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| Technical Report |
| 3rd Generation Partnership Project;Technical Specification Group Radio Access Network;Study on low-power wake up signal and receiver for NR(Release 18) |
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| ***3GPP***Postal address3GPP support office address650 Route des Lucioles - Sophia AntipolisValbonne - FRANCETel.: +33 4 92 94 42 00 Fax: +33 4 93 65 47 16Internethttp://www.3gpp.org |
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# Foreword

This Technical Report has been produced by the 3rd Generation Partnership Project (3GPP).

The contents of the present document are subject to continuing work within the TSG and may change following formal TSG approval. Should the TSG modify the contents of the present document, it will be re-released by the TSG with an identifying change of release date and an increase in version number as follows:

Version x.y.z

where:

x the first digit:

1 presented to TSG for information;

2 presented to TSG for approval;

3 or greater indicates TSG approved document under change control.

y the second digit is incremented for all changes of substance, i.e. technical enhancements, corrections, updates, etc.

z the third digit is incremented when editorial only changes have been incorporated in the document.

In the present document, modal verbs have the following meanings:

**shall** indicates a mandatory requirement to do something

**shall not** indicates an interdiction (prohibition) to do something

The constructions "shall" and "shall not" are confined to the context of normative provisions, and do not appear in Technical Reports.

The constructions "must" and "must not" are not used as substitutes for "shall" and "shall not". Their use is avoided insofar as possible, and they are not used in a normative context except in a direct citation from an external, referenced, non-3GPP document, or so as to maintain continuity of style when extending or modifying the provisions of such a referenced document.

**should** indicates a recommendation to do something

**should not** indicates a recommendation not to do something

**may** indicates permission to do something

**need not** indicates permission not to do something

The construction "may not" is ambiguous and is not used in normative elements. The unambiguous constructions "might not" or "shall not" are used instead, depending upon the meaning intended.

**can** indicates that something is possible

**cannot** indicates that something is impossible

The constructions "can" and "cannot" are not substitutes for "may" and "need not".

**will** indicates that something is certain or expected to happen as a result of action taken by an agency the behaviour of which is outside the scope of the present document

**will not** indicates that something is certain or expected not to happen as a result of action taken by an agency the behaviour of which is outside the scope of the present document

**might** indicates a likelihood that something will happen as a result of action taken by some agency the behaviour of which is outside the scope of the present document

**might not** indicates a likelihood that something will not happen as a result of action taken by some agency the behaviour of which is outside the scope of the present document

In addition:

**is** (or any other verb in the indicative mood) indicates a statement of fact

**is not** (or any other negative verb in the indicative mood) indicates a statement of fact

The constructions "is" and "is not" do not indicate requirements.

# 1 Scope

The present document …

# 2 References

The following documents contain provisions which, through reference in this text, constitute provisions of the present document.

- References are either specific (identified by date of publication, edition number, version number, etc.) or non‑specific.

- For a specific reference, subsequent revisions do not apply.

- For a non-specific reference, the latest version applies. In the case of a reference to a 3GPP document (including a GSM document), a non-specific reference implicitly refers to the latest version of that document *in the same Release as the present document*.

[1] 3GPP TR 21.905: "Vocabulary for 3GPP Specifications".

[2] 3GPP RP-222644: " Study on low-power wake up signal and receiver for NR".

# 3 Definitions of terms, symbols and abbreviations

## 3.1 Terms

For the purposes of the present document, the terms given in 3GPP TR 21.905 [1] and the following apply. A term defined in the present document takes precedence over the definition of the same term, if any, in 3GPP TR 21.905 [1].

