vivo

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Electronic Meeting, September 13 – 17, 2021

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Agenda Item: 9.0.2
Source: vivo

Motivation for new study item on ultra-low power wake up receiver in Rel-18

RP-212005

Content

- Background and motivation
- Prototype and simulation
- Questions and discussions
- Concluding remarks and proposals
- Appendix

Background

Almost zero power (AZP) receiver received strong interest and support in Rel-18

During the Rel-18 Workshop in June 2021

- vivo/Spreadturm/Genies proposed a study in Rel-18 for almost zero power (AZP) receiver
- Many companies expressed positive intensions during NWM discussion in Rel-18 WS.
- Related tdocs from email discussion summaries: RWS-210647 Email discussion summary for [RAN-R18-WS-crossFunc-vivo] vivo
  - Comments/questions received from **19** companies in the email discussion,
  - Across diversified companies, e.g., infra vendor, operator, chipset vendor, UE vendor,…

During pre-RAN#93 discussion in Aug 2021

- Being part of the tasks listed in sub-bullet for thread 14 in Rel-18 WS summary

14. Additional RAN1/2/3 candidate topics, Set 1:

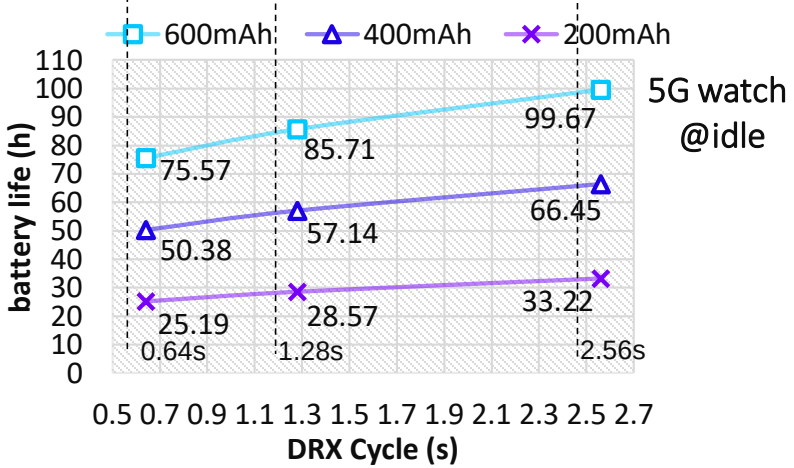
- UE power savings
- Enhancing and extending the support beyond 52.6GHz
- CA (Carrier Aggregation)/DC (Dual-Connectivity) enhancements (e.g., MR-MC (Multi-Radio/Multi-Connectivity), etc.)
- Flexible spectrum integration
- RIS (Reconfigurable Intelligent Surfaces)
- Others (RAN1-led)

- Moderators summary
  - Companies are generally positive on UE power savings but there are few companies questioning the need of a separate SI/WI. Majority preferred a separate SI/WI. Proposal to introduce enhancements based on ultra-low power UE receiver and wake up signal has received strong support. However, there were a number of companies questioning the benefit/feasibility of this proposal.

Ultra-low power receiver and wake-up signal

Challenges & use cases

- Use case specific requirements :
  - Industrial wireless sensors: The battery should last at least few years.
  - Wearables: Battery of the device should last multiple days (up to 1-2 weeks).
  - IDLE mode power consumption for 5G smartphone is expected to be further improved
- Limitation of power saving in Rel 17
  - Battery life of up to 1-2 weeks cannot be met even only in idle mode
  - eDRX is not expected to be configured for wearables and smartphone due to large latency



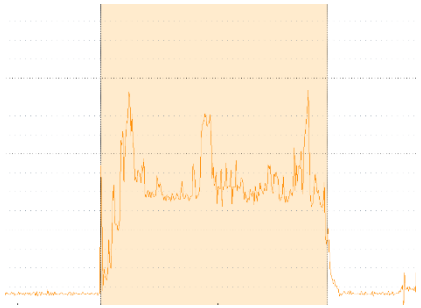
Ideal upper bound: estimated by considering idle mode operation only

Battery life with DRX cycle=1.28s

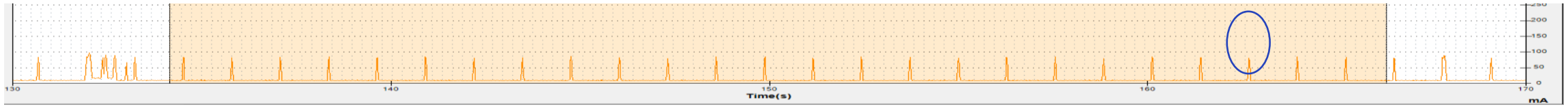
	Average current @idle	Average power @idle	Battery 200mAh	Battery 400mAh	Battery 600mAh
4G watch(1)	4mA	16mw	2.08 days	4.16 days	6.25 days
5G phone(2)	11mA	44mw	0.76 days	1.5 days	2.2 days
5G watch*	7mA(3)	28mw	1.19 days	2.38 days	3.57 days

*Not launched yet, estimated value

Big gap to 1-2 weeks !



Wakeup around PO



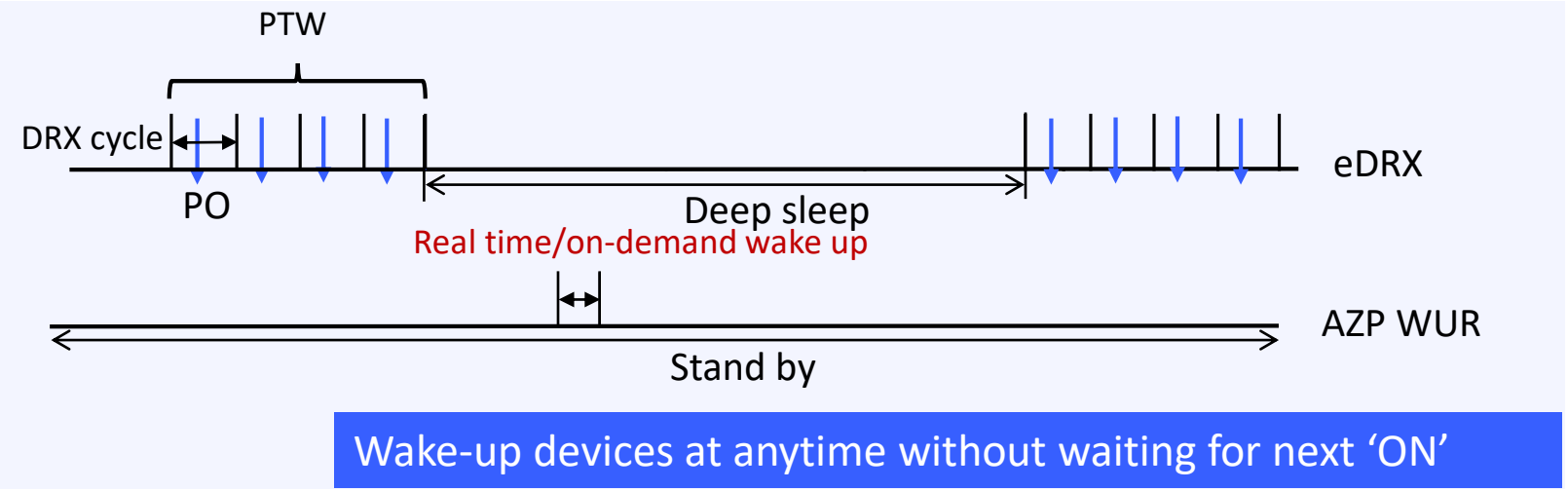
(1) vivo internal testing, TD-LTE
(2) vivo internal testing, 5G NR
(3) Assuming 1RX, scaling based on TR 38.840

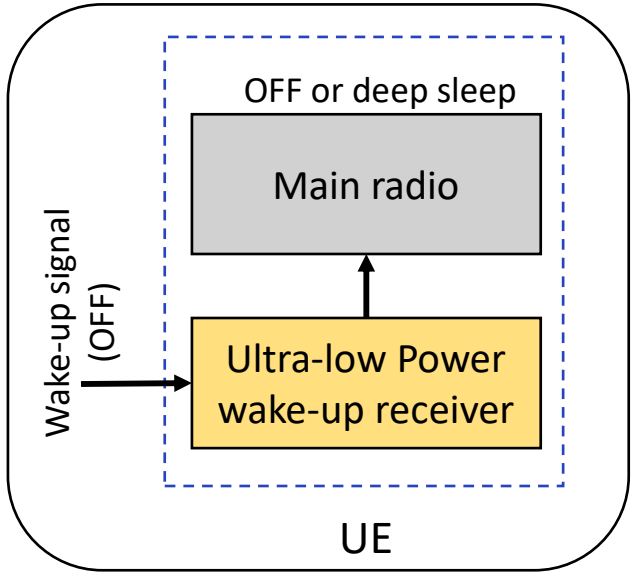
NR UE power consumption, RF + baseband @ RRC IDLE :
Band N41(CMCC), 20MHz, DRX cycle 1.28s

