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LOW-FREQUENCY LOCALIZATION AND IDENTIFICATION SYSTEM WITH ZIGBEE NETWORK

A. Ropponen, M. Linnavuo, R. Sepponen

Applied Electronics Research unit; Aalto University, School of Science and Technology, PL 13340, 00076 Aalto, Finland.

Emails: antti.j.ropponen@tkk.fi, matti.linnavuo@tkk.fi, raimo.sepponen@tkk.fi

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Abstract- Location awareness is important in health care. One way of generating this is a low-frequency radio frequency identification (RFID) location system that has been developed. The system tracks RFID tags with a quad antenna matrix that is placed under the floor surface. The tag can be also used to receive alarms and send acknowledgements via a ZigBee network. This article discusses the requirements of this kind of a tag, its structure, and its location accuracy. The demonstrated RFID system can locate people and items inside the building with an accuracy of 1.1 ± 0.5 m (S. D.).

Index terms: localization, Elderly care, RFID, Low frequency, ZigBee, Near-field imaging

I. INTRODUCTION

Rational and safe working methods and concepts are most important in health care facilities, e.g. hospitals or in elderly care. This often requires precise information about the location of staff and patients, particularly in emergency situations. The optimum localization method depends on the application, required area, and resolution. There are two main localization methods: the active method, where the person carries a tag with a transmitter or transponder, and the passive method, which uses some properties of the human being for localization [1]. Numerous systems are presented in the literature [4, 6, 7, 29, 32]. Accutech-ICS (Wisconsin, USA), HomeTronex, LLC (Baltimore and Columbia, USA), RF Technologies® (Wisconsin, USA) and STT Condigi (Sweden, Norway, Finland and Denmark), provide commercial systems for monitoring and localization with the active method using a tag. MariMils Oy (Vantaa, Finland), Future-Shape GmbH (Munich, Germany), for example, represent products for floor based location without a tag.

Cost effectiveness will be an issue when pervasive systems grow more prevalent. In case for the elderly, active methods are unacceptable because of significant maintenance and attention requirements of the transponder. Pervasive computing systems face many challenges, one of which is the requirement of invisibility and unobstructed communication [2]. This requirement is fulfilled by sensors embedded in walls or floor.

In the authors' previous work [22] an outline of a low-frequency positioning system, which can be used together with a near-field imaging (NFI) system was introduced [3]. The main benefit of the NFI system is that it is person independent. All persons are detected irrespective of tags or other signal sources attached to them. However, there are cases where the system would benefit from identifying persons localized by NFI. In elderly care facilities distinguishing between personnel and customers can be important. Also, locating certain non-human objects like ward equipment or wheelchairs could make a beneficial addition to the functionality of the NFI system. The NFI system tracks people inside a building and sets off alarms when certain conditions are met. These might be when a person leaves the room or bed or when a person falls down and cannot get up [3]. A device, preferably a mobile device or a tag which can be carried along, is needed to receive and indicate these alarms. The present alarm system, used with NFI, utilizes mobile phones through a GMS network and short message service (SMS). The solution has proved to be impractical (complicated alarm acknowledgement), slow (unpredictable delays in service of the provider's network) and expensive (in Finland, one SMS message costs about 5 euro-cents). Hence another wireless medium is needed.

II. MATERIALS AND METHODS

The goals of the study were to implement a low-frequency location and identification system and to measure how accurately it can locate people in its service area. Alarm management requires the system to know when the personnel have entered the room to correct the situation that generated the alarm (Figure 1). In emergency situations the mobile phone is not an optimal device to perform fast and simple alarm acknowledgement. A viable solution could be a tag that can be automatically tracked and to which the alarms can be sent.

a. System scenario

Figure 1 and Figure 2 illustrate a simple scenario on the operation of the system. In Figure 1 NFI system detects that a patient has fallen [4] in room X and sends an alarm wirelessly to a central unit. All the nurses have their RFID tag. The central unit then decides to whom the alarm is sent. Because of the location system the alarm can be sent to the nurse who is nearest to the room from which the alarm was sent. When the nurse enters the room, the NFI-system detects the new person arriving (Figure 2).

