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Low-Noise Amplifier Design for Improvement of Communication Range for Wake-up Receiver Based Wireless Sensor Network Application

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Abstract—The integration of wireless communication, e.g. in real- or quasi-real-time applications, is related to many challenges such as energy consumption, communication range, latency, quality of service, and reliability. The improvement of wireless sensor network performance starts by enhancing the capabilities of each sensor node. While consuming less energy, wake-up receiver (WuRx) nodes have an impact on reducing latency. The solution for sensitivity improvements of sensor nodes, and WuRx in particular, with an energy consumption expense is low-noise amplifier (LNAs) blocks placed in the RF Antenna. This paper presents a comparative study for improving communication range and decreasing the energy consumption of WuRx nodes.

Keywords—Wireless sensor network, wake-up receiver, duty-cycled, low-noise amplifier, envelope detector, range study.

I. Introduction

THE improvement of sensor node capabilities is a requirement for the creation of advanced applications for wireless sensor networks (WSN). High sensitivity range and ultra-low power design are crucial trade-offs for enhancing network coverage and lifetime. The necessity of low energy consumption, good reliability, link quality, and long-range communication imposes certain design criteria at the sensor node level [1]. The implementation of wake-up receiver (WuRx) nodes in the recent field research solves many problems related to power consumption limitations, battery lifetime minimization, and maintaining low latency. The work to improve the sensitivity of those devices is still in process and needs many investigations. One of the hardware solutions to optimize the sensitivity of the receiver is the integration of a low-noise amplifier (LNA) in the front-end antenna of the receiver.

For a close overview of WuRx works, many among them specify the need of amplifying the RF incoming signal to optimize for better sensitivity [2]. The LNA adopted in the tuned-RF architecture of WuRx is the block connected to the antenna, which has the role to boost the signal and enhance the reception of very weak signals. Reference [3] details the integration of the commercialized LNA which is MAX2640, is selected for distance analysis in this paper.

The background of the relationship between the communication range and the receiver sensitivity is issued from (1). The maximum range for communication link R is a function of RF wavelength λ, path loss exponent n, transmission power P_t, total antenna gain G_t, receiver sensitivity P_r, and fading margin F_m. The path loss exponent ranges from $n = 2$ for line-of-sight to $n = 4$ for urban environments. When talking about the indoor application, n is hard to be estimated or calculated due to the difference in obstacles material, thickness, and ability of shadowing the transmitted signal.

$$R = \frac{\lambda}{4\pi}\sqrt[n]{\frac{P_t G_t}{P_r F_m}} \tag{1}$$

In wireless communication, the shadowing effect of a signal refers to the level of the signal power attenuation. It is related to many physical phenomena present in real environments as the absorption, reflection, and diffraction of the electromagnetic waves when facing the obstruction material. In the next section, different simulations for the proposed indoor application with a variation of the attenuation level will be carried out in order to obtain different result analyses for a generic indoor algorithm.

II. Related Works

A. Energy Efficiency and Communication Range

The review [4] accentuates that the main problem of coverage is caused mainly by hardware limitations and the number of deployed nodes in the network.

The authors in [5] deal with the challenges of coverage in WSN related to the type of application. Two cases were distinguished: event-driven processing or on-demand system. With event-driven processing, an event is detected and reported to the base station. With on-demand systems, the base stations initiate the request and the receiving sensor node responds. Here the cost issue is well reduced because the deployment of nodes is done manually and on demand also.

The work presented in [6] deals with the problem of coverage area within the energy-aware consideration. The authors proposed a genetic algorithm for extending the lifetime and optimizing the coverage of the network.

B. Low-Noise Amplifiers for Wake-Up Receivers for Improving Sensitivity and Energy Consumption

Within the recent investigations in the radio on-demand communication systems is the implementation of WuRxs which are ultra-low power sensor nodes [7]. The cited paper

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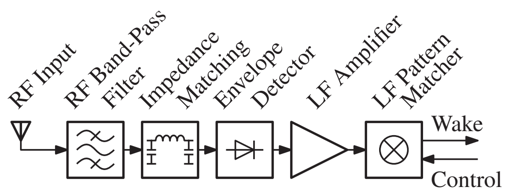
illustrates the relationship between enhancing the sensitivity while remaining in the micro-power budget. The WuRx was improved to a sensitivity of $-60\,\mathrm{dBm}$, while consuming only $2.53\,\mu\mathrm{A}$. For a transmission power of $10\,\mathrm{dBm}$, the communication range in the line-of-sight environment is nearly $82\,\mathrm{m}$. The improvement of the sensitivity was achieved by the proposed power-gated design. The LF amplifier is only activated whenever a carrier is detected on the channel. The LF amplifier allows high performance while remaining low energy consumption.

