK3) waveform is more robust to frequency error (of 390kHz) than OOK/FSK waveforms with multiple frequency segments (depending on guard-band size between segments) and both are more robust than OFDMA waveform assuming no frequency compensation/synchronization.*
* *One source showed that single frequency segment FSK-envelop-IF waveform is more robust to frequency error (of 260 kHz) than OOK/FSK waveforms with multiple frequency segments (depending on guard-band size between segments) and both are more robust than OFDMA waveform assuming no frequency compensation/ synchronization.*

In RAN1 also the impact of sampling rate to performance has been studied.

RAN1 studied spectral efficiency of OOK-1, OOK-2, OOK-3, OOK-4, FSK-1, FSK-2 and OFDMA waveform, where the best results (of spectral efficiency) from results reported by each company for each waveform are summarized in Section X.Y. Results among companies were combined across different receiver types, different power pooling assumption, different sampling rates, different tx antenna configurations, FAR target for the same waveform.

RAN1 studied RSRP and RSRQ measurement accuracy based on LP-SS (based on OOK which can be received by envelop detector) assuming TDL-C channel and observed that depending on SNR target X= {-3, -6, -9, -11}dB as seen by LP-WUR, and depending on 90% accuracy of 3 or 5 dB, different number symbols (1 -70) spread over 1-5 periods is required. Timing and frequency impairments were also considered. RAN1 studied RSRP and RSRQ measurement accuracy based on LP-SS ( based on OOK which can be received by envelop detector) assuming AWGN channel and observed that depending on SNR target X= {-9,-11}dB as seen by LP-WUR, and depending on 90% accuracy of 3 or 5 dB, different number symbols (1 -20) spread over 1-3 periods is required. Timing and frequency impairments were also considered. Corresponding SNR observed by MR and LR is different due to NF difference between them. Accuracy of RSRP and RSRQ measurement depends on sampling rate.

RAN1 studied RSRP measurement accuracy based on SSS (OFDMA received by I/Q detector) and observed that depending on SNR target X= [-3, -6] dB as seen by LP-WUR, and depending on 90% accuracy of 3dB, 1 OFDMA symbol in 1 period is required, assuming TDL-C. Timing and frequency impairments were also considered.

For waveform generation of OOK/FSK the following observations were made. Flat spectrum in frequency domain provides robustness against frequency selective fading compared to concentrated energy in frequency domain. For OOK-4, sequence before DFT/LS with variation in phase via such as ZC, M-sequence or QAM sequence can achieve more flattened spectrum. Sequences(s) used in LP-WUS symbol generation with different pulse shape or spectral shape may have different performance. Knowledge of sequence(s) used in LP-WUS waveform generation may improve performance for at least a receiver with I/Q branches.

Pre-storing of the generated frequency domain samples to be mapped to LP-WUS sub-carrier segment of iFFT at gNB may reduce complexity of waveform generation at gNB with memory requirement depending on number of possible combinations. The number of combinations is function of number of supported LP-WUS bandwidth sizes, supported values of M for OOK-4, etc. Pre-storing of the generated frequency domain samples may be up to gNB implementation. For OOK4, Manchester codingwill reduce the number of combinations for OOK-4 given the same time/frequency resource.

RAN1 studied LP-WUS bandwidth, At least for IDLE/Inactive mode, at least one BW-size smaller or equal to 5MHz is recommended to be supported for FR1. Other BW sizes are not precluded, however if additional BW-size(s) are recommended to be supported, BW-size can be up to 20MHz. LP-WUS bandwidth size (including guard-bands) is assumed to be an integer number of PRBs. From RAN1 perspective, LP-WUS and signals/channels by MR can be at least on the same carrier in the same band. From RAN1 perspective, for multiplexing with other NR signals and channels, it is beneficial if LP-WUS can be flexibly configured within a carrier.

RAN1 studied synchronization of LP-WUR. At least for LP-WUR that cannot receive existing PSS/SSS, periodic LP-SS signal is beneficial for the following functionalities: (a) RRM measurements by LP-WUR,if supported (b) At least coarse time synchronization of LP-WUR. (c) At least coarse frequency synchronization of LP-WUR. Additional periodic LP-SS system overhead depends on LP-SS periodicity, system BW, # of beams, and resource required to fulfil the target functionality, etc. Periodic signal if used for coarse synchronization may reduce overhead of signal preceding LP-WUS, if any. LP-SS can be designed to be common among UE groups (cell-specific) and such further reduce system overhead. For LP-WUR that can receive existing PSS/SSS potentially assisted by PBCH DMRS/TRS for synchronization, existing PSS/SSS potentially assisted by PBCH DMRS/TRS may be used for above functionality. Periodic LP-SS coverage should be equal or better than that of LP-WUS. For fine time and frequency synchronization, a signal (e.g. preamble) preceding or part of LP-WUS may be used.

OFDMA waveform can provide coverage for LP-WUS with lower resource overhead. LP-WUR receiving OFDMA waveform can reuse PSS/SSS to perform RRM measurement and synchronization avoiding introduction of periodic LP-SS within the carrier ~~reducing specification effort~~. Timing error robustness can be further improved using sliding window at the receiver.

Single frequency segment OOK-1/OOK-4 can provide range of spectral efficiencies while being the most robust waveform to frequency error while robustness to timing error decreased with M, but could be addressed by using sliding window at the receiver or by pulse shaping in time domain. OOK-4 with variable M can provide flexible range of spectral efficiencies for a fixed LP-WUS resource. Sequences to generate ON duration in OFDMA transmitter, if specified, can help receiver (with I/Q branches) performance.

FSK-2 can provide range of spectral efficiencies by varying M while having good robustness to frequency error and moderate timing error. Frequency error robustness can be further improved using frequency error correction (i.e., utilizing 2^M parallel receiver structure or frequency domain sliding window), larger guard band between segments at expense of less frequency diversity, and/or single frequency segment FSK2-envelope IF. Timing error robustness can be further improved using sliding window or by pulse shaping in time domain. Uniform distribution of frequency spectrum density can be achieved using single frequency segment FSK2-envelope IF which can provide robustness against frequency fading. Sequences to generate ON duration in OFDMA transmitter, if specified, can help receiver (with I/Q branches) performance.