Energy Efficient Embedded Wireless System Used For Localisation In Indoor Environments

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Abstract—**The paper presents an embedded telemetry system used in combination of localisation algorithm for a precise indoor pedestrian localisation. The system is based on the association of two wireless technologies: ultrasonic and 802.15.4. The novelty is the use of 802.15.4 RF signal to give the reference starting time of the ultrasonic emission. A ToA (Time of Arrival) measurement provides the distance between two mobiles or a mobile and a fixed beacon with a few centimeters accuracy. A material prototype implementing this method was performed and a first evaluation was conducted.**

Keywords- wireless sensors; telemetry; low power; ultrasonic; localization; 802.15.4; indoor environment.

I. INTRODUCTION

Many localization techniques could be used to track people or device in indoor or outdoor environment. In indoor, infrared, ultrasound, narrowband radio, WiFi, or UWB location systems are the most common [1-3]. In outdoor, we find essentially systems based on GPS location. The main problem is that these systems require heavy and cost infrastructure with a not easy deployment. In this context, this paper, which is part of a research project funded by the French National Research Agency (ANR) aims to define a new indoor localisation system in continuation of outdoor localisation system such as GPS [4]. The project is trying to address two specific problems:

- Helping people to locate themselves inside complex buildings.
- Helping to locate someone moving in a complex building.

Applications may be various: security, technical management, health… The system must enable the user to locate or to be located in the building with a good accuracy (centimeters) [5]. We could also consider for mobile robot applications the improvement to one cm accuracy or more using data harvesting from other sensors. Although the project is intended to compute the location from different sensors and location prediction algorithm, this paper is focused on the distance evaluation to fixed points inside buildings.

Several localisation algorithms are used to compute the exact location and to enhance the resolution [6,7]. The system presented here is a precise telemetry system composed of three nodes: a first node, which is an energy efficient mobile device and worn by an instrumented person, a second node, which is fixed (called “Beacons”). These nodes help the mobile device to locate precisely. A last node (a remote gateway) saves localisation information of all mobile devices.

In this paper, we first present the basic principles of the proposed system, then hardware and software development are described. Finally, characterization results of the system are presented. A conclusion ends the paper.

II. OPERATING PRINCIPLES

The system has two main functionalities. The first one is to estimate the distance between a user, typically a pedestrian in a building, and a fixed reference, and the second one is to send distance data to a collecting point using radio communications.

For this last function two operating modes are possible:

- The first one is called “autonomous mode”. In this mode the system collects and stores data in a flash memory. Data is harvested through the serial link when desired.
- The second mode is “normal mode”. In this mode, distance data isn’t stored in the system but immediately sent to the collecting point using radio communications. This mode will be used in the rest of the paper. Fig. 1 shows the system architecture in the two modes.

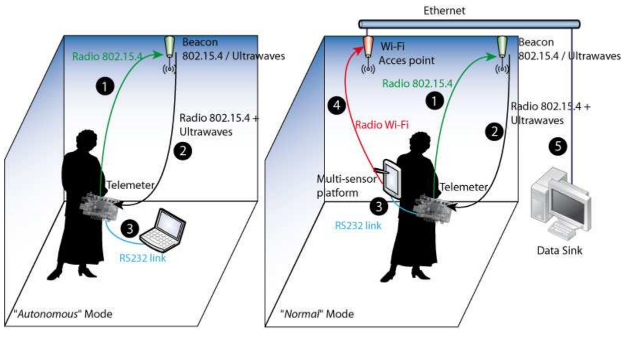

Figure 1. System architecture and two possible modes.

Depending on the mode remote data collection involves several stages:

- Stage 1: the telemeter sends a request radio frame to the beacon using its 802.15.4 interface [8]. The frame will be presented in the next section.

- Stage 2: The beacon receives the request from the telemeter and replies to the telemeter by sending simultaneously an RF response and an ultrasonic pulse.
- Stage 3: When the telemeter receives the response frame from the beacon, the telemeter starts a timer, which is going to measure the flight time of the ultrasonic pulse (ToA method [9]). When the ultrasonic pulse reaches the telemeter an interrupt is generated and the distance is computed. In autonomous mode, data (distance, beacon address) are stored on the telemeter or are immediately sent to a collecting PC using a serial RS232 link. It is the end of operations in this mode.

For normal mode, data are sent to a multi-sensor platform, which performs data aggregation from other sensors. In order to keep the free positioning of all the sensors on the person data are sent using Bluetooth protocol (not represented in Fig. 1).

