Sensors & Transducers Journal, Vol. 118, Issue 7, July 2010, pp. 110-121

Sensors & Transducers

ISSN 1726-5479

http://www.sensorsportal.com

ZigBee Radio with External Power Amplifier and Low-Noise Amplifier

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Received: 25 February 2010 /Accepted: 24 July 2010 /Published: 31 July 2010

Abstract: This paper presents the performance study of a ZigBee module with both an external power amplifier and a low-noise amplifier, measured in outdoor and indoor environments, respectively. Our previous study has already shown that the indoor campus environment such as walls and floors would reduce the radio link range drastically and the packet error rate increased. In this study, both an external power amplifier and a low-noise amplifier have been added to a ZigBee module to increase both the transmitter power and receiver sensitivity. It is shown that with an external power amplifier and a low-noise amplifier the outdoor radio range can reach up to 1600 m with a negligible packet error rate compared to 144 m without any external amplifier for point-to-point radio connection. Thus, by increasing both the transmitter power and receiver sensitivity the radio range can be increased significantly. The power consumption issue with the added amplifiers is studied as well, indicating that the module can still be battery driven with a battery lifetime of about 9 years at a normal sampling rate to the sensor. *Copyright © 2010 IFSA.*

Keywords: ZigBee, Power amplifier, Low-noise amplifier, Radio range

1. Introduction

ZigBee is an open and global standard, based on the IEEE 802.15.4 specification, for wireless low-speed data communication and sensor networking. The first version was ratified in December 2004 by the ZigBee Alliance and was latest updated in 2007. The aim of the standard is for low-cost, low power and very long battery lifetime applications [1]-[4].

Previously, we have shown that with our own-developed ZigBee modules the outdoor link can reach 144 m having negligible packet error rate (PER). However, the indoor walls and floors affect the radio signal resulting in only a few meters of the radio range with increased packet error rate [5]. With an added external low-noise amplifier (LNA) to increase the receiver sensitivity the outdoor range can reach up to 403 m. To further increase the outdoor radio range, both an external power amplifier (PA) and a low-noise amplifier have been added to a standard ZigBee module. The results show that the outdoor range can then be increased to 1600 m and the indoor radio range is also significantly increased.

2. Network Topology

The ZigBee network supports star, tree and mesh network topologies, as illustrated in Fig. 1. Depending on the environment, different network topologies can be used with the cost of network complexity, reliability and signal latency. The star network is the simplest topology with point-to-point connection and has the lowest signal latency. Since the end devices communicate directly with the coordinator, the risk for network failure is kept to the minimum. The network fails only when the coordinator fails, but the wireless network coverage is limited by the radio range between the coordinator and the end device. The wireless network coverage can be extended with a so-called tree or mesh topology, by adding routers between the end devices and the coordinator. The tree topology still uses point-to-point communication between the devices, which makes the connection predictable and the complexity of the network is moderate. The drawback is that if one of the routers fails, all the devices which have a signal path to the coordinator via that router will also be disconnected from the network. A mesh network can be used to avoid this problem by self-repair of the network, i.e., by reconnect of the disconnected devices to another neighboring router and rejoin to the network. This self-healing function provided by the mesh topology provides robustness to the network, but at the cost of increased complexity and latency time. However, for applications where low latency time is required but the star topology cannot provide enough range, adding extra amplifiers to increase the radio range (within the regulation limits) might be a better solution than adding routers between the communicating devices. Adding extra amplifiers can extend the radio range, i.e., increase the wireless radio coverage. In the case of tree and mesh network topologies, the added extra range for the routers result in fewer routers needed in a network to cover a large area [6].