**example:** text used to clarify abstract rules by applying them literally.

## 3.2 Symbols

For the purposes of the present document, the following symbols apply:

<symbol> <Explanation>

## 3.3 Abbreviations

For the purposes of the present document, the abbreviations given in 3GPP TR 21.905 [1] and the following apply. An abbreviation defined in the present document takes precedence over the definition of the same abbreviation, if any, in 3GPP TR 21.905 [1]

Abbreviation format (EW)

<ABBREVIATION> <Expansion>

# 4 Introduction

5G systems are designed and developed targeting for both mobile telephony and vertical use cases. Besides latency, reliability, and availability, UE energy efficiency is also critical to 5G. Currently, 5G devices may have to be recharged per week or day, depending on individual’s usage time. In general, 5G devices consume tens of milliwatts in RRC idle/inactive state and hundreds of milliwatts in RRC connected state. Designs to prolong battery life is a necessity for improving energy efficiency as well as for better user experience.

Energy efficiency is even more critical for UEs without a continuous energy source, e.g., UEs using small rechargeable and single coin cell batteries. Among vertical use cases, sensors and actuators are deployed extensively for monitoring, measuring, charging, etc. Generally, their batteries are not rechargeable and expected to last at least few years as described in TR 38.875. Wearables include smart watches, rings, eHealth related devices, and medical monitoring devices. With typical battery capacity, it is challenging to sustain up to 1-2 weeks as required.

The power consumption depends on the configured length of wake-up periods, e.g., paging cycle. To meet the battery life requirements above, eDRX cycle with large value is expected to be used, resulting in high latency, which is not suitable for such services with requirements of both long battery life and low latency. For example, in fire detection and extinguishment use case, fire shutters shall be closed and fire sprinklers shall be turned on by the actuators within 1 to 2 seconds from the time the fire is detected by sensors, long eDRX cycle cannot meet the delay requirements. eDRX is apparently not suitable for latency-critical use cases. Thus, the intention is to study ultra-low power mechanism that can support low latency in Rel-18, e.g. lower than eDRX latency.

Currently, UEs need to periodically wake up once per DRX cycle, which dominates the power consumption in periods with no signalling or data traffic. If UEs are able to wake up only when they are triggered, e.g., paging, power consumption could be dramatically reduced. This can be achieved by using a wake-up signal to trigger the main radio and a separate receiver which has the ability to monitor wake-up signal with ultra-low power consumption. Main radio works for data transmission and reception, which can be turned off or set to deep sleep unless it is turned on.

The power consumption for monitoring wake-up signal depends on the wake-up signal design and the hardware module of the wake-up receiver used for signal detecting and processing.

The study should primarily target low-power WUS/WUR for power-sensitive, small form-factor devices including IoT use cases (such as industrial sensors, controllers) and wearables. Other use cases are not precluded, e.g.XR/smart glasses, smart phones.

As opposed to the work on UE power savings in previous releases, this study will not require existing signals to be used as WUS. All WUS solutions identified shall be able to operate in a cell supporting legacy UEs. Solutions should target substantial gains compared to the existing Rel-15/16/17 UE power saving mechanisms. Other aspects such as detection performance, coverage, UE complexity, should be covered by the evaluation.

**The study item includes the following objectives:**

* Identify evaluation methodology (including the use cases) & KPIs [RAN1]
	+ Primarily target low-power WUS/WUR for power-sensitive, small form-factor devices including IoT use cases (such as industrial sensors, controllers) and wearables
		- Other use cases are not precluded
* Study and evaluate low-power wake-up receiver architectures [RAN1, RAN4]
* Study and evaluate wake-up signal designs to support wake-up receivers [RAN1, RAN4]
* Study and evaluate L1 procedures and higher layer protocol changes needed to support the wake-up signals [RAN2, RAN1]
* Study potential UE power saving gains compared to the existing Rel-15/16/17 UE power saving mechanisms, the coverage availability, as well as latency impact of low-power WUR/WUS. System impact, such as network power consumption, coexistence with non-low-power-WUR UEs, network coverage/capacity/resource overhead should be included in the study [RAN1]
	+ Note: The need for RAN2 evaluation will be triggered by RAN1 when necessary.