- Stage 4: Data are received from the Bluetooth interface of the platform and are processed. Then, the platform checks all sensor parameters and transmits the status of the person using its WiFi interface.
- Stage 5: Data received by a WiFi access point is sent through the Ethernet network to the data sink.

III. HARDWARE PRESENTATION

The telemeter system is constituted of two parts separated in two specific boards connected through dedicated Programmable Input/Output (PIO). The first board contains the processor and radio modem, while the second board is dedicated to the ultrasonic pulses emission/reception.

A. Processor and radio board

The main component of the device is the 13213 from Freescale Semiconductors [10]. This component is a System In Package (SIP) including a processor and a 802.15.4 compliant transceiver. Our design is inspired from 13213-ICB reference design from Freescale, and all necessary interfaces have been integrated on the board to configure and to debug our telemeter. The block diagram of the system is presented in Fig. 2.

The 13213 processor is responsible for both functionalities: handling the transceiver and commanding the application. This characteristic limits the application code size (60kBytes) but enables to decrease the delay due to Physical layer (decoding demodulation). Indeed as soon as a frame is received a software interrupt is generated on the processor, which can start a timer on a beacon response (stage 2).

Moreover, the chip handles the serial RS232 link, which enables the system to send data to the multi-sensor platform (stage 3).

At last, several Input/Output and debug ports (BDM) have been placed on the MCU board in order to check the good communication between the boards.

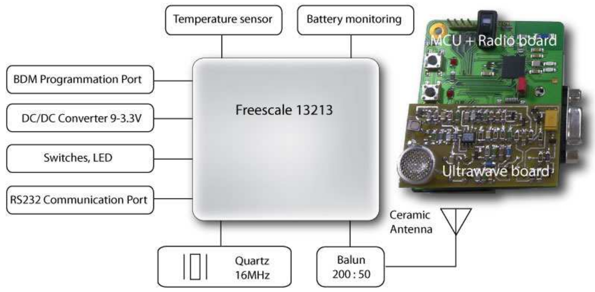

Figure 2. System block diagram.

B. RF and ultrasonic signals

The ultrasonic part aims at computing the flight time of an ultrasonic pulse in the 40kHz frequency range. The system combines the use of one RF electromagnetic wave with one ultrasonic pulse. The propagation speed of the electromagnetic wave being much more important than the sonic pulse speed, the flight time of the RF wave can be considered as instantaneous.

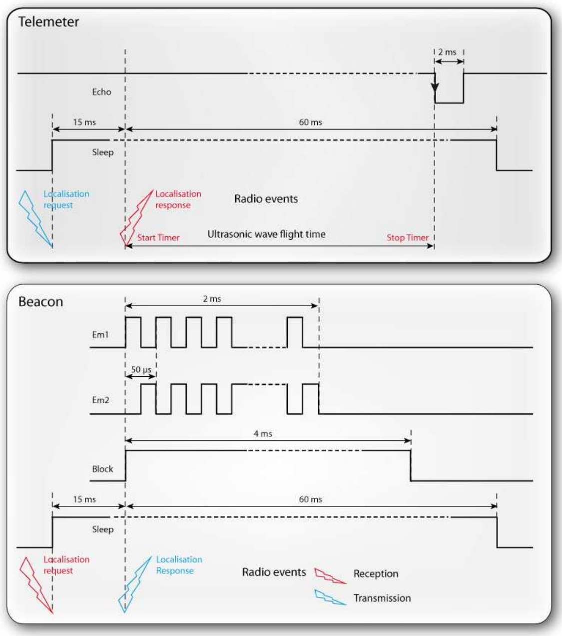

Figure 3. Ultrasonic part management signals.

Thus, the RF beacon response to a localisation request starts a timer of the processor, which timer is stopped when the ultrasonic pulse generated by the beacon node reaches the telemeter. Fig. 3 shows the temporal mode of the operation.

The ultrasonic pulse generation is managed by two programmable outputs of the beacon processor in *push-pull* mode (Em1 and Em2 signals), while on the telemeter the reception of an ultrasonic pulse in the 40kHz frequency band generates an interrupt on an input configured in the *input compare* mode (Echo signal).

Two other outputs of the processor are used for managing the ultrasonic board: the “Block” signal, enabling to block the listening while an ultrasonic pulse is generated, and the “Sleep” signal enabling to put the ultrasonic part in *low power* mode.