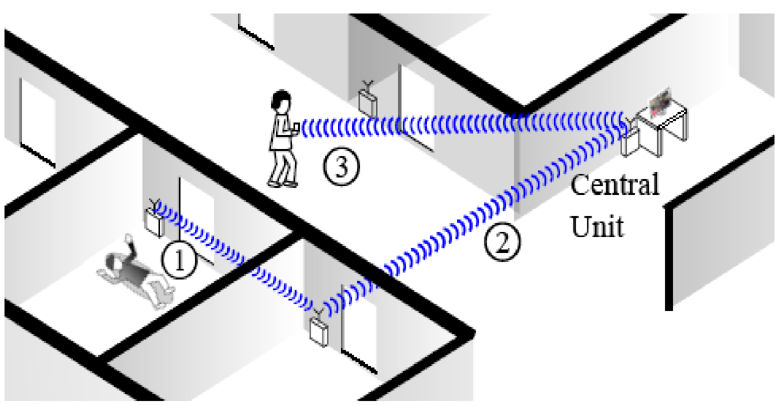

Figure 1. A person falls (1) and the information is sent to a central unit (2). The alarm then is sent by the central unit to the nearest nurse (3).

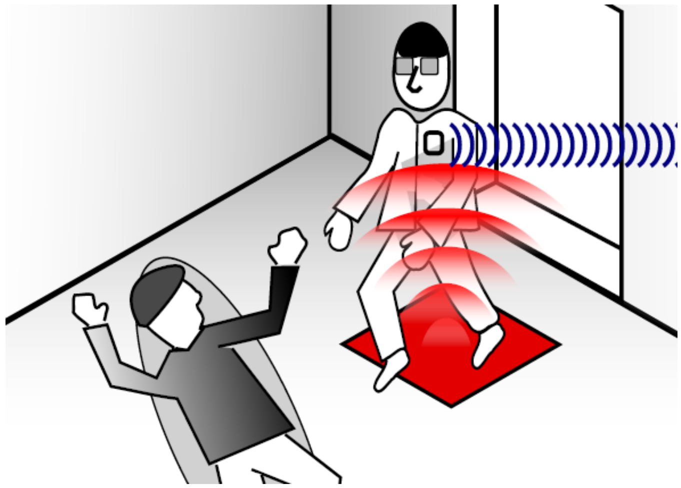

Figure 2. NFI system perceives a fallen person (grey oval). The NFI-system also detects the incoming nurse (red rectangle) and an RFID signal is transmitted to her tag (red curved signal). Location data and ID number is sent to the main system from the tag.

The tag receives the signal and acknowledges the system (blue dashed lines).A RFID scan starts right away after the detected arrival. The tag receives the low-frequency (LF) location signal and sends it back to the central unit, thus handling the acknowledgement automatically. However, the tag should have two buttons so that the nurse can inform the system that everything is alright, call more help if the situation with the patient is critical, or inform the system that she cannot go to help at all.

b. Localization method

Most of the used indoor location systems that locate a tag are based on triangulation [30, 31, 32, 33, 34]. The wireless medium can be, for example, infrared [5], ultrasound [33, 34], or a radio wave [30, 31, 32]. These systems use three types of means to locate the tags. They are based on the measured time-of-flight (TOF), received signal strength indication (RSSI) or both of them.

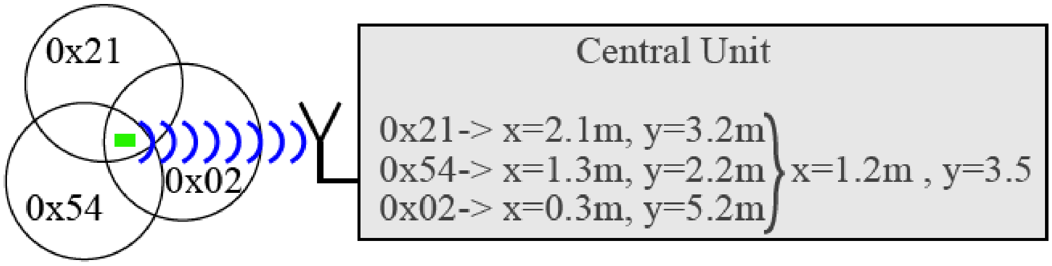

Figure 3. The location type. The tag transmits received location values to the central unit which translates them into the related coordinates and calculates the centroid.