Use the following terminology for future discussion,

* Main radio (MR): the Tx/Rx module operating for NR signals/channels apart from signals/channel related to low-power wake-up
* LP-WUR (LR): The Rx module operating for receiving/processing signals/channel related to low-power wake-up.

# 5 Use cases & KPI

*Editor’s note: The following SI Objective is included in this section.*

* Identify evaluation methodology (including the use cases) & KPIs [RAN1]
	+ Primarily target low-power WUS/WUR for power-sensitive, small form-factor devices including IoT use cases (such as industrial sensors, controllers) and wearables
		- Other use cases are not precluded

Both RRC IDLE/INACTIVE and CONNECTED modes are to be studied as part of the LP-WUS/WUR SI.

* FFS: Further prioritization if needed during the study item.

# 6 Evaluation Methodology

*Editor’s note: The section includes evaluation methodology for this SI*

## 6.1 General performance metrics

For system impact analysis, the following performance metrics are considered to be provided,

|  |  |
| --- | --- |
| **Performance Metric** | **Note** |
| System overhead | expressed as percentage of used part of all REs for LP-WUS (including guard band or time or others resource used for LP-WUR if any) among all resourcesOther assumptions related to the system overhead analysis can be reported, e.g., the LP-WUR raw data rate evaluated in the coverage evaluations. |
| Capacity impact | Evaluate the system capacity impact due to introducing of LP-WUSNote: it is for UEs which are in connected mode. Definition is the same as in XR TR. |
| FFS: NW power consumption / Energy Efficiency | [Impact of LP-WUS/WUR operation on gNB energy consumption as performance metric in system impact analysis.] |

For power and latency evaluation of the LP-WUS, the following performance metrics definitions provided for future study

|  |  |
| --- | --- |
|  **Performance Metric** | **Note** |
| Power consumption | Relative power consumption in units. The power consumption includes main radio and LP-WUR. For comparison, the relative power consumption and evaluation period for baseline schemes should also be provided, as well as the power saving gain (i.e., percentage of power consumption reduction of the proposed power saving scheme from the baseline scheme). |
| Latency | For IDLE/INACTIVE state, * the latency is the time interval between the data arrival time at the gNB and the time of the first PO UE can monitor the paging message
* alternatively, if UE is not required to monitor a PO after wake-up, company to report detailed procedure and definition of the latency

. In RAN1#111, there are no definitions being precluded* sync/re-sync for main radio is included
 |
| UPT | The definition is the same as in [TR38.840]Note: it is for connected mode purpose. |

* Companies to report baseline scheme, e.g., PO monitoring with i-DRX, e-DRX, with or without PEI
* Companies to report the power consumption / power saving gain considering the FAR impact, latency considering MDR impact
* Other performance metrics (e.g., mobility) can be reported by companies (if any)

## 6.2 General evaluation assumptions

RRC IDLE/INACTIVE evaluation assumptions

The following is assumed for RRC IDLE/INACTIVE evaluation,

|  |  |
| --- | --- |
| **Parameters** | **Value** |
| i-DRX cycle length | 1.28s and other values not precluded and reported by companies, consider both with PEI/ without PEI |
| e-DRX cycle length | 20.48s, 61.44s and other values not precluded, company to report which value(s) are used.  *Note: ‘ultra-deep sleep’ state can be assumed for eDRX whenever necessary for baseline UE* |
| Number of POs in Paging Frame | 1 |
| Number of DRXs per PTW | 4 |
| Number of SSB before PO / PEI | 1, 2 or 3, (used for e.g., AGC adjustment, T/F tracking, serving cell and intra-F measurement)company to report which value(s) are usedNote: the assumptions is for MR wakes from ‘Deep sleep’ |
| Sync/re-sync after ultra-deep sleep | companies to report the timeline of sync/re-sync and X value, X is the time for sync/re-sync |
| RRM Measurement | Company to report whether and how the RRM measurement is assumed, e.g., whether RRM performed by main radio or LP-WUR, whether RRM is relaxed or not. |
| LP-WUS monitoring | Option 1: continuously monitoringOption 2: discontinuously monitoring, with [T] ms as the period for complete an on-and-off cycle, and [D] ms as the active time for monitoring LP-WUS every cycle. |
| Traffic | Option 1 (baseline):* The traffic arrival is modeled as a Poisson Arrival Process where inter-arrival times are exponentially distributed, the mean arrival time is P = YREF / RE, REF, where
	+ RE, REF= 1%, 0.1%, 0.01% or 0.001% and YREF = 1.28s
	+ Per group paging probability RG = 1 – (1 – RE)N, where N is the number of UEs in the group
		- FFS: Value of N
* For LP-WUS
	+ Both per group and UE paging can be assumed.