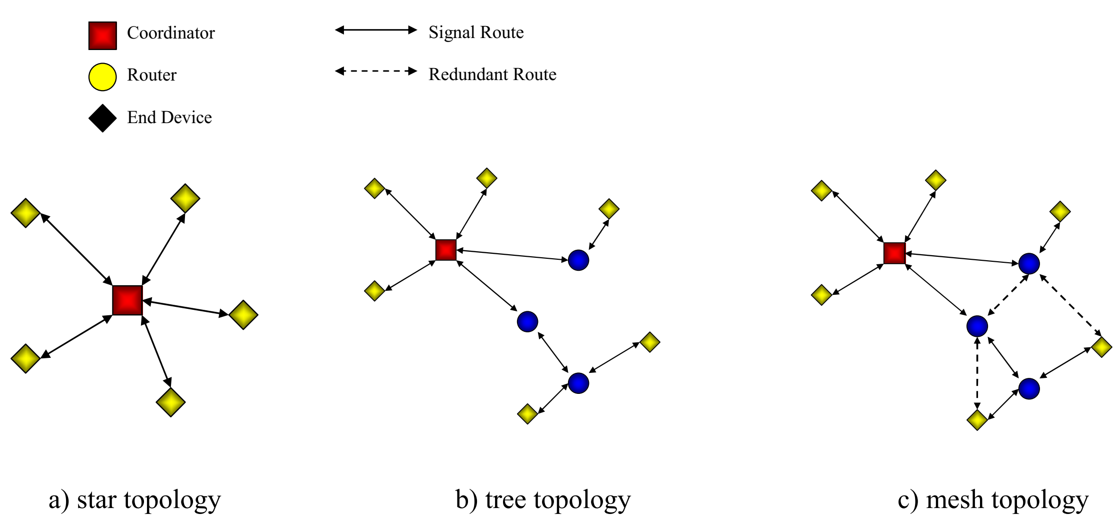


Fig. 1. Illustration of different network topologies.

3. Radio Range and Receiver Sensitivity

To increase the wireless transmission range, Friis transmission formula shown in (1) is normally used for analysis of point-to-point radio transmission.

$$P_r = G_t G_r \left(\frac{\lambda}{4\pi R} \right)^2 P_t, \tag{1}$$

where P_t, P_r, G_t, G_r, λ and R are transmit power, receive power, antenna gain of the transmitter, antenna gain of the receiver, radio wavelength and the distance between the transmitter and receiver, respectively [7]. Equation (1) shows that the easiest way to increase the wireless transmission range is to increase the transmit power and to increase the transmitter and receiver antenna gains. However, for omni-directional data transmission, the value for G_t and G_r is maximum equal to one. Fig. 2 illustrates P_r at the receiver with respect to the distance to the transmitter having different power outputs, according to (1) when both G_t and G_r is assumed to be 1.

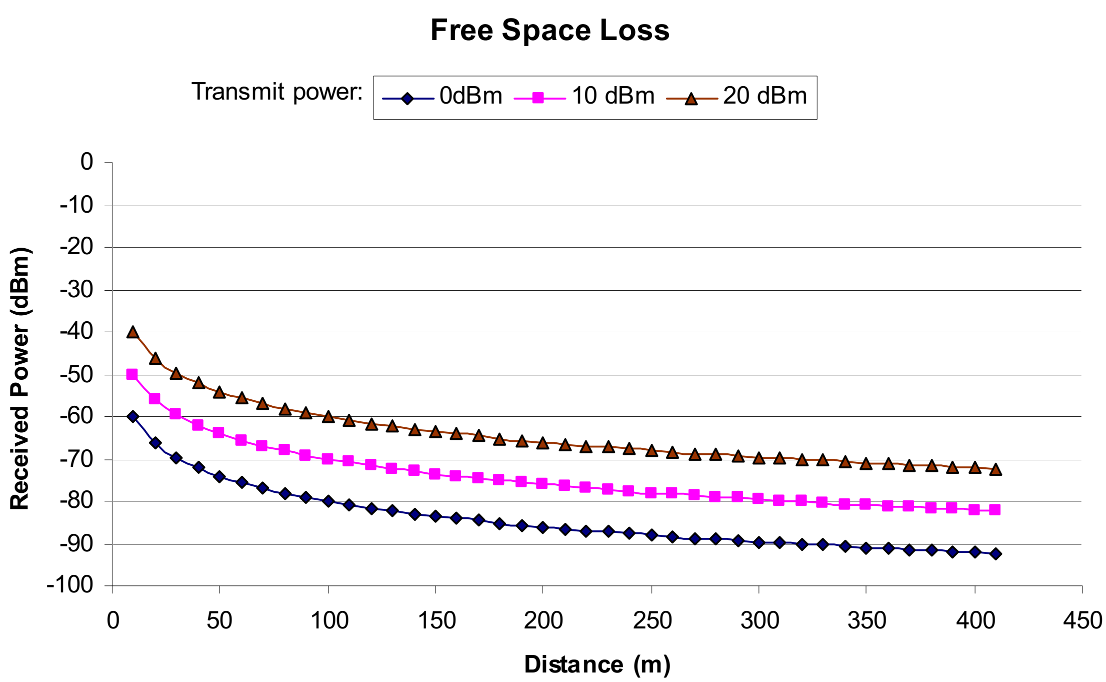


Fig. 2. Received power with respect to the range between the transmitter and receiver.