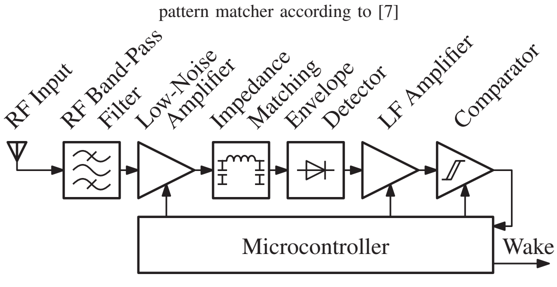
A different approach of enhancing the sensitivities of the WuRx is the integration of an LNA. LNAs come typically with a high supply current in the range of $1\,\mathrm{mA}$. The WuRx must be operated duty-cycled to ensure a low average energy consumption. Recent works introducing an LNA are [2, 3].

Fig. 1 shows the common building blocks of different hardware architectures in the state of the art (SoA). Fig. 1a describes an ultra-low power WuRx constrained for real-time application in WSNs. The architecture is based on a passive envelope detector that transfers the RF signal to LF signal A low-pass filter to adapt to the operating frequency of the LF pattern matcher, the AS3933. The AS3933 is able in receiving a wake-up pattern in the LF range of $15-150\,\mathrm{kHz}$. The AS3933 has a voltage of sensitivity that depends on many factors.

Fig. 1b describes a tuned RF architecture with improved sensitivity. The RF signals are characterized by low amplitude and high noise. The LNA amplifies the signal severely, resulting in an increased WuRx sensitivity. The proposed architecture is tuned between active and inactive periods as a result it is called duty-cycled WuRx.



(a) Building blocks of wake-up receiver based on passive envelope detector and LF pattern matcher according to [7]



(b) Building blocks of wake-up receiver based on low-noise amplifier according to [3]

Fig. 1 Building blocks of different wake-up receiver architectures

In [8], a duty-cycled based WuRx was implemented using an uncertain-IF architecture, designed specifically for the ultra-low power wake-up application. The design hardware reach $-72\,\mathrm{dBm}$ sensitivity with $5\,\mu\mathrm{W}$ energy consumption. The power reduction and the sensitivity level are maintained using an LNA built in a combination of a CMOS, local oscillator, and RF micro-electromechanical resonator technology.

C. Improvement of Communication Range for Indoor Application

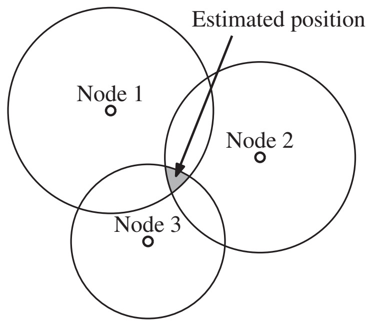


Fig. 2 Cross coverage area for trilateration method for localization

Indoor localization application is one of the most interesting applications in the recent research scope [9]. An improved trilateration localization method is introduced in [10] with minimum uncertainty on the localization accuracy. The authors propose an optimized selection algorithm for distance estimation and a probabilistic discussion about the obtained localization equations. The used method is based on only software solution and the hardware implementation could deliver plenty of problems as the attenuation of the data packet.

In [11], an indoor localization application based WuRx is introduced for the energy-aware constraint. The main role is such an application that is dedicated to the anchor nodes, which have the known positions and have the role to identify the location of target nodes. The distance between nodes should be accurate to ensure the right application of trilateration method to locate the desired node. Also, the anchor nodes should be powerful nodes from the energy efficiency point of view and good communication range.

Environmental conditions such as the presence of obstacles [12] or temperature and humidity have the ability to degrade the performance of the link quality [13]. To improve link communication, it is mandatory to focus on the receiver sensitivity better than increasing the transmit power so resulting in an increase of power consumption. The scenario proposed in this paper is to build an observation for the same application based on WuRx nodes with the improvement of receiver sensitivity using the integration of a low noise amplifier in the receiver front-end.

In [14], the indoor localization is based on data collection training samples. Nine calibration nodes were placed in a room of $9\times9\,\mathrm{m}$. The anchors sends the collected data to a base station where an machine learning algorithm based on an artificial neural network is implemented to estimate the distance. This scenario is WuRx-based that make it on demand application. Sensors send data when they are requested from the gateway. They are distributed on the whole building, which improves both application range and energy consumption.