The 15ms guard time is due to the charging of the ultrasonic board input capacitor. The ultrasonic pulses have been limited to 2ms in order not to fill the environment of parasitic echoes. If the telemeter doesn't receive the ultrasonic pulse in less than 60ms, the telemeter puts the ultrasonic board in low power mode and goes to sleep mode until the next localisation request.

The localisation request can be either executed periodically from a timer, or requested from the serial link from the multi-sensor platform.

IV. Software Presentation

In order to program easily the application Freescale offers several software solutions called Code Bases: a basic solution called SMAC, a more complex 802.15.4 compliant stack and a Zigbee compliant stack [8].

For our system we have chosen the basic SMAC (Simple Media Access Controller) for several reasons. The most important reason is that this code base is completely open source and gives access to very low level primitives enabling maximal energy savings. Moreover this code base is very small and easy to implement. The source code is in standard C language and the development environment is Code Warrior [11].

A. Application software

The application code is integrated in a state machine running on the Beacon node and the Telemeter. Localisation requests are done periodically using a timer on the telemeter.

1) Telemeter: The state machine is described in Fig. 4.

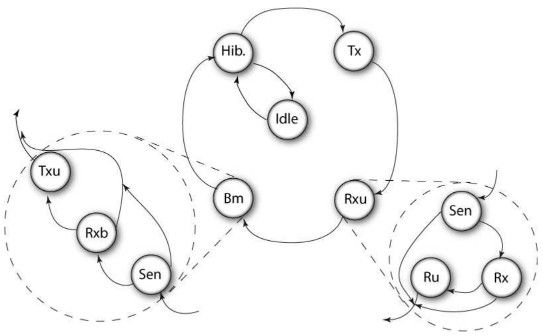

Figure 4. Telemeter state machine.

In order to save energy the system spends the most of its time in a deep sleep mode called *Hibernate mode*. In the *Hibernate mode* both the transceiver and the processor are powered off. Only a crystal is powered allowing the processor to wake up and after to wake up the radio stage.

The system is wake up from *Hibernate mode* (Hib) every 1 second by the real time interrupt timer to manage pending commands (Idle). If the telemeter doesn't receive any command from the multi-sensor platform the telemeter returns to hibernation.

Every 5 seconds, the telemeter wakes up from hibernate and broadcasts a localisation request (Tx).

Then it waits first the Radio localisation response (Rx) and in a second step it waits the ultrasonic pulse (Ru). These two states and the sensing stage constitute the macroscopic reception state (Rxu).

When the pulse is received or after 60ms the telemeter enters the beacon mode macroscopic state (Bm). This mode is used by the system data sink to increase beacon range and the robustness of the architecture. In this mode the telemeter plays the role of a beacon node for another telemeter out of the range. It waits a 3s guard time for localisation request from other telemeters (Rxb). If a request is received the state machine goes to the Txu state where a radio localisation response frame and an ultrasonic pulse are generated. Then, the telemeter enters Hibernate mode. If there is no received localisation request the telemeter directly goes to Hibernate state.

A special attention must be given to the Rxb guard time since radio stage activation consumes more energy.

2) Beacon: The beacon node state machine is a special case of the telemeter state machine since it is the beacon mode macroscopic state. The beacon node is always in reception mode sensing (Sen) localisation request. As soon as the beacon node receives a localisation request (Rxb) the beacon node generates a localisation response and an ultrasonic pulse (Txu) before returning to sensing mode (Sen).

B. Frame format

1) Radio frames: The radio frame format uses the 802.15.4 standard header and adds some fields. Frames are between 12 and 14 bytes long and are composed of three parts described in Fig. 5.

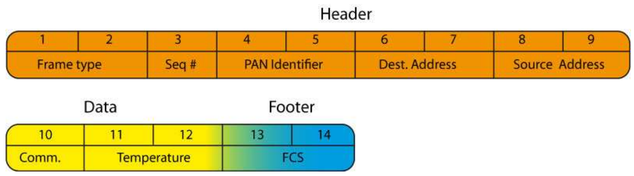

Figure 5. Radio frame format.

For energy savings it is important to note that several fields are useless (Frame type, Sequence number, PAN ID). Moreover the address field are oversized (2 Bytes) and could be limited to 1 Byte. However the 802.15.4 frame header enables to use most of network analyser such as Daintree Network SNA [12] to monitor the radio communications.