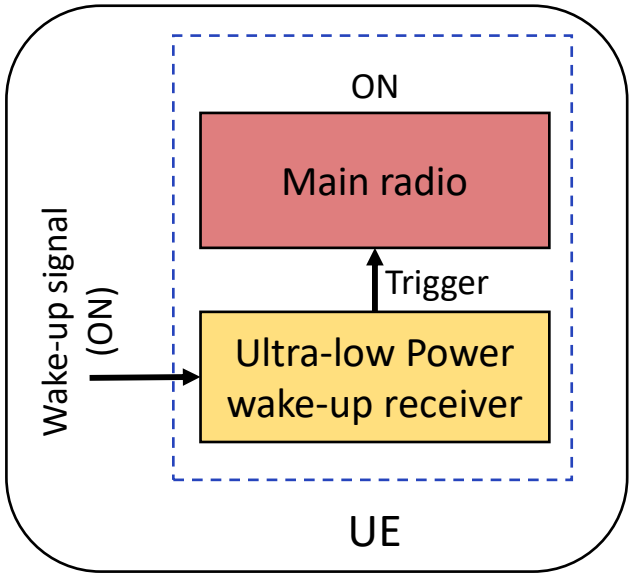
Ultra-low power receiver and wake-up signal

A key improvement for almost zero power and real-time/on-demand wake-up

- The battery life depends on the paging cycle. The system design is a tradeoff between power consumption and latency
  - However, a separate wake-up receiver can wake up devices at any time without long waiting time and still low power consumption





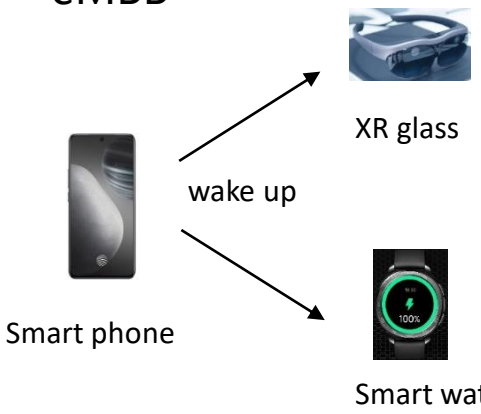


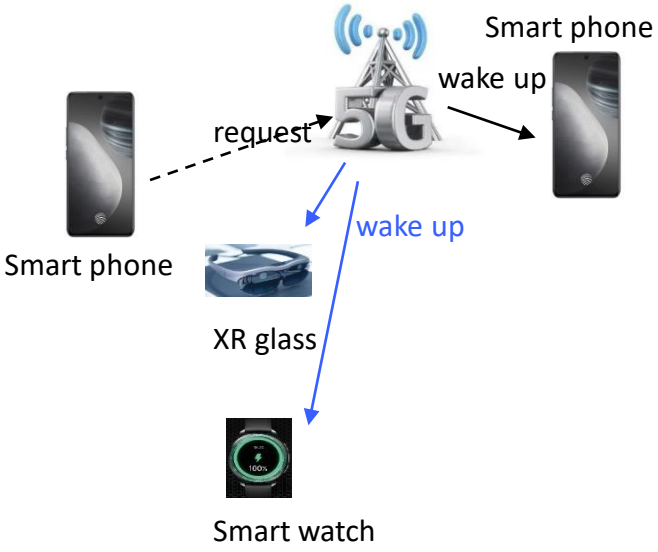
- Separate wake-up receiver can largely reduce the power consumption
  - For main radio, upon reception of the wake-up signal,
    - The ultra-low power receiver wake up the main radio,
    - Otherwise, the main radio is OFF or keep in a deep sleep mode
  - For ultra-low power wake-up receiver,
    - It can be operated in an always 'on' manner with very low power consumption.

Ultra-low power receiver and wake-up signal

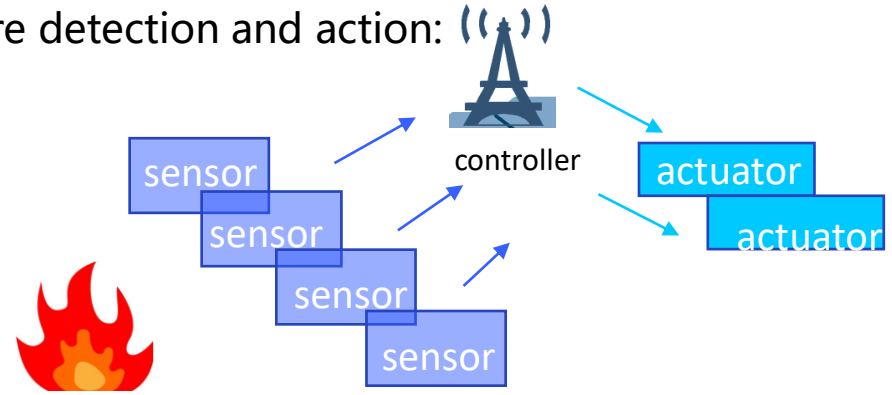
Challenges & use cases

- eMBB



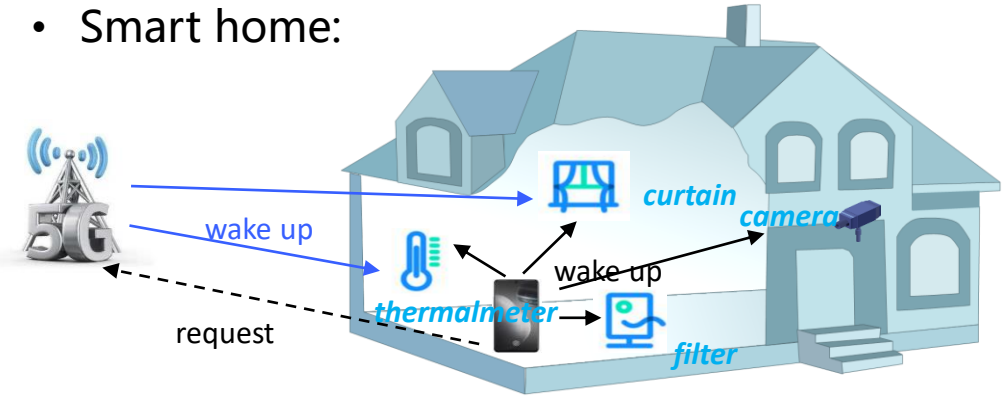


- Fire detection and action:

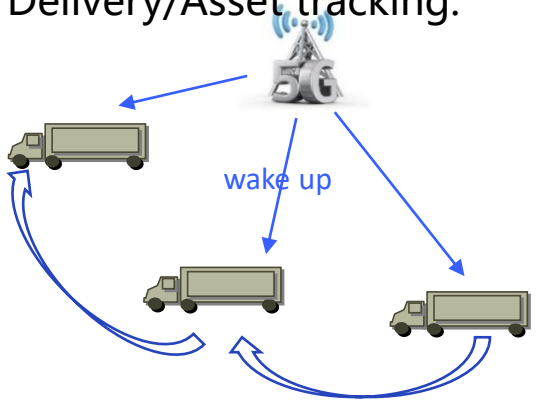


Fire shutters shall be closed and fire sprinklers shall be turned on within 1 to 2 seconds

- Smart home:



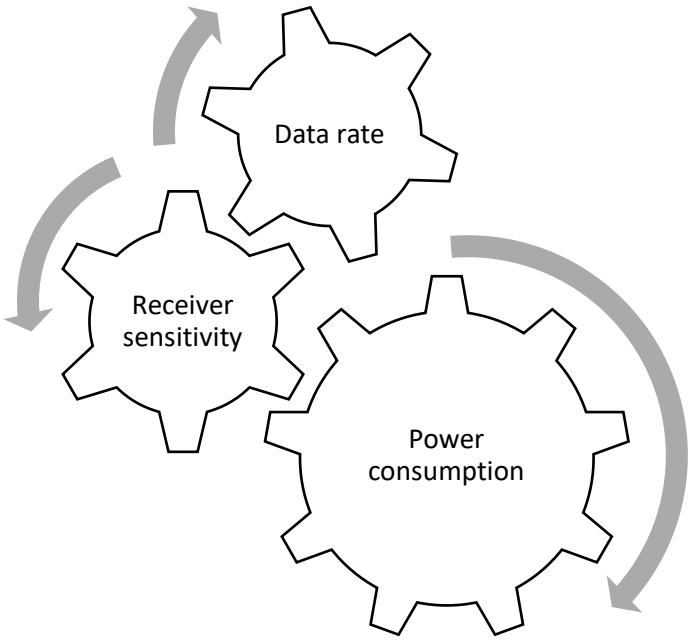
- Delivery/Asset tracking:



(1) Wearables, battery of the device should last multiple days (up to 1-2 weeks), 3GPP TR38.875 Study on support of reduced capability NR devices
(2) Delivery/asset tracking, 3GPP TR 22.104 Service requirements for cyber-physical control applications in vertical domains
(3) Smart home, 3GPP TR 22.859 Study on Personal Internet of Things (PIoT) networks
(4) Fire detection and action, 3GPP TR 22.804 Study on Communication for Automation in Vertical Domains

Ultra-low power receiver and wake-up signal

Tradeoff among multiple aspects



Sensitivity vs. Power Consumption

- The supply voltage varies in a range thus the receiver sensitivity is impacted
- Usage of LNA can improve the receiver sensitivity but largely increase power

Data Rate vs. Power Consumption

- Lower down the sampling rate (gross data rate) thus less power consumption is expected

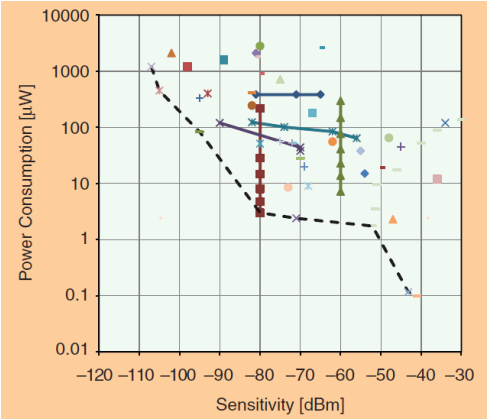
Dara rate vs. Sensitivity

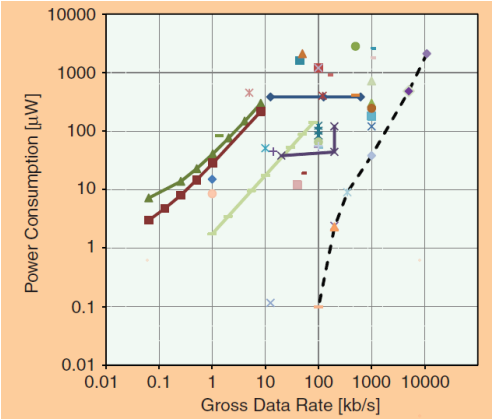
- Using spreading techniques to increase the reliability
- Using coding techniques to ensure reliability

Figures

(Left). Sensitivity of the low-power receivers vs. their power consumption together with Pareto front

(Right). Gross data rate of the low-power receivers vs. their power consumption together with Pareto front.





Reference:

A Survey of Low-Power Transceivers and Their Applications, IEEE circuits and systems magazine, Johannes Blanckenstein, Jirka Klaue, and Holger Karl

Ultra-low power receiver and wake-up signal

Tradeoff between power consumption and sensitivity/coverage

- Smartphone and wearables are expected to further reduce the power, for standby purpose

Poor — Power consumption — Good

Good — Coverage — Poor

NR Idle	• Traditionally UE power consumption, RF + baseband @ RRC IDLE • Power consumption **30~50mW**, and RF sensitivity **-100dBm**(1)
Rel-17 PEI	• Paging early indication is used to indicate UE paging monitoring • PEI is based on legacy signals, either PDCCH based or sequence based (SSS or TRS like) • Power consumption is 0.8x~0.9x of Rel-15/16 IDLE mode, sensitivity is the same as Rel-15

Almost Zero Power (AZP)	• Almost zero power receiver: passive circuit with envelope detector
	  • Power consumption **7.4nW**, and RF sensitivity **-71dBm** @433MHz(2)
	  • Power consumption **99μW**, and RF sensitivity **-97dBm** @2.4GHz (3)
	  • Power consumption **45μW**, and RF sensitivity **-87dBm** @900MHz(4)

Zero Power	• Zero power: energy harvesting • Power consumption **0**, and RF sensitivity**@-20Bm** or higher(5)

- ***Need tradeoff between power consumption and received signal sensitivity***
- ***Almost zero power receiver achieve 100x~1000x power reduction with some sensitivity degradation is feasible.***
- ***Very low power receiver by RF front-end can achieve about 5x power reduction with almost no or minor RF sensitivity degradation.***

Reference AZP Receiver minimum input

- -77dBm ~ -82 dBm (802.11ba)
- -97dBm [Salazar ISSCC'15]
- -72dBm [Pletcher ISSCC'08]

(1) vivo internal testing, 5G NR
(2) A -76dBm 7.4nW Wakeup Radio with Automatic Offset Compensation, Jesse Moody et al.
(3) A −97dBm-sensitivity interferer-resilient 2.4GHz wake-up receiver using dual-IF multi-N-Path architecture in 65nm CMOS, Camilo Salazar et al
(4) Abe, VLSI'14
(5) NXPRFID, UCODE G2iM https://www.nxp.com/products/rfid-nfc/ucode-rain-rfid-uhf/ucode-g2im-and-g2im-plus:SL3S1003_1013

Ultra-low power receiver and wake-up signal

Academic and Industry achievement of almost zero power (AZP) receiver

CMOS RF front-end with OOK energy detection which is designed for low power receiver with enough receiving sensitivity is being popularly studied in academic community long time, with quite feasible and convincible results for practical usage

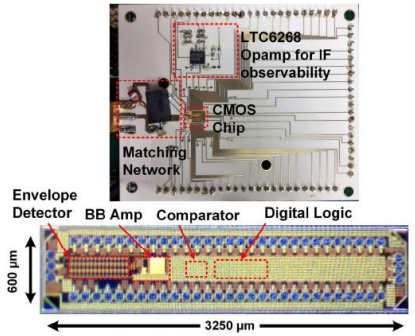


Figure 28.6.7: Die micrograph and PCB photo of the wakeup receiver.

-71dBm, 433MHz, 7.4nW

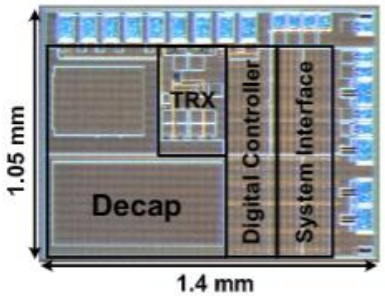
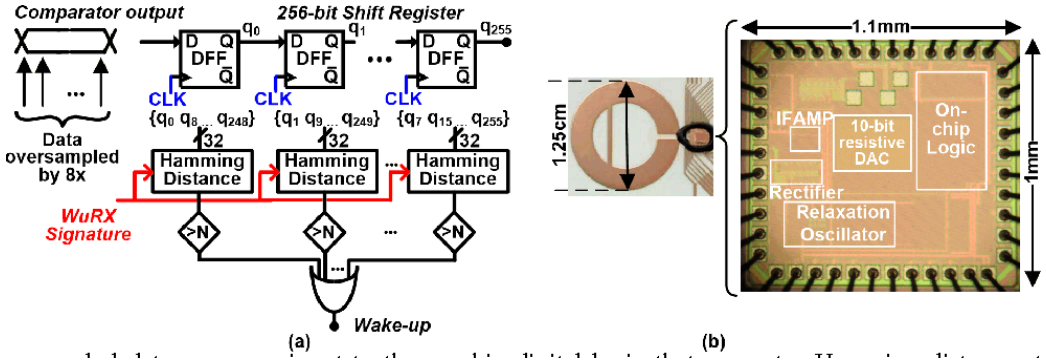


Fig. 16. Radio die photograph in 55-nm DDC CMOS.