When P_r drops below the minimum detectable signal power the receiver cannot process the data properly and the packet error rate will increase. Therefore, another approach to extend the wireless radio range is to improve the receiver sensitivity of radio modules. However, when the desired signal and undesired noise are applied to an input of a noiseless network, both the signal and noise are attenuated or amplified by the same factor, so that the signal to noise ratio (SNR) is unchanged. Therefore, just adding an amplifier to the receiver would not help increasing the wireless transmitting range if the receiver sensitivity and noise figure (NF) are not carefully considered. The equation below shows the minimum signal power that a system can detect with the minimum SNR [8].

$$P_{in.min}\,[\text{dB}] = -174\ [\text{dBm/Hz}] + 10 \log B\ [\text{dB}] + SNR_{min}\ [\text{dB}] + NF_{tot}\,[\text{dB}], \tag{2}$$

where $P_{in.min}$ is the minimum detectable power with SNR_{min} required for a certain data rate and modulation order, B and NF are bandwidth and noise figure, respectively. From (2), the first three terms are predefined parameters by the thermal noise and standard, which cannot be changed. Consequently, the only term left to improve the receiver sensitivity is NF_{tot}.

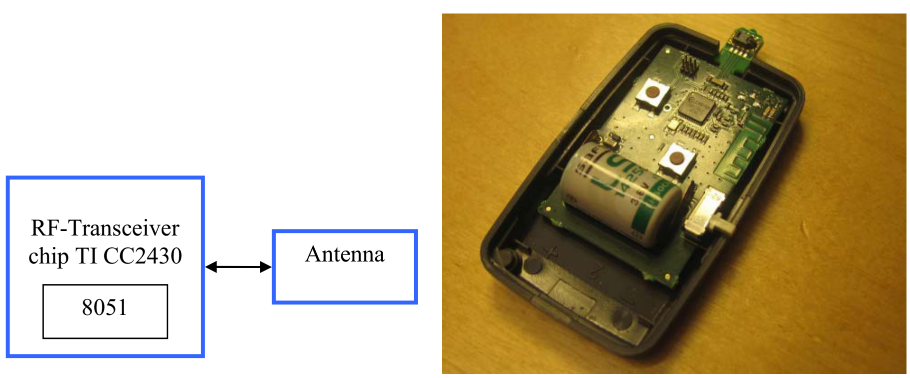
Consider a cascade of amplifier, the total noise factor (NF_{tot}) of the system can be expressed with (3) [8]-[10].

$$NF_{tot} = NF_1 + \frac{NF_2 - 1}{G_1} + \frac{NF_3 - 1}{G_1 G_2} + \cdots, \tag{3}$$

where NF_1, NF_2 and NF_3 are the noise factor of the first, second and third stages of amplifier. G_1 and G_2 are the power gain from the first and second stages of components, respectively. As the equation shows, the noise figure of a system is dominated in the first few stages. Thus, to maximize the wireless transmission range, it is important that the first stage of the receiver has a low NF but high gain (G_1). This indicates that to add a high quality LNA to the receiver will increase the radio range even though the transmitter keeps the same output transmit power.

4. ZigBee Modules

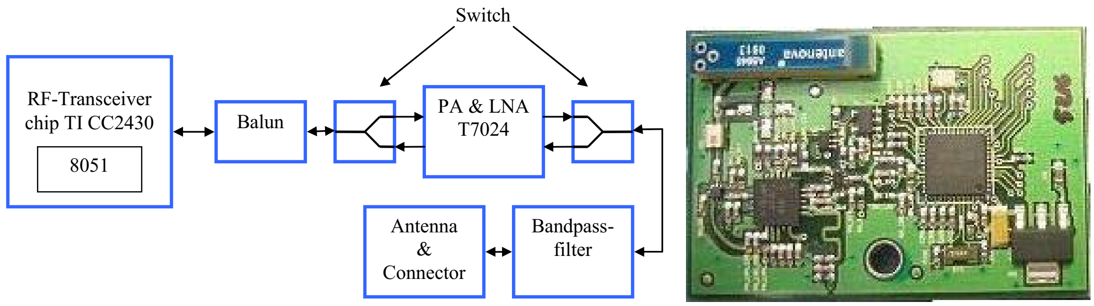
Fig. 3 shows a block diagram and photograph of our own-developed ZigBee sensor module. The RF part utilizes the Texas Instruments (TI) CC2430 system-on-chip solution for IEEE 802.15.4 and ZigBee applications. The TI CC2430 RF transceiver includes an industrial-standard 8051 microcontroller unit for signal processing [11]. The photograph shows that the module has various push buttons and a sensor head connected to the transceiver. In this paper, only the radio-part of the module is evaluated while the other parts are not concerned.