III. Simulation of Indoor Localization Application with Wake-Up Receiver Nodes with Different Sensitivity Levels

A. Proposed Scenario

As described in the previous sections, the purpose of this paper is the examination of the sensitivity level of two different WuRx designs. The first WuRx achieves −60 dBm sensitivity and the WuRx-based LNA achieves −80 dBm. The enhancement of sensitivity will prove the improvement of communication range according to (1).

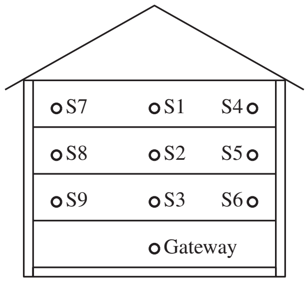


Fig. 3 Cross-sectional view of the proposed scenario with a transmitter node placed in the earth ground and three wake-up nodes in three different floors (S1–S9)

For an accurate comparison, the evaluation will be based on an adequate scenario for concluding an enhancement of certain performances of WSN. The chosen application is the indoor localization scenario inspired by the work of [11]. Starting from the application of the scenario in one laboratory area with a dimension of $4 \times 5 \times 5$ m to an extension of the same scenario on different floors of the same building. Fig. 3 describes the proposed scenario that will be simulated and emulated using both designed WuRx hardware. Each floor is equipped with three WuRx nodes. The floor separation is composed of brick material, which has the ability also to decrease the transmit power and degrade the quality of data transmission.

Running simulation and emulation with taking into consideration such disturbing factors will lead to a good conclusion for optimization of communication range. This will improve many WSN aspects such as the huge decrease in the power consumption and the number of deployed nodes.

B. Simulation of the Proposed Scenario on OMNeT++

All WSN applications should include a conception and design phase followed by a testing phase [15]. The simulation phase helps both designers and researchers to get general proof of the network behavior. An evaluation between the most popular WSN simulators such as OMNeT++, NS2, and TOSSIM had been made. The OMNeT++ simulator has been addressed due to its various framework, models, the large library of protocols and prototypes included hierarchically as different modules.

Fig. 4 is a representation taken from the graphical interface of OMNeT++. The floor separation into the building is taken into consideration in the simulation, the defined ideal obstacle module in OMNeT++ that attenuate signals passing through. Such nature of attenuator has the ability to decrease the emit signal literally as in real-life conditions. The gateway

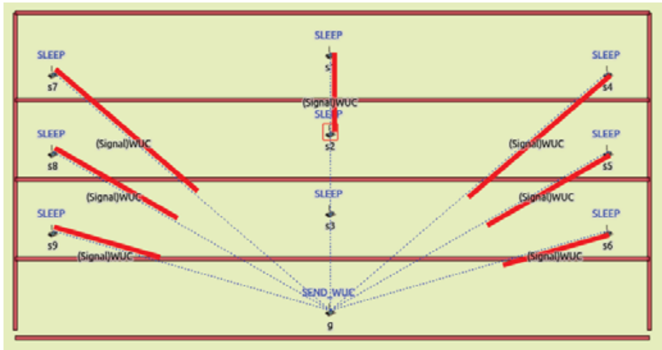


Fig. 4 Simulation of wake-up peer-to-peer communication between a transmitter node placed in the earth ground and three wake-up nodes on three different floors

is responsible for data transmission is configured at 11 dBm transmission power at 868 MHz carrier frequency.

The floors are separated each with 4 m height. Three receivers are placed on each floor for the imitation of anchors role.

The used receiver sensor nodes in the simulation are considered as WuRx nodes, with the ability to consume ultra-low power during the reception of the wake-up packet (WuPt).

The simulation was elaborated on three sensitivity levels −60 dBm, −70 dBm, and −80 dBm for the prediction of behaviour of the two different WuRx nodes. The simulation results are extracted in a bar chart as shown in Fig. 5. For each sensitivity level, the node receiving data from the transmitter shows the amount of received data.