-97dBm, 2.4GHz, 99uW



-61.5dBm, 2.4GHz, 365nW

Other organization has already finalized similar low power wake-up receiver standardization work, which believes to be having widely interests from industrial community

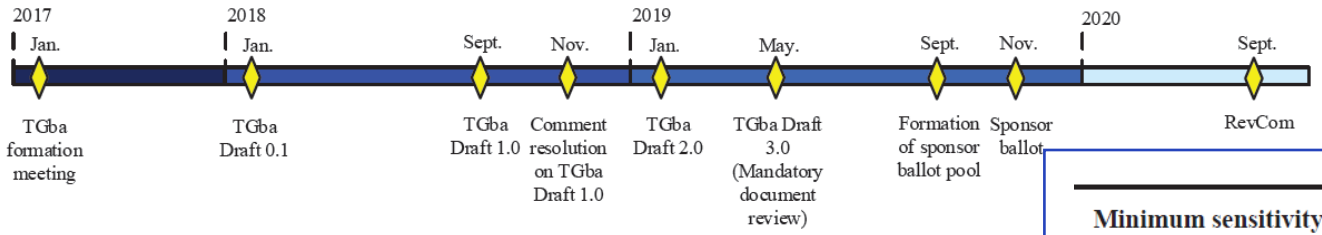


Figure. Timelines of IEEE 802.11ba standardization progress

Minimum sensitivity (dBm)
-82
-77

LP-WUR: <u>not</u> for user data; serves as a simple "wake-up" receiver for the main radio

- LP-WUR is a simple <u>receiver</u> (doesn't have a transmitter)
- Active while the main radio is off
- Target power consumption < 100 µW in the active state
  - Simple modulation scheme such as On-Off-Keying (OOK)
  - Narrow bandwidth (e.g. < 5 MHz)
- Target transmission range: LP-WUR = Today's 802.11

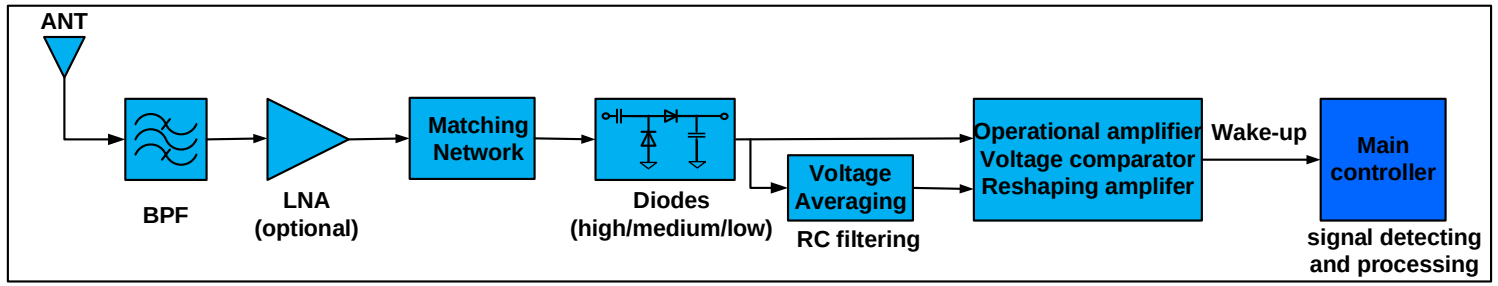
Ultra-low power receiver and wake-up signal

Evolution for IDLE/INACTIVE power saving

solution	Supported by harvested energy?	Range	Sensitivity	Power consumption
Rel-15 IDLE	No	> 500m	~-100dBm	1 X
Rel-17 WUS (PEI)	No	> 500m	~-100dBm	0.8 ~ 0.9 X
AZP receiver for WUS	Possible	100~200m	-70~-90 dBm	0.001 ~ 0.01 X

Rel-17 WUS (PEI)

- PDCCH/sequence based WUS requires full receiver operation, including RF, modem and etc.
- Expected power consumption around 30 ~ 50 mW



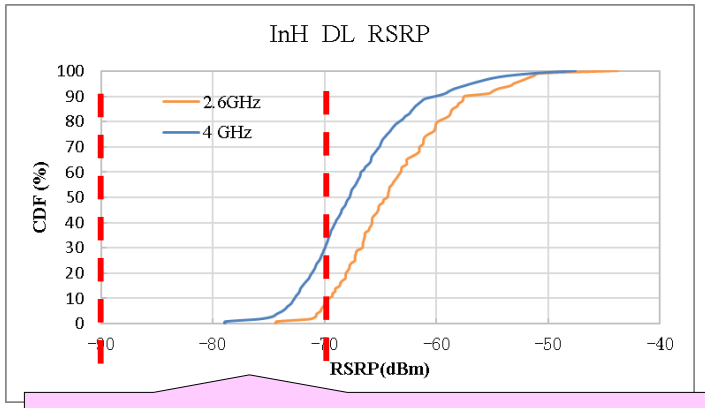
Almost-zero-power receiver, e.g., Envelop detector

- No high performance local oscillator needed. Non-coherent detector.
- If receiver power is enough, then possibly bypass LNA
- Remove/simple ADC: a simple energy accumulation and comparator is enough
- Separate RF channel to the main radio (but can shared antenna)
- Very simple processing by digital state machine or simple MCU
- Expected power consumption around 1 ~ 100 uW

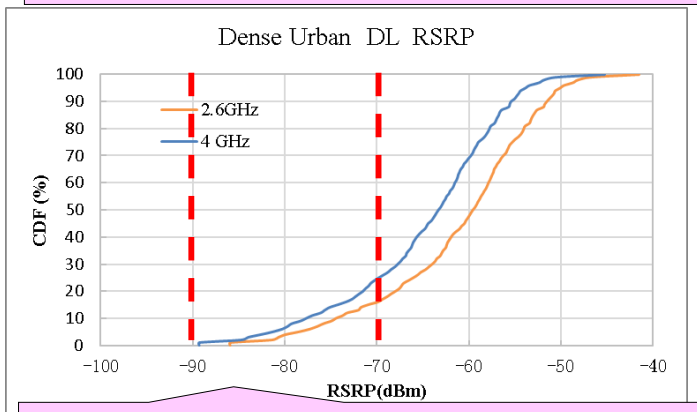
Ultra-low power receiver and wake-up signal

Coverage and mobility

- Design should consider the impact to UE performance
  - The feasibility (e.g., RF sensitivity) is scenario dependent (deployment, UE speed, etc)



- **70%-90%** feasible for receiver sensitivity @ -70dBm
- **100%** feasible for receiver sensitivity @ -90dBm

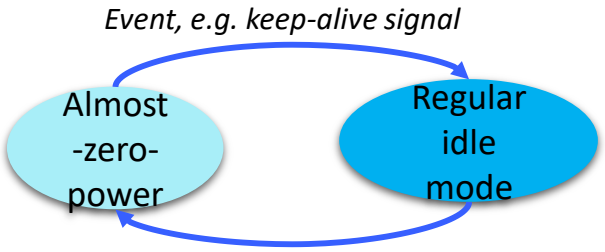


- **75%-85%**feasible for receiver sensitivity @ -70dBm
- **100%** feasible for receiver sensitivity @ -90dBm

- Category of the usage in a cellular network
  - Limited coverage / mobility
    - Stationary IoT with limited coverage/area, e.g., home, factory
  - Extended coverage / mobility
    - Wireless sensor network
    - Consumer electronics, such as wearable, glasses, smartphone, e-Health
    - …