a) Block diagram   b) Photo of the module

Fig. 3. ZigBee module as End Device powered with a 3.6 V lithium battery.

Fig. 4 shows a block diagram and a photograph of the ZigBee module with external PA and LNA. The PA implemented in Atmel T7024 [12] is a three stage amplifier with an analog input control (ramp) for control of the signal output power. The same control signal can also be used to switch the PA to the power-down (standby) mode when the module is not transmitting any data over the air. The PA has a maximum gain of 23 dB. Typical noise figure (NF) of the LNA is 2.1 dB at the frequency range between 2.4 and 2.5 GHz. Two extra switches are added to switch the module between transmit (PA on, LNA off) and receive (PA off, LNA on) modes [12].



a) Block diagram b) Photo of the module

Fig. 4. ZigBee module with external power amplifier and low-noise amplifier.

5. Current Consumption Measurement Set-up

The current consumption establishment and description list are shown in Fig. 5 and Table 1, respectively. This test is performed to verify the current consumption of the ZigBee module with external PA and LNA. The measurement is based on the measurement method presented in the Application Note AN053 [13] from TI. The current consumption of the module is calculated by measuring the voltage drop over the resistor and divided the result by the resistance of the resistor used during the measurement. Since the ZigBee module with external PA and LNA used does not have any sensor mounted on, special software was developed to imitate the sensor working sequence. This is done to make the result comparable with the results presented in [3].

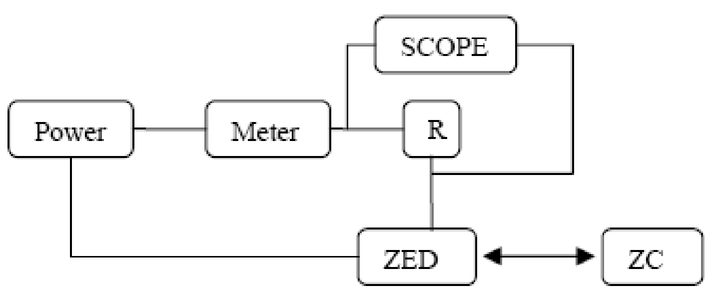


Fig. 5. Power consumption test establishment, see block definitions in Table I.

Table 1. Equipment list used for current consumption measurement.

Symbol	Description	Type
Power	Power supply	Agilent E38833A
Meter	Current meter	HP34401A
R	Resistor	10 Ω
Scope	Oscilloscope	Agilent 54612D
ZED	End Device	ZigBee module under test
ZC	Coordinator	ZigBee module (used to establish required communications)

The software used during the measurement is a real case implementation of a wireless sensor network used in a research project [14]. A typical ZigBee module will have the following operation modes:

- Sensing data
- Send data request
- Status check
- Send sensor data

The current consumption for each of these operations is captured with the oscilloscope and calculated accordingly. Since the interval of the above four operations can be configured, the power consumption of the module and the battery lifetime can be calculated according to different interval configurations.

6. Software

The ZigBee system uses the direct sequence spread spectrum RF modulation format defined in IEEE 802.15.4. The data sending over air is in the form of packets and frames, which includes both the synchronization word and cyclic redundancy check (CRC) in addition to the payload data. The range and packet error rate (PER) measurements are performed for point-to-point transmission at both outdoor and indoor environments. The software used is self-developed; it can set the modules into transmitting or receiving mode. While the module is set into the transmitting mode, the module will send indexed data packages at a pre-selected channel and packet rate. The module which is set into the receiver mode will only try to receive the data packets sent from the transmitter in a pre-selected channel. After receiving 1000 data packets, the PER value and the received power at the TI CC2430 RF pins are calculated for further printout on a HyperTerminal. The PER value is calculated using (1).

$$PER = \frac{Lost\_packets + CRC\_errors}{Transmitted\_packets} * 100 \quad (\%), \tag{1}$$

A data packet is valid only if it was successfully received and passed the CRC. The received power is calculated by offsetting the received signal strength indication (RSSI) value at -45 dB as shown in (2).

$$P = RSSI + RSSI\_offset \quad (dBm), \tag{2}$$

where *P* is the received power at the RF pin on the TI CC2430 chip and *RSSI_OFFSET* is equal to -45 dB.

