

Fukuoka City, Japan, May 20th – May 23rd, 2024

Agenda item: 9.4.1.2
Source: Everactive
Title: Ambient IoT device architectures
Document for: Discussion and Decision

1. Introduction

In [1], a new study item (SI) is approved for the solutions for Ambient IoT (Internet of Things) in NR. Objectives of this SI include the following:

The following objectives are set, within the General Scope:

1. Evaluation assumptions
 - a) Conclude at least the following aspects of design targets left to WGs in Clause 5 (RAN design targets) of TR 38.848 [RAN1].
 - Clause 5.3: Applicable maximum distance target values(s)
 - Clause 5.6: Refine the definition of latency suitable for use in RAN WGs
 - Clause 5.8: 2D distribution of devices
 - b) Define necessary further evaluation assumptions of deployment scenarios for coverage and coexistence evaluations [RAN1, RAN4]
 - c) Identify basic blocks/components of possible Ambient IoT device architectures, taking into account state of the art implementations of low-power low-complexity devices which meet the RAN design target for power consumption and complexity. [RAN1]
 - d) Define link budget calculation for coverage, including whether/how to model carrier wave from node(s) inside or outside the connectivity topology.

NOTE: Assessment performance of the design targets is within the study of feasibility and necessity of proposals in the following objectives, e.g. by inspection of reference implementations in the field, simulations, analytically.

NOTE: strive to minimize evaluation cases in RAN1.

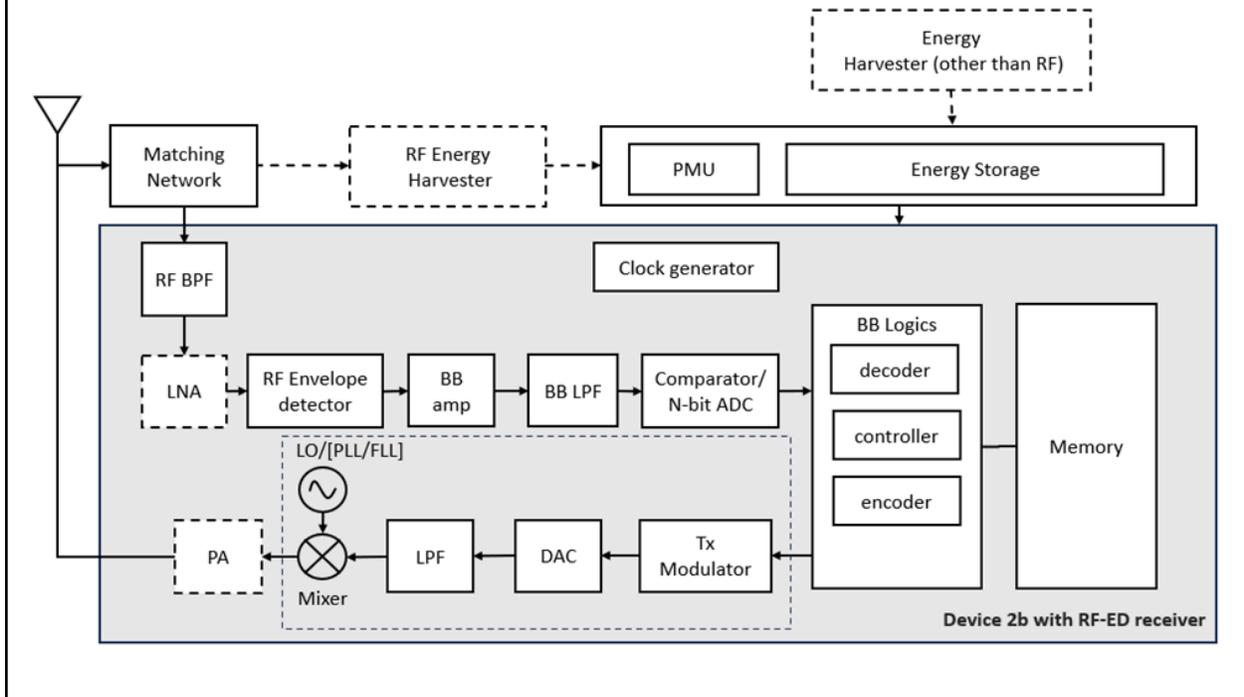
1. Device Architecture

Agreement

Study device 2b architecture w/ RF-ED receiver with following blocks.