Note:* For i-DRX with cycle duration Y second,
	+ Per UE paging probability RE = 1 – (1 – RE, REF )Y/YREF
* For e-DRX with K i-DRX cycles duration, PTW duration of L i-DRX cycles, and an i-DRX cycle duration Y second
	+ Per UE paging probability is
		- RE = 1 – (1 – RE, REF )(K-L)Y/YREF for the first i-DRX cycle within the PTW
		- RE = 1 – (1 – RE, REF )Y/YREF for each of the remaining L-1 i-DRX cycles within the PTW
	+ L=4

Other options are not precluded can be reported by companies. |
| Others | Reported by companies |

RRC CONNECTED mode evaluation assumptions

For R18 LP-WUS/WUR power evaluation in RRC connected mode, the following can be considered,

* XR traffic model with evaluation methodologies and assumptions captured in TR 38.838.
* eMBB traffic model with evaluation methodologies and assumptions captured in TR 38.840
* Heartbeat traffic models in 3GPP TR 38.875.
* Other models are not precluded.

Company to further provide the followings,

* Parameters (e.g., frame rate, data rate, jitter range, DRX configurations and etc if needed.)
* How to use LP-WUS, e.g., LP-WUS to trigger/adapt PDCCH monitoring
* Other details if any

Coverage evaluation

For evaluation of the coverage of LP-WUS, the methodology and assumptions in R17 CovEnh SI (described in TR38.830) is reused as baseline.

* MIL is used as the metric for LP-WUS coverage evaluation
* urban (2.6GHz/4GHz), rural(700MHz) scenario for FR1 are considered to be evaluated, others (e.g., FR2) are not precluded.
* Note: For IoT/wearables devices, refer to R17 Redcap SI TR38.875 if the assumptions differ from TR38.830.
* Companies report any other assumptions which differ from the TR38.875/ TR38.830, e.g., Tx and Rx loss
* Companies are encouraged to compare LP-WUS with at least PDCCH for paging, PUSCH, others are not precluded. FFS: Target coverage of LP-WUS

For LP-WUS coverage evaluation, the noise figure of LP-WUR is

* + Options : [9, 12, 15, 18, 21, 24], Other values can be reported by companies
* FFS: how to determine the NF option.
* The values provided is for the purpose of studying coverage of LP-WUS, and it can be further revisited depending on the receiver architecture discussion.

For evaluation, 1 Rx chain for LP-WUS receiver is baseline.

Link performance evaluation

For the performance evaluations of LP-WUS candidate designs, it is assumed that

* The miss-detection rate (MDR) of LP-WUS [1%],
* The false-alarm rate (FAR) of LP-WUS
	+ [0.1%, 1%, 10%]
	+ Other values are not precluded for studying reported by companies
* Note: if LP-WUS for wake-up indication consists of two parts or even multiple parts, the proposed MDR/FAR should take into account the reception performance of the two or more parts jointly
* The above values applied in both RRC CONNECTED and IDLE/INACTIVE mode.
* FFS FAR requirement based on the study outcome of the impact of FAR on power consumption / power saving gain / system overhead
* FFS: Note: FAR should be evaluated both in the absence of gNB transmissions and in the presence of transmissions from gNB. Proponent to provide the details.