7. Results

Measurements are done in terms of the performance of PA and LNA, the radio range in the outdoor and indoor environments and the power consumption. All the indoor distances are measured using the laser distance meter Leica Disto D5 [15].

7.1. PA Performance

The PA is designed to have a nominal input power of 0 dBm, which is the signal output from the TI CC2430 chip if using the default setting in the Z-stack software provided by Texas Instrument [16]. Table 2 lists the specification of the amplifier chip Atmel, Fig. 6 shows the measurement result of a modulated signal from the ZigBee module with an external PA (red/dark line) and from the standard ZigBee module (green/light line). The spectrum measurement is done at the center frequency of

2.48 GHz with 10 MHz span, in which the ZigBee channel 26 is located. The resolution bandwidth and video bandwidth are both selected to be 100 kHz. The result shows that the amplification delivered by the PA is 18 dB, which is lower than the specified maximum gain 23 dB but gives better signal-to-noise ratio and linearity compare to those at the maximum gain.

Table 2. Characteristic of the power amplifier [12].

Parameter	Typical Value
Frequency range	2.4 – 2.5 GHz
Current consumption, I_s	165 mA
Standby current	10 µA
Maximum power gain	23 dB

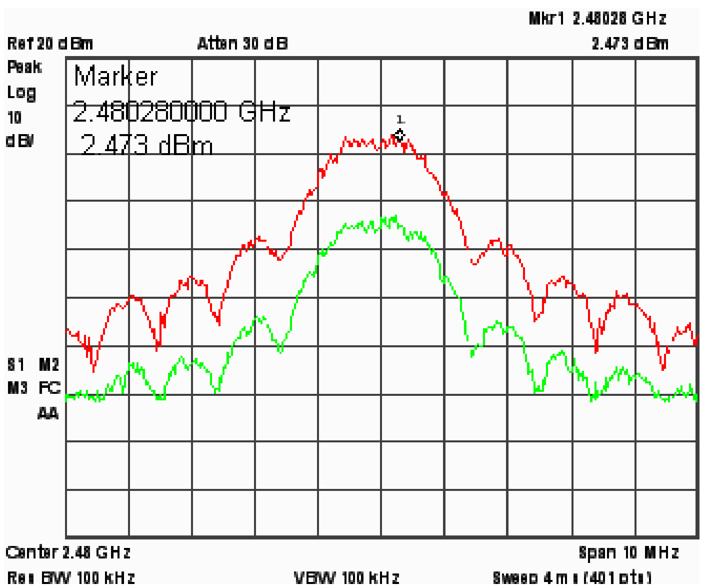


Fig. 6. Modulated signal output from modules with (red/dark line) and without (green/light line) external PA.

7.2. LNA Performance

The LNA implementation in Atmel T7024 is a two-stage amplifier with an internal matching at 2.45 GHz. Table 3 lists the specification of the LNA from Atmel and Fig. 7 shows the measured transfer function.

Table 3. Characteristic of the low-noise amplifier.

Parameter	Typical Value
Current consumption, I_s	9 mA
Standby current	1 µA
Power gain	16 dB
Noise figure	2.1 dB
Gain compression	-7 dBm
3^{rd}-order IIP	-14 dBm