- **Antenna** could be either shared or separate for RF energy harvester (if present) and receiver/transmitter.
- **Matching network** is to match impedance between antenna and other components (including RF energy harvester (if present) and receiver related blocks).
- **Energy harvester** for harvesting energy from e.g., RF signal, solar, vibration/movement, temperature difference, etc
- **Energy storage** (e.g., capacitor) stores harvested energy from energy harvester.
- **Power management unit (PMU)** manages storing energy to energy storage from energy harvester and supplying power to active component blocks which needs power supply.
- **Digital BB logic** includes functional blocks like encoder, decoder, controller, etc.
- **Memory** can include two types of memory: 1) Non-Volatile Memory (NVM) such as EEPROM for permanently storing device ID, etc, and 2) registers for temporarily keeping any information required for its operation only while energy is available in energy storage.
- **Clock generator** provides required clock signal(s).
- **Reception related blocks**
 - **RF BPF** filter for improving selectivity.
 - Depending on implementation, it may not exist. RAN4 RF requirement (if any, e.g., ACS) and peak power consumption target also need to be considered.
 - **FFS: LNA** for improving signal strength and sensitivity of receiver, if present
 - **RF envelope detector (RF-ED)** detects envelope from RF signal.
 - **BB amplifier** amplifies BB signal to improve signal strength.
 - **BB LPF** can filter out harmonics and high frequency components to improve input signal quality to comparator/ADC.
 - Depending on implementation, it may not exist.
 - **Comparator or N-bit ADC**
- **Transmission related blocks**
 - **Tx Modulator**: baseband bits are modulated according to modulation scheme. This block could be the part of BB logic.
 - **Digital to Analog Converter (DAC)** converts digital signal to analog signal.
 - **Low pass filter** for filtering out undesired signal

- **Mixer** performs up converting baseband signal to RF range.
- **Local oscillator (LO)** for carrier frequency generation
 - FFS: PLL/FLL
- **FFS: Power amplifier (PA)** amplifies tx signal, if present
- Details on transmitter related blocks depends on tx waveform/modulation.



In RAN1 #116bis, it is agreed to further study the LNA in device 2b architecture with RF-ED receiver. In general, LNA is known for being the first block of a radio receiver chain, and it dominates the overall noise figure of the RF frontend, thus the sensitivity. RF-ED consumes low power, but its conversion gain is proportional to its input power, and its noise figure is generally high. It is being demonstrated that LNA can significantly improve the sensitivity of RF-ED architecture from -60dBm to -90dBm range with the receiver frontend power consumption within 400 μ W [2].

Observation 1: LNA is critical if the sensitivity of RF-ED architecture needs to be improved. Specifically, if the sensitivity needs to be lower than -50dBm.

Proposal 1: Support considering LNA as a building block of device 2b

2. Modulation/waveform choices on device architecture

The modulation plays an important role in the specifications of the receiver and hence its power consumption. Coherent communication (e.g. BPSK, OFDM, QAM) requires significantly higher power to demodulate as shown in the figure below [3]. This is because the carrier phase is needed for coherent detection which necessitates using a PLL in the receiver.

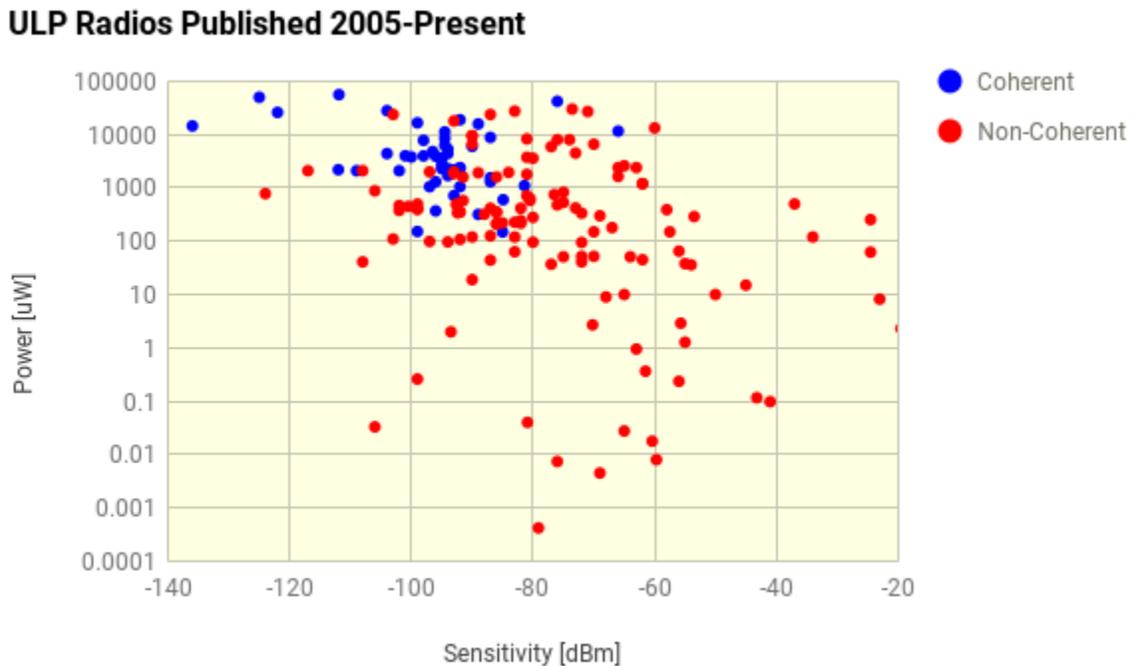


Figure. Power vs. sensitivity for coherent and non-coherent low-power receivers. Available at <https://wics.engin.umich.edu/ultra-low-power-radio-survey/>.