The frame is composed of three parts:

- The header field.
- Bytes 1 and 2 define the 802.15.4 frame type (Data, ACK, Beacon…)
- Byte 3 is the sequence number incremented with each emission.
- Bytes 4 and 5 define the network identifier and allow creating several networks.
- Bytes 6 and 7 identify the destination address. 0xFF is used for broadcast (localisation request).
- Bytes 8 and 9 identify the source address. The first one identifies the node type (beacon or telemeter) and the second one gives them a number (short address).

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- Data field: Byte 10 identifies the command type. Two commands are implemented: Localisation Request and Localisation Response. Bytes 11 and 12 enable to send the temperature from the beacon node to the telemeter in order to take into account for US wave propagation speed compensation. This field can be used as parameters for other non implemented commands.
- The footer field: Bytes 13 and 14 are generated automatically by the data transmission primitive implemented in the SMAC code base. The FCS enables frame error detection.

2) Serial frames: After the telemeter has received the localisation response from a beacon node, the telemeter activates a 60ms watchdog and a timer enabling the US wave flight time computation. When the US wave reaches the receiver (a MEMS microphone) or when the watchdog expires, a serial data frame is sent to the multi-sensor platform. The format of serial frames is given in Fig. 6.

1	2	3	4	5	6	7	8	9
Start	Flight time		Temperature		Battery level		RSSI	Stop

Figure 6. Serial frame format.

Byte 1 is used as a start frame delimiter in order to limit erroneous frames.

Bytes 2 and 3 transmit the US wave flight time calculated with (1)

$$T_f = field \times 0{,}5\mu s. \qquad (1)$$

Bytes 4 and 5 transmit the beacon temperature information to the multi-sensor platform.

Bytes 6 and 7 transmit the battery level from the integrated battery monitoring system.

Byte 8 gives the link quality indicator, which will enable us to compute the Receive Signal Strength Indicator (RSSI) with (2)

$$RSSI = -\frac{field}{2} dBm. \qquad (2)$$

Byte 9 is used as a stop frame delimiter in order to limit erroneous frames.

V. SYSTEM CHARACTERIZATION

Electrical and radiofrequency characterization have been performed. Comparison with a well-known system is also made.

A. Electric consumption

In order to characterize electrically the telemeter, we have measured the current going through a serial 50Ω resistor before the 9V to 5V DC/DC converter. Fig. 7 represents a telemeter cycle, which is done every 5 seconds. In the picture, we have simplified the cycle by removing the beacon mode state after the macroscopic receive state (Rxu). Four different stages can be identified:

- The first stage is the wake up period. This stage is fixed by the LED in initialisation and lasts 40ms while current consumption sensed is 5mA.
- The second stage consists of both radio transmission and ultrasonic part powering. This stage lasts 20ms and while the mobile device starts to transmit localisation request the ultrasonic part is enabled in order to compensate analog component delay. The current consumption is about 65mA.
- The third stage is the received period. The device listening and the beacon response consume 35mA. This stage can be divided in two cases, superposed in Fig. 7: In the first case the beacon is in range and the radio data frame is received. After the reception, the waiting for the ultrasonic (US) wave starts and the ultrasonic power is sensed by the analog circuit, the radio and the analog circuit are turned off. If no power is received the max power is reported. In the second case the beacon is not in range. The watchdog expires and the device returns to Hibernate mode.
- The last stage is the going to Hibernate mode. This stage lasts 30ms and is controlled by adjusting the LED on delay indicating the US received.

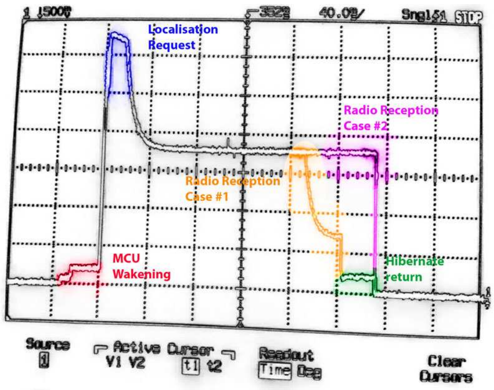

Figure 7. Telemeter current consumption.

B. Ultrasonic characterization

1) Test environment

The analog part characterization has been realized in an empty 9m x 7m lab room. Fig. 8 shows the room configuration and angular tests performed.

The room height is about 3m and the ground and walls are mixed reflective surface (concrete, plaster, bricks…).

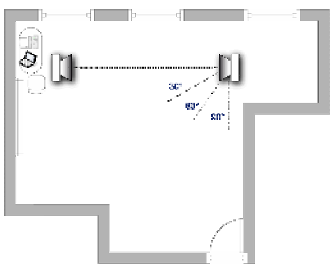

Figure 8. Test room configuration.