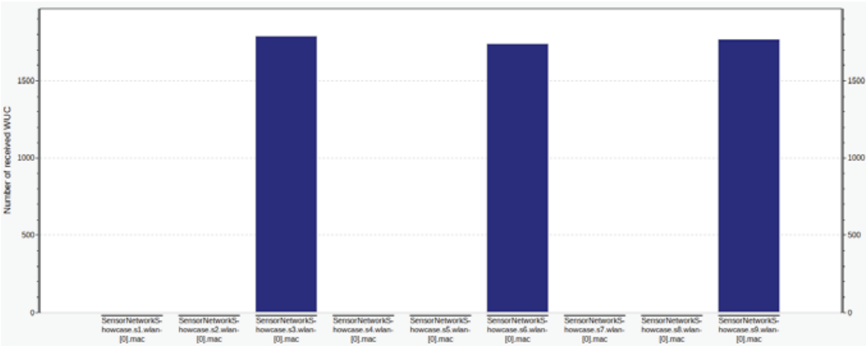
For the simulation of WuRx with a sensitivity of −60 dBm, only nodes placed on the first floor (S3, S6, S9) are receiving WuPt. When increasing the sensitivity with a 10 dB gain, the reception of data on the 2nd floor turned to receiving mode also. The nodes (S2, S5, S8) were able to detect the incoming signal from the transmit node. Finally, using the enhanced sensitivity of the LNA-based WuRx, the sensitivity of −80 dBm allows the reception of the WuPt to the WuRx nodes placed on the third floor. With the presence of three parallel floors made of brick material, the capabilities of LNA-based WuRx are proved from the simulation point of view. In a later stage, the emulation of the same scenario using hardware components will confirm the powerful challenges of the designed WuRx.

IV. Proof of Concept

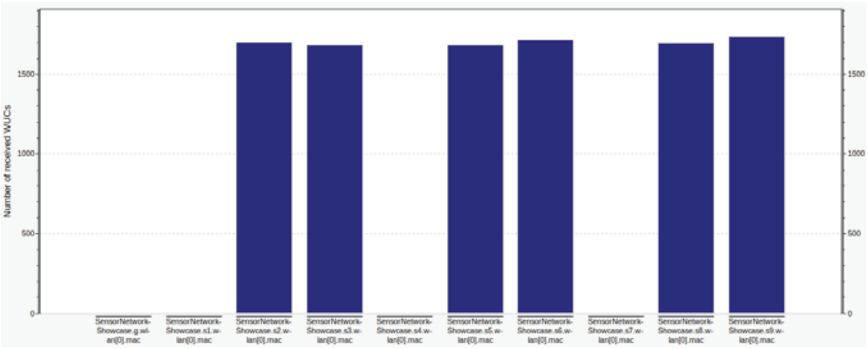
A. Hardware Setup

According to Fig. 1, the different WuRx architectures have been already designed and tested. The implementation of both hardware PCBs are well detailed in [3, 16]. Those two boards will be used for the emulation of the proposed scenario in order to extract the improved communication range performance of WuRx when integrating the LNA into the receiver node.

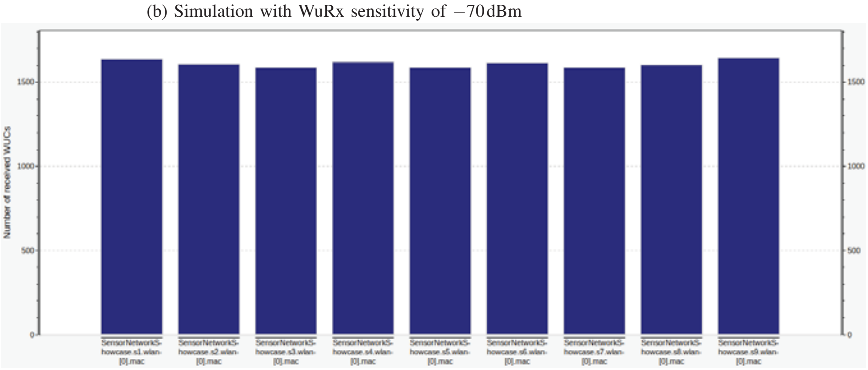
Fig. 6 shows both implemented hardware printed circuit boards (PCB) and the measurement of the sensitivity curve. The first WuRx architecture (Fig. 6a) is based AS3933 [16] and limited with sensitivity of envelope detector which is



(a) Simulation with WuRx sensitivity of −60 dBm



(b) Simulation with WuRx sensitivity of −70 dBm



(c) Simulation with WuRx sensitivity of −80 dBm

Fig. 5 Simulation results for reception of wake-up packets for WuRx nodes with different sensitivity levels

−60 dBm as shown in the PER measurement (Fig. 6c). The second implemented hardware is the WuRx board based on a duty-cycled approach with the integration of LNA (6b) shows in the PER measurement test sensitivity of −80 dBm (Fig. 6d).

Same as in the simulation phase, the hardware measurements were carried out on the floor of 3 roofs separated with 4 m height as described in Section III-A. The transmitter node was installed on the earth's ground floor and generated to send a WuPt with 11 dBm power at 868 Mhz. The receiver nodes were detecting the reception of data and send back an acknowledgment to the transmitter. The distance between two communicating nodes was predicted with consideration of the 4 m height between each two floors.