Proposal 2: Support OOK or ASK for the downlink path (gNB to UE) for device 2b

3. Selectivity, multi-band support

The selectivity performance in terms of signal to interference rejection (SIR) of a receiver has a clear power and performance tradeoff. High receiver selectivity is usually achieved with precise RF down conversion using a LO and multiple stages of active filtering along the receiver signal path, which are high power and unfavorable for self-powered operation. Low-power circuit techniques such as high-Q off-chip filtering, automatic gain and comparator offset compensation, PID control, time-domain integrator, and replacing comparator with a high-resolution ADC plus phase encoding have been demonstrated [3]. They can provide around -15dB in-band (SIR) performance for continuous-wave type (CW) interference.

Observation 2: SIR of Device 2b is around -15dB

4. Feasibility of energy storage

There is a wide range of capacitor technologies ranging in volume, capacitance, cost, ESR (equivalent series resistance), and energy density. However, a critical metric for any capacitor that will be used for long-term energy storage is the leakage current, or self-discharge time, of the capacitor.

For example, consider the GW103 supercapacitor from Cap-XX [4]. This capacitor is 1040mF, and supports 2.5V. It also has a leakage current of 1 μ A. For a capacitor, $I = C \cdot dV/dt$. Using this equation, it would take this capacitor 18 days to self-discharge from 2.5V to 1.0V. This is under nominal conditions. At the rated temperature, this would be less. These are also relatively small volumes.

For comparison, an aluminum electrolytic capacitor with a capacitance of 500mF and 6.3V rated voltage has a leakage current of 10.4mA [5]. This would discharge from 6.3V to 1V in 4 minutes. It also has a relatively large volume.

Observation 3: Leakage current of a storage capacitor is critical for energy harvesting devices to sustain operation during periods of no new harvested power. Supercapacitors offer low leakage, high energy density options that are good candidates for A-IoT devices. From full charge, their self-discharge time is 10-20 days.

Another metric to consider is peak current of the capacitor, limited by the ESR. This may only be a consideration for active transmitters with TX power levels >10dBm. Generally, ESR will not impact or limit low-power receivers, or back-scatter devices.

Observation 4: Storage capacitor ESR is critical for active transmitters with TX power levels generally >10dBm.

Cold start of a batteryless device is the most challenging requirement for an energy-harvesting PMU, and will define the minimum harvested power required for the device. Once a device is started up, a switching PMU will become more efficient, and can harvest power from lower input power levels. Startup DC voltages for EH PMUs are on the order of 10's of mV for state-of-the-art. 100's of mV is typical. RF rectifiers can cold start from about -40dBm, but will take many seconds to start up under this condition.

Observation 5: Cold start is the most challenging requirement for an energy-harvesting PMU.

5. Conclusions

Observation 1: LNA is critical if the sensitivity of RF-ED architecture needs to be improved. Specifically, if the sensitivity needs to be lower than -50dBm.

Observation 2: SIR of Device 2b is around -15dB

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Observation 4: Storage capacitor ESR is critical for active transmitters with TX power levels generally >10dBm.

Observation 5: Cold start is the most challenging requirement for an energy-harvesting PMU.

Proposal 1: Support considering LNA as a building block of device 2b

Proposal 2: Support OOK or ASK for the downlink path (gNB to UE) for device 2b

References

[1] RP-240826, Revised SID: Study on solutions for Ambient IoT (Internet of Things) in NR.

[2] C. J. Lukas et al., "15.2 A 2.19 μ W Self-Powered SoC with Integrated Multimodal Energy Harvesting, Dual-Channel up to -92dBm WRX and Energy-Aware Subsystem," 2023 IEEE International Solid-State Circuits Conference (ISSCC), San Francisco, CA, USA, 2023, pp. 238-240.

[3] D. D. Wentzloff, A. Alghaihab and J. Im, "Ultra-Low Power Receivers for IoT Applications: A Review," 2020 IEEE Custom Integrated Circuits Conference (CICC), Boston, MA, USA, 2020, pp. 1-8.

[4]

<https://www.cap-xx.com/wp-content/uploads/datasheets/CAP-XX-GW103-GW203-Datasheet.pdf>

[5] <https://www.cde.com/resources/catalogs/CGS.pdf>