## 6.3 power consumption model

### 6.3.1 Power model for Main Radio (MR)

Take the following power model for main radio for evaluation in LP-WUS/WUR SI,

* For IoT and wearable cases, reuse TR38.875 power model as baseline.
* For eMBB and other cases, reuse TR38.840 power model as baseline.
* Introduce ‘*Ultra-deep sleep*’ power state for main radio of UEs with LP-WUS receiver

The following power models are used for ‘*Ultra-deep sleep*’ power state for main radio for evaluation

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Power State | Relative Power (unit) | Ramp-up and down transition energy (Note1):(unit multiplied by ms) | Ramp-up time | Time for sync/re-sync |
| **Ultra-deep sleep** | **[0.015]** | [2000 ~ 40000]* Study to converge on candidate numbers to use for evaluation
* FFS: other values and reported by companies.
* FFS: down-selection of the values,
* companies are encouraged to provide details for down-selection
 | [400ms], FFS: 100ms | **X** |

 Note1:

* + Ramp-up time may consist of the procedure for [main radio hardware tune on e.g., boot, memory load and etc.],
	+ Time for sync/re-sync consists of the procedure for [main radio to re-synchronization with the serving gNB etc.],
		- FFS: X and whether/how to have different values depending on other factors, e.g., signal-to-noise ratio
		- Companies can report the assumption of X in the initial evaluation.
	+ Ramp up and down energy includes power for ramp-up and ramp-down. Energy consumption for sync/re-sync is separately calculated.
* The total time for main radio transition from ultra-deep sleep to active/micro sleep state is the sum of ramp-up time and time for sync/re-sync.
	+ FFS whether/how to define ramp-down time, whether to separately describe the ramp-down energy consumption

Note 2: the power state transitions in this table refer to transitions between ultra deep sleep state and active / micro sleep state.

Note 3: The values inside of ‘[ ]’ are to be used as starting point of future study on LP-WUS

For MR, at least for FR1 evaluation,

* Number of SSBs for sync/re-sync for MR is up to 10
	+ Companies to report timeline and energy consumption
* Companies to provide feasibility analysis for transition time and transition energy with aim to converge to one or two set of values in RAN1#112

### 6.3.2 Power model for LP-WUR (LR)

The following power model for LP-WUR is used for evaluation for FR1,

|  |  |  |  |
| --- | --- | --- | --- |
| Power State | Relative Power (unit) | Transition energy:(unit multiplied by ms) | Ramp-up timeTLR, ramp-up (ms) |
| **Off[1]** | 0.001 | [TLR, ramp-up \*(PON+POFF)/2] | TLR, ramp-up = FFS, and company to report TLR, ramp-up FFS: Relation between Receiver architecture and its relative power and value of TLR, ramp-up |
| **On[2]** | ~~0.005/~~0.01/~~0.02/0.03/~~0.05/0.1/~~0.2/~~0.5/1/2/4FFS: If other values are needed |

* FFS: whether further categorization/sub-categorization is needed and how.
* FFS: Mapping from values to a LP-WUR architecture or LP-WUR mode of operation
* FFS: LP-WUR power consumption values for FR2.
* Note1: A unit of power is defined to be the same for main receiver and LP-WUS receiver.
* Note2: the values provided is for the purpose of studying power saving gain, and the values can be further revisit and categorization depending on the receiver architecture discussion.
* Note3: For LP-WUR ‘on’ state, more than one values within the above range may be used for evaluation (e.g. for a single LP-WUR architecture)

[1] Relative power unit for LP-WUR ‘off’ state, i.e., the LP-WUR does not perform monitoring

[2] Relative power unit for LP-WUR ‘on’ state, i.e., the LP-WUR performs monitoring

# 7 LP-WUR and LP-WUS Design

## 7.1 LP-WUS receiver architectures

*Editor’s note: The following SI Objective is included in this section.*

* Study and evaluate low-power wake-up receiver architectures [RAN1, RAN4]

This section includes the studies for LP-WUR architectures. It does not intend to mandate the implementation of any specific type(s) of LP WUR architecture at the UE. Note this does not prevent RAN4 from defining requirements for LP WUR in the normative phase.