B. Measurement Results

As described earlier, the emulation phase or simulating with real hardware components is as important for performance evaluation [17]. A simulator is software-based that model the real environment and the physical testing supports accurate results and discussions. Only the gateway was fixed in the laboratory on the earth ground floor, and the WuRx nodes were moved all along the upper floors in order to figure out the sensitivity limit of both WuRx architectures.

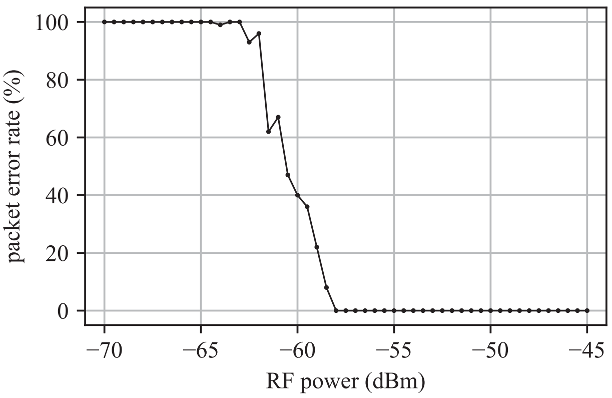
The observed results in Table I show that the WuRx based on AS3933 with the limited sensitivity can receive WuPt only on the first floor with a maximum distance of 35 m. Otherwise, the improved sensitivity WuRx shows an impressive comportment, that the node continues receiving the data until the third floor, end of the corridor. Reaching a distance of 75 m with three parallel roofs of brick material and the presence of many doors and obstacles.

C. Discussion

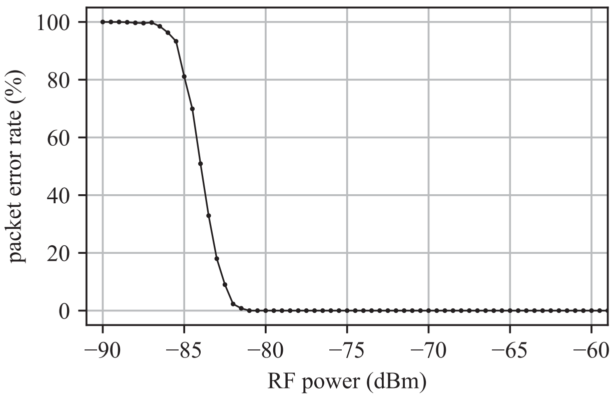
The simulation and emulation results also proved the theoretical aspects behind the implementation of LNA for

(a) Wake-up receiver prototype based on LF pattern matcher

(b) Wake-up receiver prototype based on low-noise amplifiers



(c) Wake-up receiver sensitivity curve based on LF pattern matcher



(d) Wake-up receiver sensitivity curve based on low-noise amplifiers

Fig. 6 Wake-up receiver photographs and sensitivity curves

TABLE I
COMPARISON OF WSN SIMULATORS USING THE PROPOSED CRITERIA

	Communication range between gateway and WuRx (m)		
WuRx sensitivity	1st floor	2nd floor	3rd floor
-60 dBm	35	no reception	no reception
-80 dBm	70	72	75

the receiver nodes. The integration of LNA into the WuRx node enhances the sensitivity of the receiver while keeping a low power consumption for the overall circuit, with the ability to introduce those powerful sensor nodes into different indoor applications. The treated scenario of indoor localization application is a good example for running the previous scenario with improved sensitivity anchors for better coverage and connectivity of the fixed position nodes. Many other indoor applications could introduce the WuRx nodes based LNA for dealing with problems of indoor harsh environmental conditions that attenuate the signal and lead in many cases to loss of data.

V. CONCLUSION

In recent WSN applications, the focus of researchers concentrate mainly on energy-aware systems for extending the network lifetime. Also, indoor wireless communication faces a lot of challenges related essentially to the disturbance of obstacles with certain materials, which demand an observation for optimization coverage and connectivity. Deploying a huge number of sensor nodes could be a solution for the coverage problem, but will increase the cost level of the application. To balance cost criteria and solve coverage problems, it is important to investigate the communication range between the sensor nodes while keeping the minimum number of deployed nodes. This paper presents a comparative study for two different architectures of wake-up receivers, with the integration of LNA into the sensor node design, the sensitivity is increased and the communication range is improved.

Finally, the solution for an energy-aware, low-cost, and wide-range connected system is the implementation of WuRx-based LNA in indoor WSN applications.

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