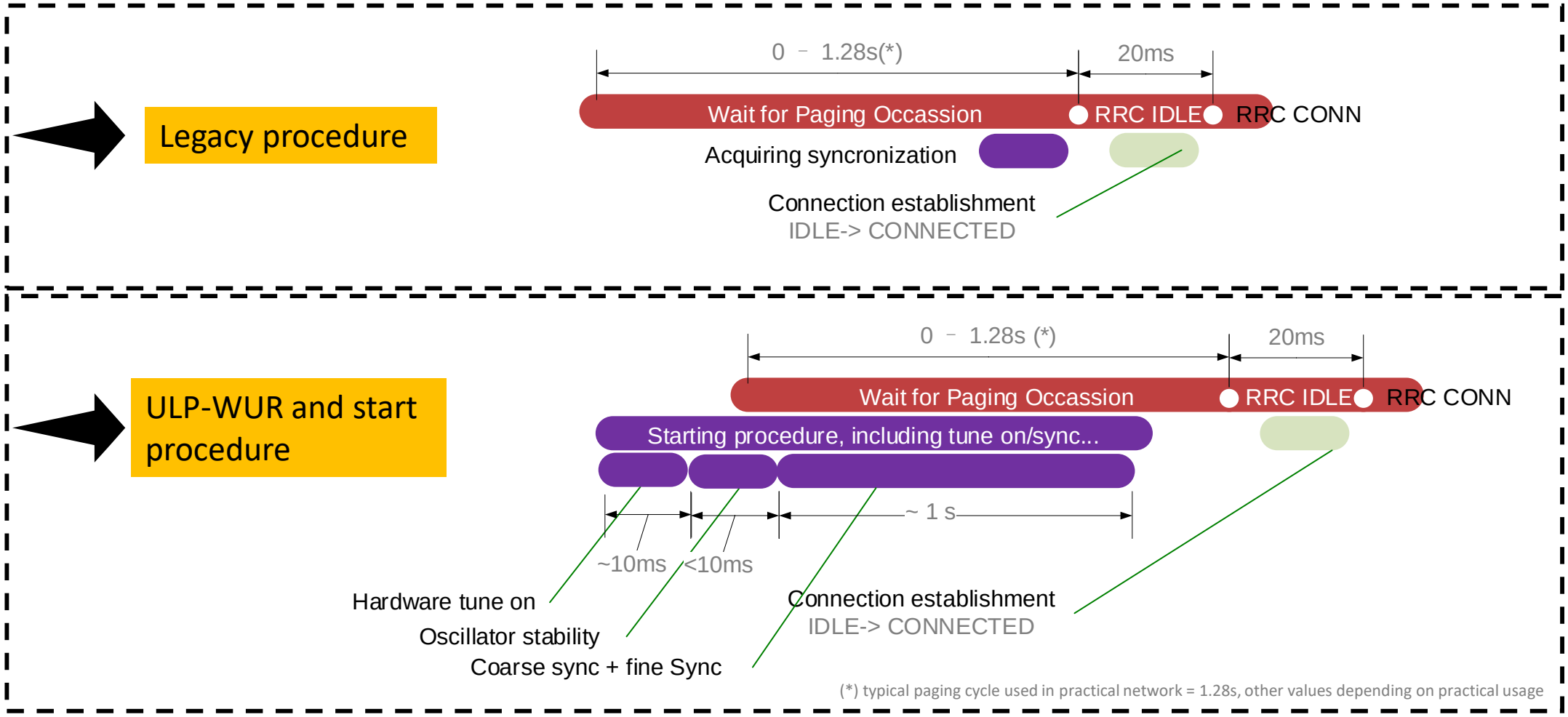
- Supporting a feature in a cellular network deployment important for creating value for operators, customers and manufacture
  - Network is fully controlled of the AZP receiver and assist UE for keeping power consumption as lower as possible.

Necessary methods to ensure network and UE reachability.



Ultra-low power receiver and wake-up signal

Latency analysis



- Latency increase due to 'warm-up time', including hardware turning on, synchronization, paging reception and etc.
- The overall latency from 'incoming paging' to 'connection establishment accomplished' does not change much.

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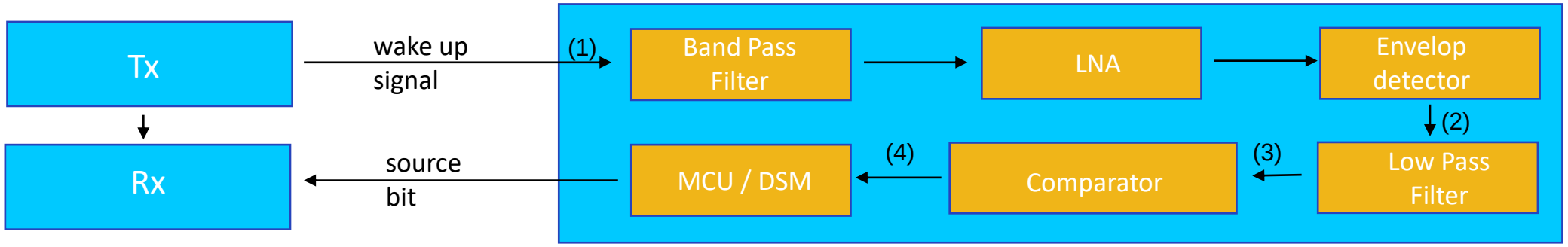
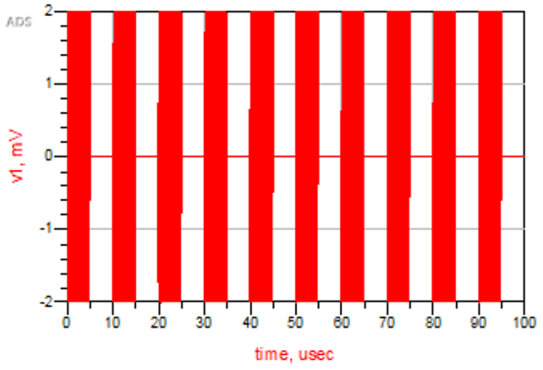
Ultra-low power receiver and wake-up signal

Proof of concept

- **Test framework**





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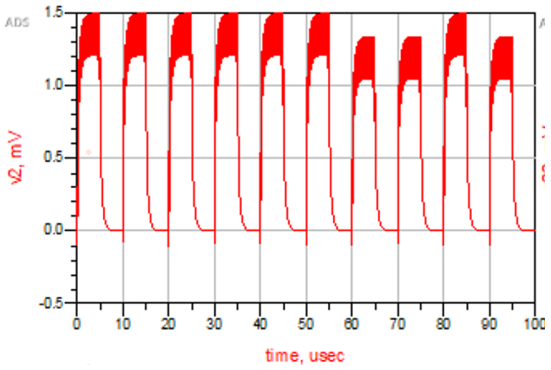
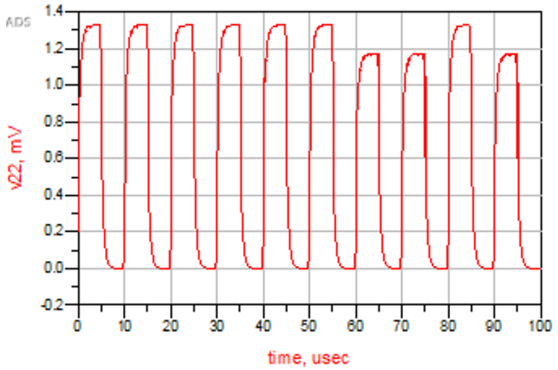
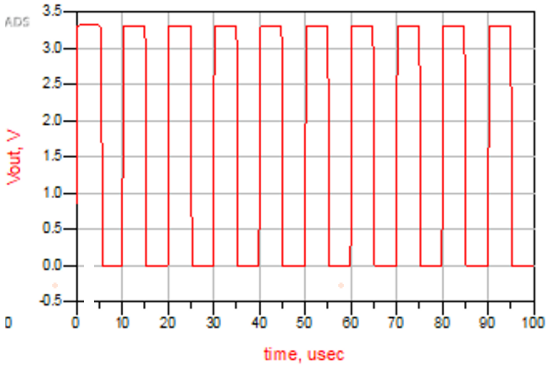


(2)



(3)

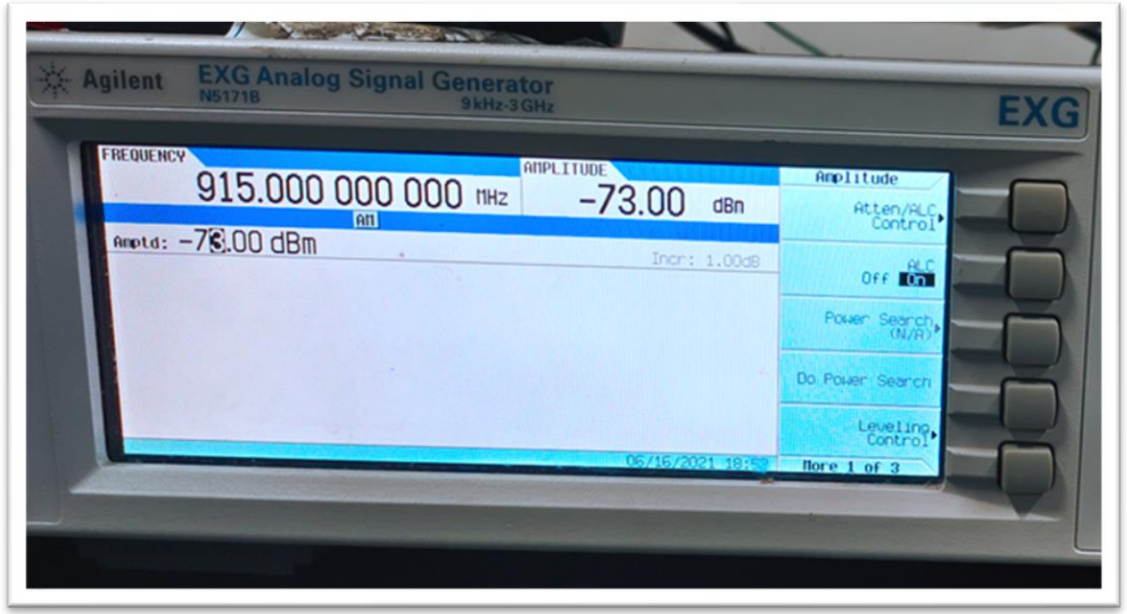


(4)