### 7.1.1 General description of receiver types

*Editor’s note: Any general description of the receiver types from RAN 1/RAN4 related conclusions*

Study at least the following three types of receiver architectures for LP-WUR:

* Architecture with RF envelope detection
* Heterodyne architecture with IF envelope detection
* Homodyne/zero-IF architecture with baseband envelope detection
* Note: The details of each type of receiver architecture are discussed separately.
* Note: Above receiver architectures are considered suitable for OOK modulation. Some of the architectures

can be applicable for other modulations such as FSK.

#### RF envelope detection

The architecture with RF envelope detection based on at least the following diagram for LP-WUR.

* The RF signal is converted into baseband signal directly via an RF envelope detector.
* There is no Local Oscillator (LO) and no Phase-Locked Loop (PLL).
* 1 bit or multi-bit ADC is applied.
* Some component(s), e.g., RF LNA and/or BB AMP, can be optionally applied.
* High-Q matching network and/or RF BPF [and/or BB LPF] can be used to suppress adjacent channel interference or interference from legacy NR signals and/or other LP WUS on adjacent subcarriers.
* FFS the support of band and/or carrier tuning



**Figure 7.1.1-1 RF envelope detection based LP-WUR diagram**

For the architecture with RF envelope detection,

* It can achieve relatively low power consumption due to the removal of LO/PLL.
* Interference suppression for adjacent channel interference requires very high-Q matching network and/or RF BPF, which is challenging due to the high Q values and may require off-chip components.
* Interference suppression for interference from legacy NR signals and/or other LP WUS on adjacent subcarriers, if performed in RF, requires very high-Q matching network and/or RF BPF, which is challenging due to the high Q values and may require off-chip components.
* The support of multiple bands and/or carriers may require multiple high-Q matching networks and/or RF BPFs or multiple off-chip components.
* RF LNA can be applied to improve sensitivity, with the cost of additional power consumption.
* The noise figure can be relatively high.

#### Heterodyne architecture with IF envelope detection

The heterodyne architecture with IF envelope detection based on at least the following diagram for LP-WUR.

* The RF signal is down converted into IF signal via an RF mixer with a LO. The IF signal is converted into baseband signal via an IF envelope detection.
* There may be one or multiple IF stages depending on design.
* The choice of the LO is one of the major factors that determines the power consumption.
* Lower power consumption can be achieved by relaxing the accuracy and stability requirements of the LO. However, such increased frequency offset and phase noise should be taken into account in the design and evaluation.
* FLL (frequency locked loop) may replace PLL for non-coherent detection.
* 1-bit or multi-bit ADC is applied.
* High-Q matching network and/or RF BPF and/or IF BPF [and/or BB LPF] can be used to suppress adjacent channel interference or interference from legacy NR signals and/or other LP WUS on adjacent subcarriers.
* Some component(s), e.g., RF LNA and/or IF AMP and/or BB AMP, can be optionally applied.
* Image rejection filter or an image rejection mixer is required.
* FFS the support of band and/or carrier tuning
* FFS the choice of IF frequency range



**Figure 7.1.1-2 Heterodyne architecture with IF envelope detection based LP-WUR diagram**

For heterodyne architecture with IF envelope detection,

* For the support of band and/or carrier tuning, the band and/or carrier tuning can be achieved via tuning the LO frequency.
* The matching network and RF BPF for LP WUR may or may not reuse those of the main radio.
* It is more effective and less complex to use IF BPF instead of high-Q matching network and/or RF BPF to suppress adjacent channel interference or interference from legacy NR signals and/or other LP WUS on adjacent subcarriers.
* Using FLL instead of PLL consumes less power, but it may result in larger frequency error.
* The IF frequency can be properly selected to avoid LO leakage (DC offset) and flicker (1/f) noise.
* Image rejection can be done via either image rejection filter or image rejection mixer.
	+ Image rejection filter can be done in either RF or IF, which may require high-Q filter.
	+ Image rejection mixer requires two-branch (I/Q) mixing with good matching in gain and phase, which consumes additional power.
* RF LNA and/or IF AMP can be applied to improve sensitivity, with the cost of additional power consumption.