2) Distance and polarity impact

This characterization is focused on the distance and polarity impact on measurements. The temperature during these tests is kept around 22°C (+/- 2°C).

The measures presented in Fig. 9 were realized at 1.1 meter from the ground and with constant temperature.

Due to piezoelectric transducer directivity we tried several test pointing positions to compute the directivity effects on measurements. Four test positions were performed: 30, 60 and 90° from the direct view position.

The maximal range of the system is 9m but it can be improved by increasing the US pulse power. However, this modification increases the measurement variance.

The absolute error in all position stays under 8cm and the maximal error is observed when the device is in the 90° from the beacon position.

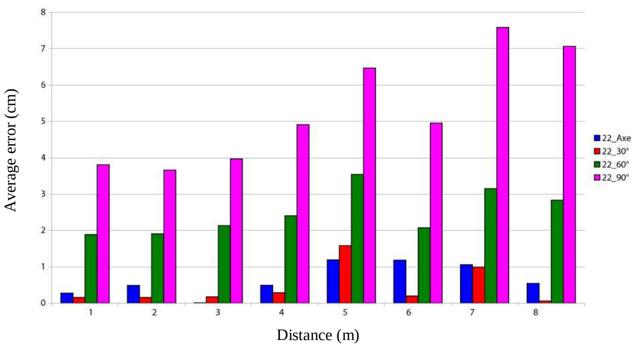

Figure 9. Distance error function of time and position (22°C).

Fig. 10 represents the polarization impact on measurements. For these measures we only made a quarter turn in the board plane to measure the XY directivity of the transducer but we haven't noticed any impact on the flight time measured.

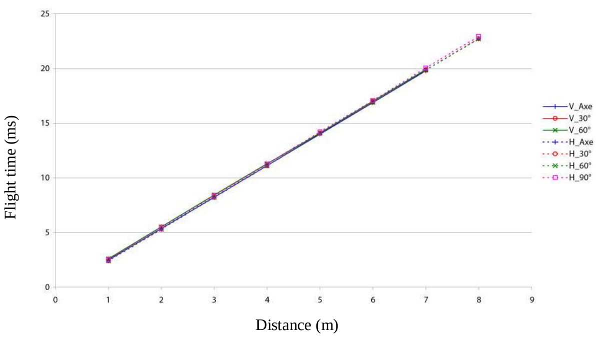

Figure 10. Polarity impact on flight time measures.

3) Temperature impact

For these tests we kept the same color convention for position. Fig. 11 describes the absolute error in function of distance for different positions at 12°C (+-2°C). The error measured is computed without any temperature compensation. We notice that we have the same behaviour as for 22°C. The computed propagation speed is decreased from 344.8m/s to 336.9m/s. The maximal error is obtained for the 90° position. Although the absolute maximal error is increased to 30cm, the relative error stays below 5%.

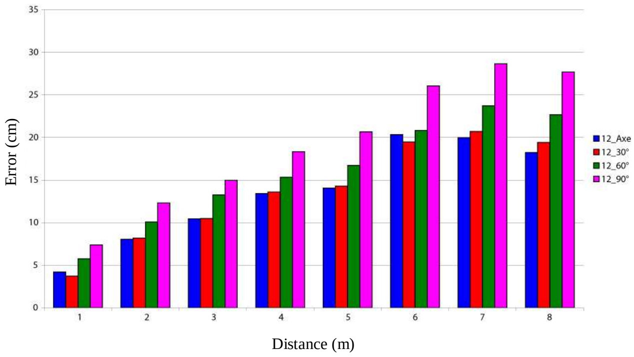

Figure 11. Distance error function of time and position (12°C).

4) Attenuation impact

We covered the mobile device with a piece of cotton tissue and we have measured the absolute error in function of distance and position. The attenuation due to the tissue increases the absolute error and has an important impact on the error when the position is at 90° from the direct view. However, the results are clearly satisfying since the maximal absolute error without any compensation of temperature or attenuation stays below 35cm and the relative error stays below 8%.

5*) Multi-path impact*

Fig. 12 shows the two test scenarios performed to evaluate multipath effects. The first scenario in configuration (a) evaluates the case where the power of the echo is superior to the power of the direct path while the scenario presented in configuration (b) evaluates the impact of a reflective object in parallel at the direct path for different distance (Pdirect > Pecho).

For these scenarios several distances between the reflective elements and devices have been tested but none of them showed an impact on the computed distance. In the case (a) the direct path is always reported.