Ultra-low power receiver and wake-up signal

Proof of concept

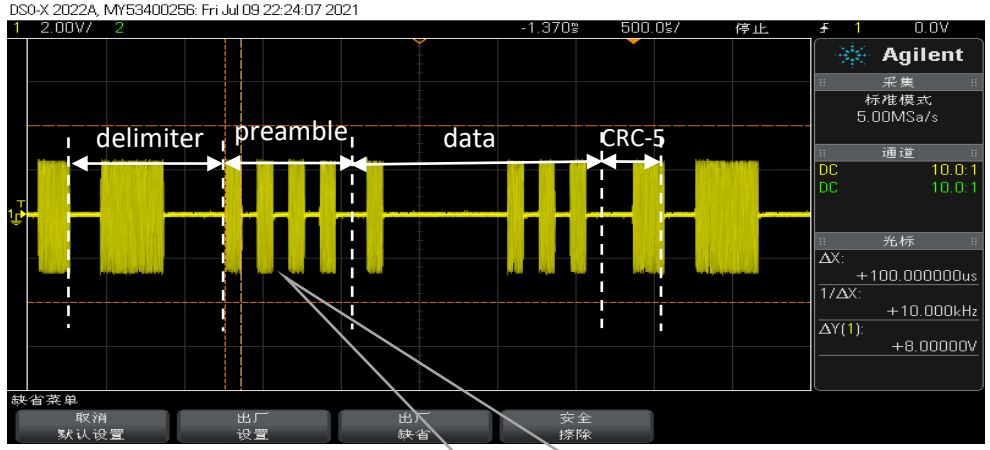
- **Hardware test result**
  - Carrier of 915MHz, data rate of 1kbps, 10kbps
  - Rx Sensitivity of -55dB is achieved without LNA; -75dB is achieved with LNA



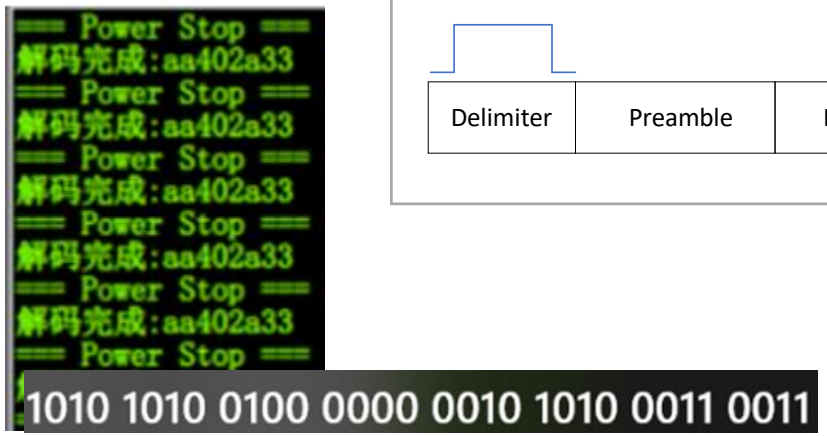
Almost-Zero-Power (AZP) wake-up receiver

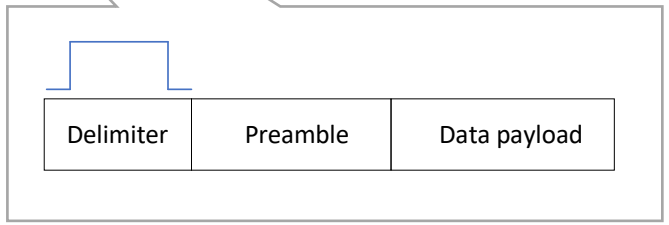
Proof of concept

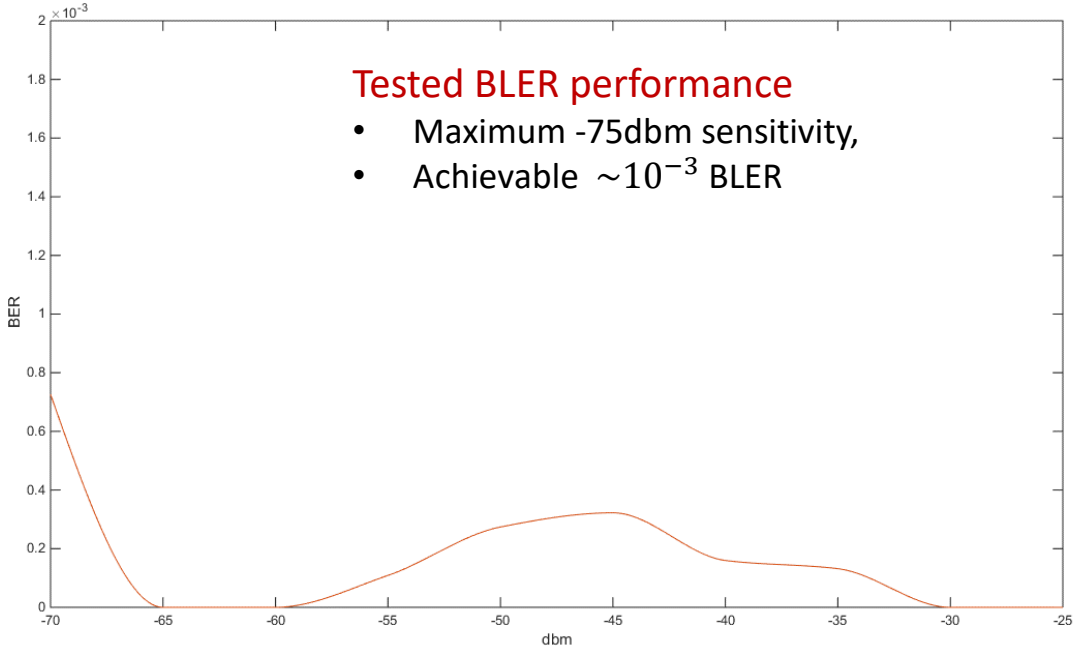
- **Joint test of hardware and software of wake-up receiver**
  - Input



  - Output



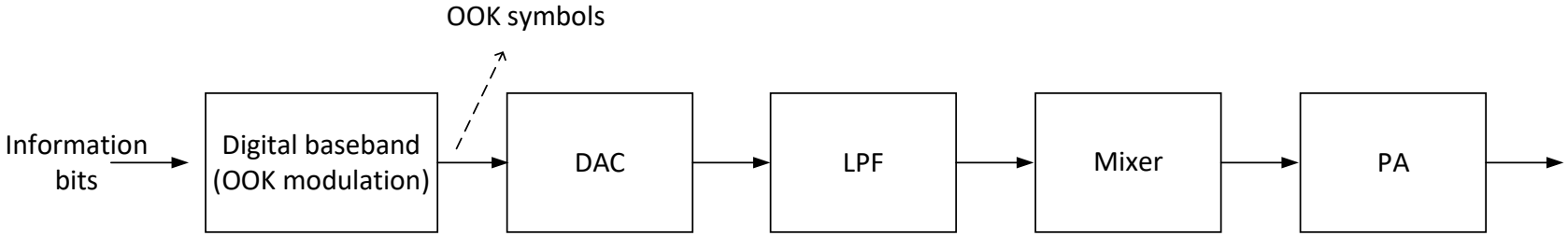




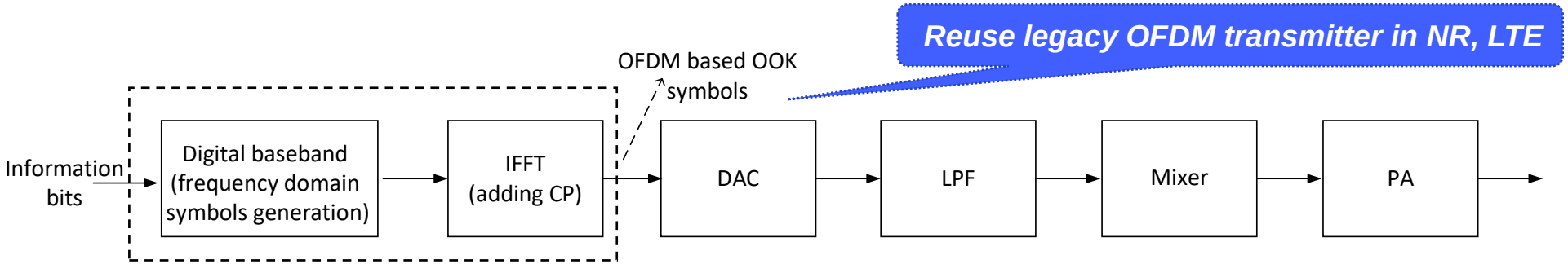
Almost-Zero-Power (AZP) wake-up receiver