#### Homodyne/zero-IF architecture with baseband envelope detection

The homodyne/zero-IF architecture with baseband envelope detection based on at least the following diagram for LP-WUR.

* The RF signal is directly down converted into baseband signal via an RF mixer with a LO.
* Baseband envelope detection can be done either in analog domain or in digital domain depending on design, which is not explicitly shown in the diagram.
* The choice of the LO is one of the major factors that determines the power consumption.
* Lower power consumption can be achieved by relaxing the accuracy and stability requirements of the LO. However, such increased frequency offset and phase noise should be taken into account in the design and evaluation.
* FLL (frequency locked loop) may replace PLL for non-coherent detection.
* 1-bit or multi-bit ADC is applied.
* High-Q matching network and/or RF BPF and/or BB BPF [and/or BB LPF] can be used to suppress adjacent channel interference or interference from legacy NR signals and/or other LP WUS on adjacent subcarriers.
* No image rejection filter is required.
* Some component(s), e.g., RF LNA and/or BB AMP, can be optionally applied.
* FFS the support of band and/or carrier tuning



**Figure 7.1.1-3 Homodyne/zero-IF architecture with baseband envelope detection based LP-WUR diagram**

For homodyne/zero-IF architecture with baseband envelope detection,

* For the support of band and/or carrier tuning, the band and/or carrier tuning can be achieved via tuning the LO frequency.
* The matching network and RF BPF for LP WUR may or may not reuse those of the main radio.
* It is more effective and less complex to use BB BPF/LPF instead of high-Q matching network and/or RF BPF to suppress adjacent channel interference or interference from legacy NR signals and/or other LP WUS on adjacent subcarriers.
* Using FLL instead of PLL consumes less power, but it may result in larger frequency error.
* It can suffer from LO leakage (DC offset) and flicker (1/f) noise. The impact may be alleviated by using BB BPF in some cases.
* RF LNA can be applied to improve sensitivity, with the cost of additional power consumption.
* The baseband envelope detection can be done in either analog domain (before ADC) or digital domain (after ADC).

#### FSK receiver

Two examples for FSK receiver architectures are shown below:

* Example 1: parallel OOK receivers and a comparator circuit, e.g.,
	+ Each path can be implemented using either of [the architecture with RF envelope detection,] heterodyne architecture with IF envelope detection, or homodyne/zero-IF architecture with baseband envelope detection.



**Figure 7.1.1-4 FSK receiver with parallel OOK receivers and a comparator circuit based LP-WUR diagram**

* Example 2: using an FM-to-AM detector [or an FM detector]
	+ Alt 1: Use an analog FM-to-AM detector with a similar architecture as for OOK (e.g. heterodyne or zero-IF architecture), except that the envelope detector is replaced by a FM-to-AM detector.
		- Analog FM-to-AM detector can be implemented at least in BB or low-IF.



**Figure 7.1.1-5 FSK LP-WUS receiver with FM-AM detector- Alt 1**

* + Alt 2: Use a FM-to-AM detector [or an FM detector] implemented in digital domain after ADC, with a heterodyne or zero-IF architecture.
		- Digital FM-to-AM detector implementation can be considered as part of digital baseband processing.
		- Here is an example of using zero-IF architecture: 

**Figure 7.1.1-6 FSK LP-WUS receiver with FM-AM detector - Alt 2**

* + The FM-AM detector can be implemented using a frequency discriminator, which converts frequency variations into amplitude changes. It can be implemented in either analog domain (as in Alt 1) or digital domain (as in Alt 2).
		- One example, as shown in the figure below, is a conventional quadrature FM discriminator. It multiplies received frequency modulated signal with a phase shifted version, followed by a low pass filter. The amplitude of the output signal is proportional to the frequency of the input signal.