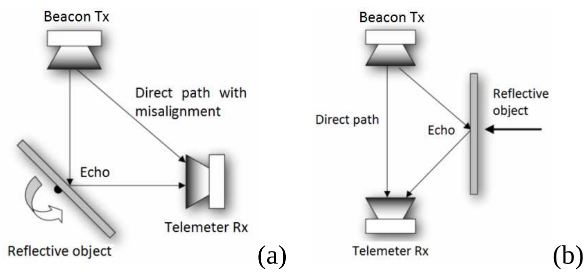

Figure 12. Test configurations for evaluating multipath effects.

6*) Obstacles and acoustic environment impact*

We tried to evaluate the impact of different objects being in the direct path. Several obstacles materials and sizes have been tested (cork, wood, carton, persons). The results have not allowed us to model precisely the behaviour in function of the size or the material but we noticed that for a constant distance position and temperature when the obstacles size increases the flight time increases. The error is superior but the relative error due obstacles is negligible (<1%).

The last tests evaluate the impact of a noisy environment on the measurements. In targeted applications (health) the main noise source is voice that's why we have focused our tests on FM radio noise source, white noise and pink noise (-3dB/octave). The tests have been processed in the same lab room with an ambient audio noise measured of 38dBSPL (Sound Pressure Level). The noise source was placed at 20cm behind the transmitter (worst case) and the noise measures were taken at 20cm perpendicularly to the direct path. The noise source was a speaker whose indicated bandwidth was 50-25000Hz. Four noise levels have been tested 68, 78, 88 and 100dBSPL for the 3 noise sources. Until 88dBSPL, no change in measured flight time has been noticed. But for 100dBSPL the device started to indicate incoherent measurements.

C. System performance comparison

The Cricket system from the MIT laboratory [13] is a compact embedded system for indoor localisation. It is constituted of ultrasonic piezoelectric transducers (40kHz) and a 433MHz Radio frequency transceiver. The distance computation is based on the round-trip flight time. An ultrasonic wave is generated by a transducer and is received by the other on the same board. Then, the distance is transmitted via the RF transceiver. This system has been chosen as the reference level for performance evaluation.

Another difference between our system and the Cricket is that we use omnidirectional transducers whereas the Cricket only has a 40° opening. Even if the cricket datasheet announced a 40° opening all the position tested above 30° have been unreliable and the measurements only have been done in the direct path. Moreover the system has been designed for short range measurements (anti-collision robotic application). Due to the round trip of the ultrasonic wave, the attenuation is important and the maximum range measured is about 7m. Fig. 13 indicates the relative error in function of distance for our telemeter localisation system and the Cricket system.

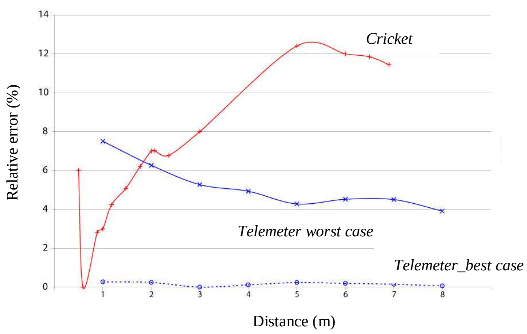

Figure 13. Relative error of systems comparison.

The two extreme cases are presented: the best case is obtained at 22°C in direct path (dashed) and the worst case at 12°C plus attenuation without any compensation in 90° position. The Cricket system stays under 10% of relative error from 30cm to 3m. In this range, the Cricket system is more precise than the worst case of our system however only the direct path was measurable for the Cricket system. Obviously, this comparison would need to be complemented and more detailed for example in energy efficiency.

VI. Conclusion

This paper proposed an original telemeter system allowing localisation for pedestrian in indoor environment. The system uses the 802.15.4 RF signal to start the time of an ultrasonic emission. The measure is computed from the flight time of the ultrasonic signal between the telemeter worn by the user and a beacon fixed in the environment. Characterization of ultrasonic performances shows good reliability, linearity and multipath immunity. This system have been tested and compared with the MIT Cricket system and have demonstrated several advantages such as:

- Good accuracy (better from 5% to 10% in the worst case and over 3m).
- Good opening angle (90° from the direct path.
- Good maximal range (up to 10m).
- Energy efficiency: The 802.15.4 low power modes enable up to two weeks with standard alkaline batteries (for a measurement every second).

Now, the system is integrating before deploying in real building.

Acknowledgment

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