LLS simulation methodology

- **Transmitter block**
  - Type I: time-domain generation



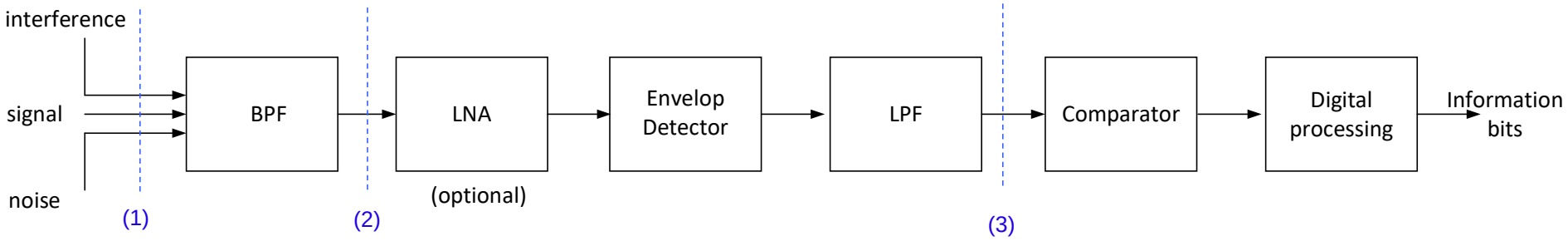
  - Type II: frequency-domain generation (Reuse current Tx signal processing)

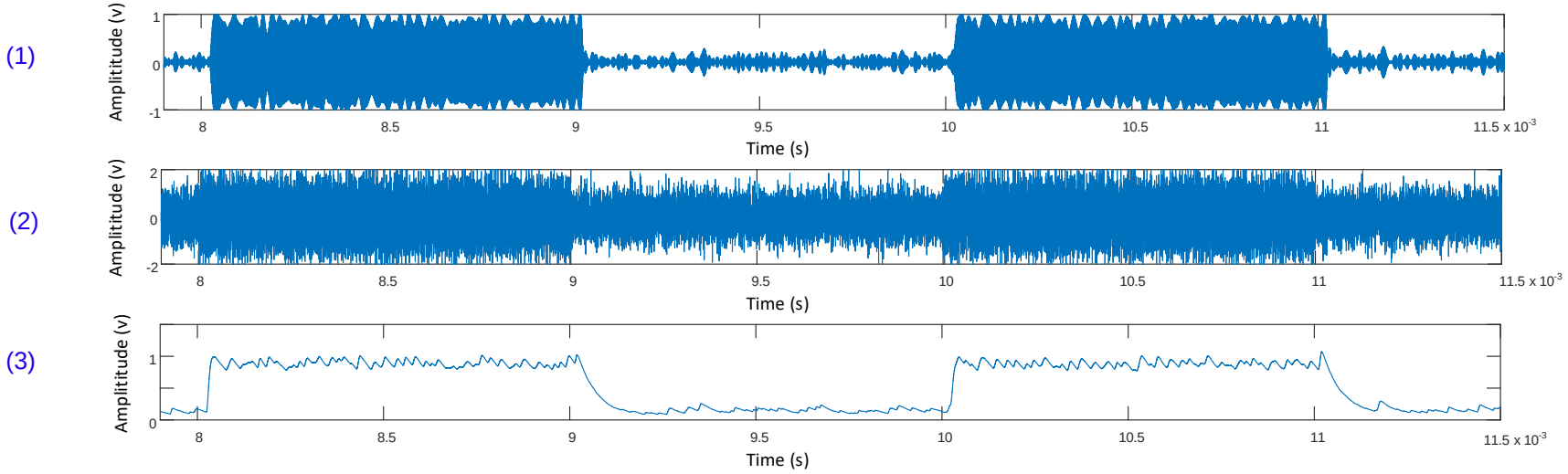


Ultra-low power receiver and wake-up signal

LLS simulation methodology

- **Signal processing for Receiver block**





*please refer to appendix for simulation details

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- Appendix

Further information

Quick summary of topics from NWM discussion for AZP WUR

	Questions	views
(1)	Investigate ultra-low-power wake-up mechanism applicable for all UE types	Yes, including IoT, consumer electronics, smartphone and etc.
(2)	Mobility support of AZP WUR for low speed, nomadic, …	Not limited to stationary scenario, others like, nomadic, low-mobility scenario is also considered. (see Page XX in slides) • Option 1: no measurement, applicable for certain scenarios for example based on BS type • Option 2: relaxed measurement, applicable for certain scenarios based on cell type, low mobility and so on. • Option 3: design new low power RS for such measurement for RRM, the measurement can be operated by this separate WUS receiver.
(3)	RRC state support	The ultra-low power wake-up signal/receiver is mainly proposed for reducing power consumption in idle/inactive state. Some companies asks whether it can be useful for CONNECTED mode.
(4)	Wake-up of Multiple RAT	The WUR may wake-up the main radio which include but not limited to NR, LTE, sidelink, LTE-M, NB-IOT, etc.
(5)	“warm-up time” for main radio by wake-up indication need to be addressed	See Page 12 in this slide
(6)	New waveform or new sequence	The waveform design is UE hardware specific and need further investigation. On-off-keying and

Further information

Quick summary of topics from NWM discussion for AZP WUR

	Questions	views
(7)	Cost	Additional hardware cost is also very important to take into consideration. A simple envelop detector receiver, can be used. From literature, the size of such receiver based on 65nm CMOS can be designed as small as 1mm * 1mm. The chipset cost can be estimated based on the die size. And it is expected that the cost increase is marginal for such a small die size. We can further discuss the cost in the study item.
(8)	trade-off between power consumption, sensitivity and data rate.	See page 7 in this slides
(9)	Differences to Rel-17 PEI.	For AZP WUS, the wake up receiver is used to receive WUS only. See Page X in the slides See page 10 in this slide

Content

- Background and motivation
- Prototype and simulation
- Questions and Discussions
- Concluding remarks and proposals
- Appendix

SID Scope

What need to be solved for almost zero power (AZP) receiver

- For UE stand-by, study the ultra-low-power wake up to trigger main radio considering the following aspects:
  - Study and evaluate the trade-off between receiver sensitivity and power consumption for the candidate receiver architectures, e.g., RF/Analog Front-end and/or dedicate wake-up receiver, with ultra-low power consumption [RAN1, RAN4]
  - Study the usage scenarios for the candidate ultra-low power wake-up receiver, develop the suitable evaluation methodology [RAN1]
  - Study the wake-up signal design enabling the UE wake-up with ultra-low power consumption and efficient system operation. [RAN1 ,RAN4]
    - Basic structure of wake-up signal
    - Narrow bandwidth
    - Multiplexing of wake-up signals
    - In-band and/or out-band operation by considering the following
      - coexistence with the legacy signal/channels for in-band operation
      - inter-cell interference
    - operation on licensed/unlicensed band
    - method to ensure network reachability
  - Study the possible procedures to support the ultra-low power UE wake up [RAN2,RAN1]
    - The ultra-low UE wake up feature is configured by the network
    - UE procedure for ultra-low power wake up signal monitoring
    - UE procedure for main radio activity triggered by ultra-low power wake up signal
    - Potential UE state transition

  Note: The main radio may include but not limited to NR, LTE, sidelink, LTE-M, NB-IOT, etc.