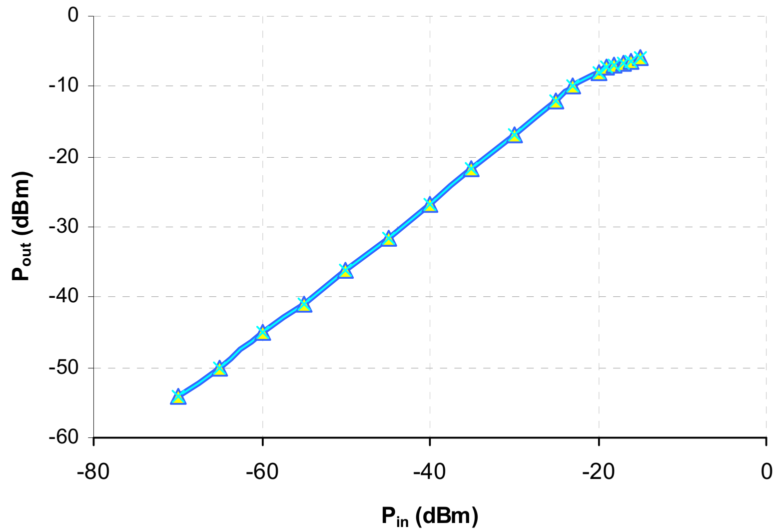


Fig. 7. Measured transfer function of the external LNA used on the ZigBee module.

7.3. Outdoor Radio Range

The outdoor line-of-sight (LOS) measurement is performed both in an open field called Himelstalund and an old abandoned airport in Norrköping, Sweden. Both the terrains are pretty even with minimum obstruction and the measurement was performed during the time when no human activity was present in the field. To avoid other proximity effects such as human bodies, the modules were mounted on a wooden stand about three meters above the ground when the measurement is ongoing. The measurement was performed by mounting the transmitter at one fixed position and the receiver was moved away until PER starts to increase. Thereafter, another receiver was taken and the same test was repeated to get three results from three different modules. Although the external influence was kept to the minimum, the radio signal reflection by the ground cannot be avoided. However, it is shown that the outdoor LOS radio range of 1600 m can be achieved with 0 % PER, when both the external PA and LNA are added to the transmitter and receiver. Fig 8 and Table 4 show the maximum range for different modules used.

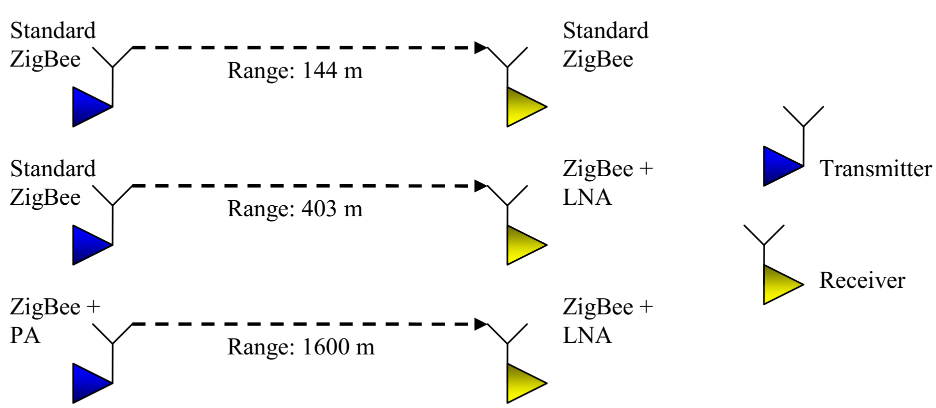


Fig. 8. Outdoor LOS radio range using different modules.

Table 4. Outdoor radio range with line-of-sight.

Device	Distance (m)
Standard ZigBee module	144
ZigBee module with LNA activated only	403
ZigBee module with both PA and LNA	1600

7.4. Indoor Radio Range

This measurement is made to evaluate the radio indoor performance of the ZigBee module with both the external PA and LNA. The modules are mounted at a height of 1 m above the floor when the measurements were performed.

The measurement was done in a campus environment where the walls are made of light materials with wood and plaster. The frame and floor of the building are made of steel and concrete. The classrooms have all large windows to the outside and small windows near the ceiling to the corridor. The whole campus environment is covered with the WLAN 802.11b/g wireless connection which cannot be deactivated during the measurement. The test was done after office hour to get as little radio activity as possible in the air, but the radio traffic was never quiet.