**Figure 7.1.1-7 FSK LP-WUS receiver with FM-AM detector by using a frequency discriminator**

* Note: Other architectures are not precluded.

### 7.1.2 [RAN4 studies of the receiver]

*Editor’s note: RAN4 related conclusions*

## 7.2 LP-WUS design and L1 procedure

*Editor’s note: The following SI Objective related to LP-WUS design and L1 procedure is included in this section.*

* Study and evaluate wake-up signal designs to support wake-up receivers [RAN1, RAN4]
* Study and evaluate L1 procedures and higher layer protocol changes needed to support the wake-up signals [RAN2, RAN1]
* Study generation and link performance of multi-carrier (MC)-ASK (including OOK) waveform
	+ study techniques to generate waveform by modulating sub-carriers of CP-OFDM symbol, consider up to M bits transmitted per OFDM symbol, where M is FFS.
		- Note that above does not preclude DFT-S-OFDMA
* Study generation and link performance of multi-carrier (MC)-FSK waveforms
	+ study techniques to generate waveform by modulating sub-carriers of CP-OFDM symbol symbol, consider up to M bits transmitted per OFDM symbol, where M is FFS.
* Study link performance of OFDMA-based signals/channels considering at least the existing signal/channel structure (e.g. CSI-RS, SSS)
	+ Other signal/channel structures are not precluded

For the purpose of study, the BW of one LP-WUS is not greater than X (FFS X is 5 or 20) MHz for FR1, study further

* whether BW of LP-WUS is configurable (implicitly or explicitly)
* size of guard band [FFS: within or outside of BW X], if any
* whether there is different X for Idle, Connected, Inactive modes

FFS: Whether FR2 is included in the scope of LP-WUS SI

For a UE support LP-WUR in IDLE/INACTIVE mode,

* Study how to reduce UE power consumption due to existing RRM measurement requirements at least for mobility support,
	+ study feasibility of RRM measurements performed by LP-WUR, at least for serving/camping cell, based on signals detected by LP-WUR
		- FFS: measurement metric
		- FFS: whether and how to identify cell/ tracking area
		- FFS: need for neighbouring cells
		- FFS: need for relaxation of existing RRM measurement requirements (for UE)

## 7.3 Higher-layer aspects

*Editor’s note: The following SI Objective related to higher layer aspects is included in this section.*

* Study and evaluate L1 procedures and higher layer protocol changes needed to support the wake-up signals [RAN2, RAN1]

# 8 Evaluation Results

*Editor’s note: The following SI Objective is included in this section.*

* Study potential UE power saving gains compared to the existing Rel-15/16/17 UE power saving mechanisms and their coverage availability, as well as latency impact. System impact, such as network power consumption, coexistence with non-low-power-WUR UEs, network coverage/capacity/resource overhead should be included in the study [RAN1]
	+ Note: The need for RAN2 evaluation will be triggered by RAN1 when necessary.

# X Conclusions

Annex <A>:
Simulation assumptions

 Annex <X>:
Change history

|  |
| --- |
| **Change history** |
| **Date** | **Meeting** | **TDoc** | **CR** | **Rev** | **Cat** | **Subject/Comment** | **New version** |
| 2022-10 | RAN1#110bis | R1-2208666 |  |  |  | Baseline TR skeleton | 0.0.0 |
| 2022-10 | RAN1#110bis | R1-2210430 |  |  |  | Baseline TR skeleton after discussion | 0.0.1 |
| 2023-02 | RAN1#112 | R1-23XXXXX |  |  |  | Update TR and incorporating agreements for evaluation and receiver architecture from RAN1#110bis and RAN1#111 | 0.1.0 |