Propose to have a study item in Rel-18 for almost zero-power receiver

vivo

THANK YOU.
谢谢。

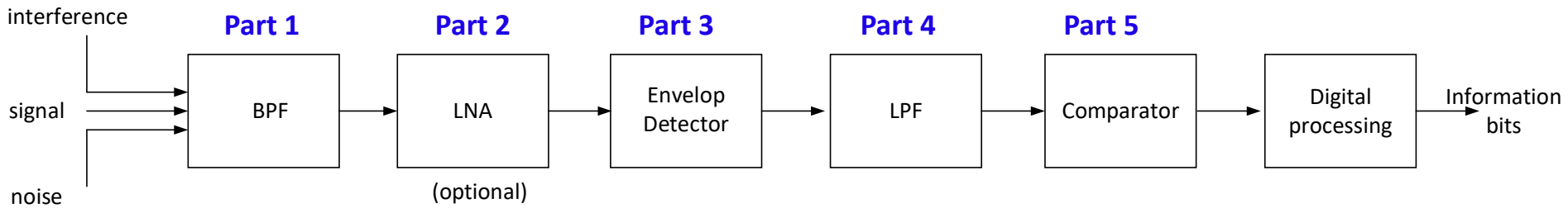
Appendix 1: Link-level simulation

Models for each block

Ultra-low power receiver and wake-up signal

LLS simulation methodology

- **Receiver block**



- **Part 1: Bandpass filter**
  - Modeling RC bandpass filter by FIR filter
  - For example, setting sampling rate, stop frequency , pass frequency , e.g., for carrier frequency 915MHz, set sampling rate of 10^3MHz, with pass range [865,965]MHz
  - Some sophisticated tools can be used to generate FIR and model the bandpass filter

Ultra-low power receiver and wake-up signal

LLS simulation methodology

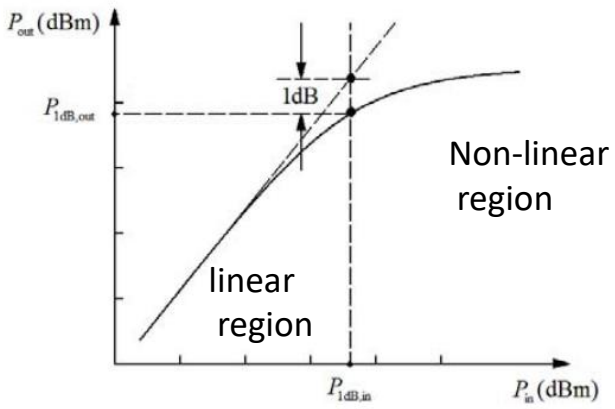
- **Part 2: LNA**
  - Input : $v_{in} = V_0 \cos \omega_0 t$
  - Output: $v_{out} = a_0 + a_1 V_0 \cos \omega_0 t + a_2 V_0^2 \cos^2 \omega_0 t + a_3 V_0^3 \cos^3 \omega_0 t + \cdots$
  - Apply Taylor's series to output:

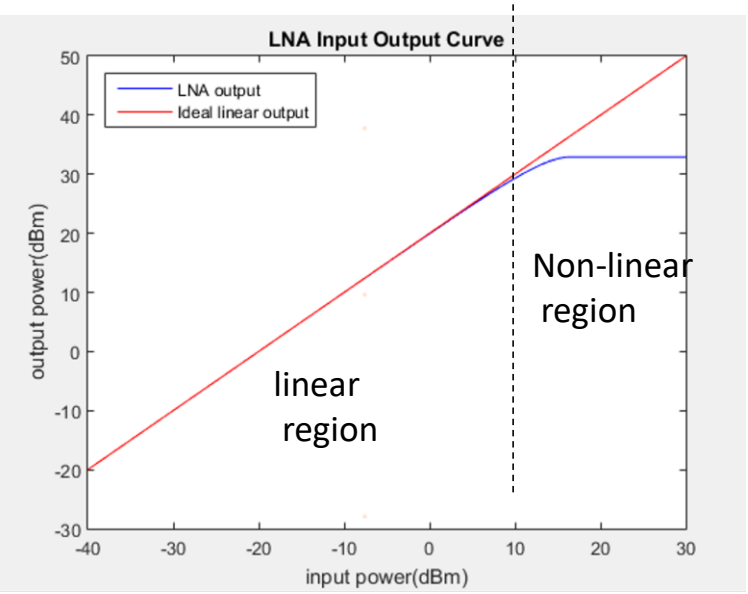
amplifying factor

$$v_0 = (a_0 + a_2 V_0^2) + \boxed{(a_1 V_0 + \frac{3}{4} a_3 V_0^3)} \cos \omega_0 t + \frac{1}{2} a_2 V_0^2 \cos 2\omega_0 t + \frac{1}{4} a_3 V_0^3 \cos 3\omega_0 t + \cdots$$

  - 1dB saturation point: linear amplifying to non-linear amplifying

1dB saturation point

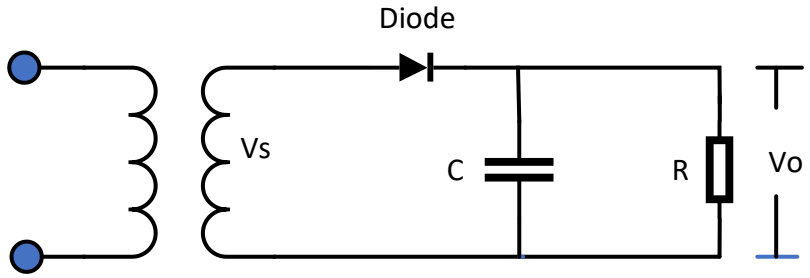




Ultra-low power receiver and wake-up signal

LLS simulation methodology

- **Part 3: Envelop detector**
  - Output voltage V_o is determined based on capacity charging/discharging process triggered by input voltage V_s
  - When $V_s > V_o$, capacity is charged; when $V_s < V_o$, capacity is discharged
  - Speed of capacity charging > > speed of capacity discharging
  - Modeling the charging and discharging process to determine the output voltage V_o of envelop detector:



step 1 get absolute value of input voltage of envelop detector, i.e., V_{abs}=abs(V_s)

step 2 if $V_{abs}(n)<V_O(n-1)$, to model the discharging process: set $V_O(n)$ to a *down scale* of $V_O(n-1)$, i.e., $V_O(n)= a \times V_O(n-1)$, where a is smaller than 1 and depending on diode, C, and R

step 3 if $V_{abs}(n)>V_O(n-1)$, to model the charging process: set $V_O(n)$ to a *up scale* of $V_O(n-1)$, i.e., $V_O(n)= b \times V_O(n-1)$, where b is larger than 1 and depending on diode, C, and R

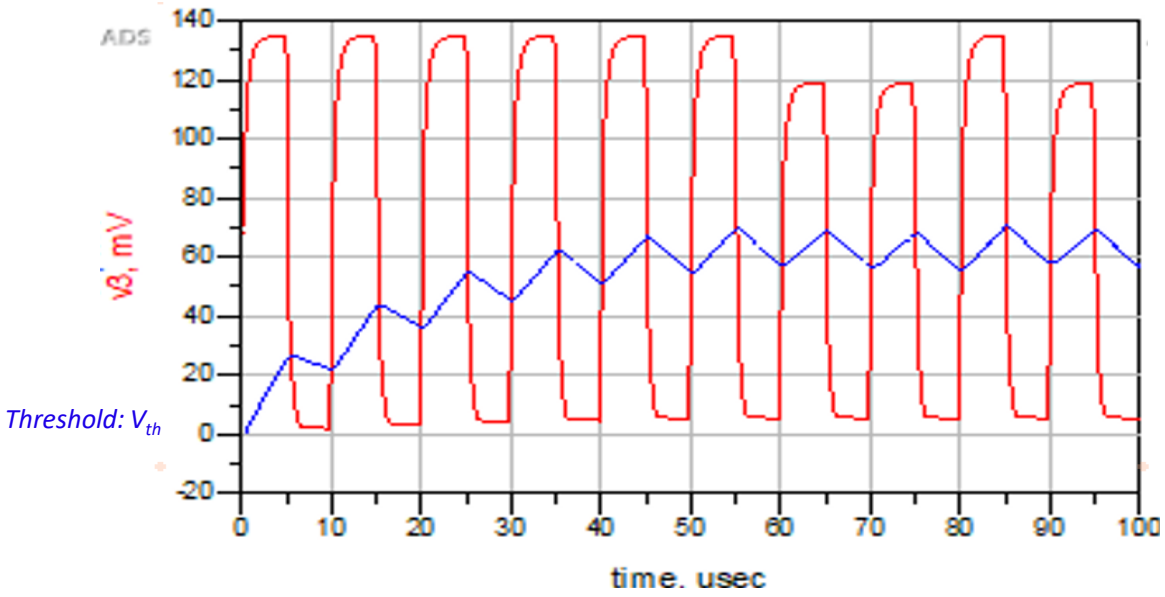
Ultra-low power receiver and wake-up signal

LLS simulation methodology

- **Part 4: Lowpass filter**
  - Modeling RC low pass filter by FIR filter
  - Setting sampling rate, stop frequency , pass frequency , e.g., set sampling rate of 10MHz, stop frequency at 150k, pass frequency at 100k
  - Some Sophisticated tools can be used to generate FIR and model the bandpass filter

Ultra-low power receiver and wake-up signal

LLS simulation methodology

- **Part 5: Comparator**
  - 1bit ADC like: compare the input of comparator with a threshold, if larger than it, output ‘1’, otherwise, output ‘0’.
  - Threshold determination： V_{th} is updated iteratively by a accumulative average of input

    e.g., $V_{th} = \frac{1}{N_k}\sum_{n=0}^{N_k} v(n)$