Fig. 9 shows the results of indoor range measurement using both the standard ZigBee module and the ZigBee module with external PA and LNA. The red square indicates where the coordinator (receiver) is located when the measurements were performed. The ZigBee module with external PA and LNA were used as the coordinator for all the tests. However, since the coordinator is used as a receiver the PA on the module is set to the standby mode. Yellow diamond marks in Fig. 9 are positions where the PAR measurement shows 0 % when using the standard ZigBee module and the blue circles are at the position where PAR measurement shows 0 % when using the module with external PA and LNA. The transmitter was placed for measurement on both the fifth and sixth floors, to check how walls and floors affect the radio. All the measurements done are point-to-point connection to the coordinator, which is the same connection scenario as in a star network topology. Also it is the place where the closest router should be located if one wants to use a router to extend the radio range, like in tree and mesh network topologies. The yellow diamond located in Floor 5 is placed vertically under the coordinator, which is located on Floor 6. A ZigBee module with both external PA and LNA was also placed vertically under coordinator but on Floor 4 with successful connection and having 0 % PER, but is not illustrated in the figures.

It is clear form Fig. 9, that the added PA and LNA have improved the radio performance significantly for indoor radio communication compare to modules without external amplifiers. The module with external PA and LNA gives longer indoor range on the same floor and even limited coverage at the adjacent floor. Thus, a module with PA and LNA can be placed in the second adjacent floor operating as a router to extend the wireless network coverage.

Note that the coordinator module has an external LNA so the indoor range has been improved even with the standard module when compared to our previous results [5].

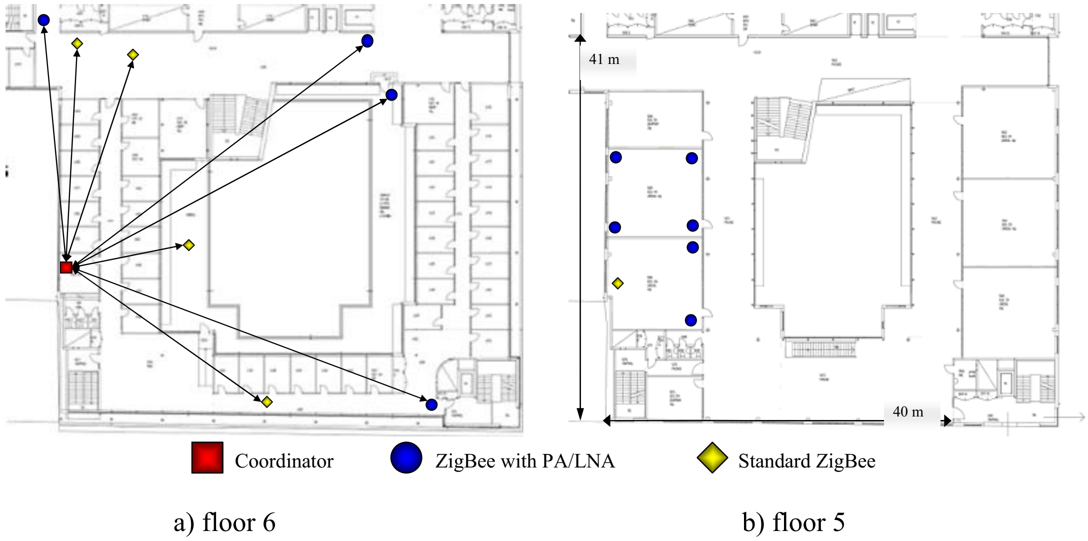


Fig. 9. Measurement setup for ZigBee module with external PA and LNA.

7.5. Power Consumption

Fig. 10 and Table 5 show the current consumption during the data request sequence mode. The numbers listed in Fig. 10 correspond to those in Table 5. As seen in Table 5, the module with external amplifiers increases the current consumption during the power saving, receiving (Rx) and transmitting (Tx) modes in comparison with a standard ZigBee module.

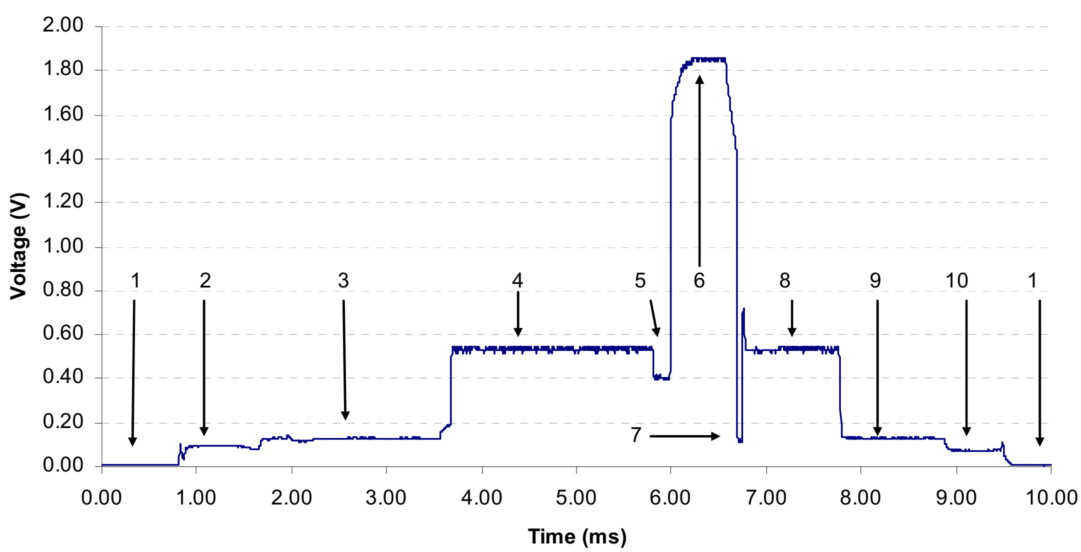


Fig. 10. Voltage drop over the serial resistor.

The external amplifiers on the module were designed such that the PA activates only when transmitting data and the LNA activates only when receiving data; else both of the amplifiers were in the standby mode. It is seen that a battery-powered End Device with external PA and LNA is applicable on a wireless sensor network as shown in Table 6. With two different sampling intervals, a battery lifetime of 625 and 3294 days is obtained, respectively.

Table 5. Power consumption summary for data request sequence.

Interval	Description	Standard		With PA and LNA	
		Current (mA)	Duration (ms)	Current (mA)	Duration (ms)
1	Power saving mode	0.0008	-	0.64	-
2	Start-up @ 16 MHz	11.0	0.92	9.5	0.81
3	MCU @ 32 MHz	14.7	1.86	13.1	2.11
4	Rx	34.0	1.92	54.8	2.00
5	Rx –> Tx	22.5	0.20	39.1	0.21
6	Tx	31.6	0.56	184.5	0.63
7	Tx –> Rx	24.6	0.12	11.0	0.08
8	Rx	34.0	1.18	54.8	1.02
9	Packet processing @ 32 MHz	14.7	1.19	12.8	1.22
10	Processing sleep @ 16 MHz	9.2	0.64	7.4	0.53
	Total	**191.4 mA*mS**	**8.59**	**345.7 mA*mS**	**8.61**

Table 6. Battery lifetime comparison for modules with and without extra external amplifiers.

Module Operation	Interval	Interval
Data request	Every 1 min	Every 20 min
Sensor sensing	Every 6 min	Every 30 min
Sending data	Every 30 min	Every 60 min
Status report	Every 60 min	Every 60 min
Battery lifetime of ZigBee module **without** external amplifier	658 days	3383 days
Battery lifetime of ZigBee module **with** external PA/LNA	625 days	3294 days

Table 7 shows the total current consumption in different operation modes. Clearly the sensor sensing operation is the most current consuming mode for the ZigBee end device. Adding an external PA and LNA will raise the total current consumption, but the total impact is still limited in comparison with the current consumption by the sensor sensing operation. However, if only the radio part is considered, the total power consumption on the module has been increased by 2-3 times.

Table 7. Total current consumption for different operations.

Module Operation	Current consumption (mA*mS)	
	Standard ZigBee	ZigBee with external PA/LNA
Data request	186	346
Sensor sensing	23907	23907
Sending data	207	618
Status report	207	618

8. Conclusions

A performance study of a ZigBee module with external power amplifier and low-noise amplifier has been done. It has been shown that by adding external PA and LNA, the outdoor radio link range can be extended from 144 to 1600 m and the indoor range can be improved significantly with retained packet error rate. The total power consumption on the module has been increased by 2-3 times if only the radio part is consider. However, since the power consumption by the radio part is only a small portion in comparison with the sensor sensing part, the battery lifetime still can be maintained up to about 9 years. Thus, ZigBee modules with external PA and LNA can be used not only for the mains-powered coordinator and routers but also for the battery driven end devices in a ZigBee network.

Acknowledgements

Swedish Energy Agency, Energimyndigheten, is acknowledged for financial support of this work. Moreover, Adriana Serban and Gustav Knutsson at Linköping University are acknowledged for valuable discussions and assisting with technical support.

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