The system implemented here uses proximity to locate the tag [6]. It sorts out in which LF antenna's coverage area the tag is and sends the received location value back to the system via a high-frequency (HF) radio [22]. The central unit has a table of these values. Each value corresponds to one coordinate in the service area. The system translates the values into the coordinates and calculates a centroid (Figure 3). This is a simple way to localize compared to measuring TOF or RSSI. The LANDMARC location system uses a similar approach [7].

c. Main requirements

To create a system described in sections 2.1 and 2.2, the following basic requirements have to be determined:

1) tag size and power requirements,
2) wireless network and topology requirements,
3) requirements for the LF-channel.

The tag size is dictated by the size of the display, battery, buttons, and other components (microcontroller, antennas etc.). The display has a major effect on the dimensions and shape of the tag. The displayed messages are short but the text should be easily readable also in unfavorable conditions. For two buttons, like in the system scenario, the buttons should be clearly separated to prevent false actions. However, a tag with a display and two buttons could be of credit-card size.

In a hospital or elderly care the staff shifts might be 8 hours long. This would be the absolute minimum for the battery life. However, daily charging affects the battery life. Mobile phones are charged every 4-7 days. Modern mobile phones with many different radios, touch screens, and color displays, are much more complex devices than the RFID tag. Thus a recharge interval of at least a month with a normal 3.6V/1000 mAh battery could be possible.

The parts that consume most power in the RFID tag are the display, a microcontroller and the HF radio. The most straightforward way to reduce power consumption is to switch the display on only when an alarm is received. The microcontroller's power consumption can be reduced using the sleep state. The controller should be kept in a sleep state waiting for an interrupt from the LF or HF radios or from the buttons. The LF and HF radios have to listen continuously for eventual signals from floor antennas and the HF network. Receiver can use a sleep state in various remote sensor systems [8, 9] but not in this application. The power consumption could be reduced by using beaconing: The tag polls the network for new messages at a fixed interval. For example, a poll might take 20 ms every second in a general ZigBee application [10]. Thus the radio and the microcontroller are in the sleep state for 98% of the time. Extending the polling interval would decrease the power consumption even more but eventually this would affect the response time of the tag.

Different networks can be connected together to combine different healthcare services [11]. However, only the creation of the location and alarm system in a single network is described here. The topology of the wireless HF network should provide reliability and scalability. The system should function in different sized buildings. The star topology for the network is the simplest but a cluster-tree or peer-to-peer network is more scalable [12]. There are four major choices to implement a scalable network for a mobile device: wireless local area network (WLAN, IEEE 802.11a/b/g), Bluetooth (IEEE 802.15.1), ultra-wideband (UWB, IEEE 802.15.3) and ZigBee (IEEE 802.15.4) [13].

WLAN has a great advantage because it is already installed in almost every building and the network is easy and relatively cheap to build. However, WLAN is quite bulky for this kind of mobile devices that transmit small amounts of data [14]. After all, the location and alarm messages are a couple of bytes long so that there is no need for tens or hundreds of megabits of transfer rate even if there are hundreds of devices in use.

The UWB network is used mostly for short-range wireless personal area networks (WPAN) with high-speed communication [15]. UWB networks can implement peer-to-peer, ad-hoc, or piconet topologies. However, the range of a UWB network is about 10 meters [16] and thus it is more suitable for high data rate short-range applications [13].

ZigBee and Bluetooth are low-power and rather low data-rate protocols [13]. Both can implement larger networks, Bluetooth with piconet [17] and scatternet topologies [18], ZigBee with its mesh-network topology [19]. However, Bluetooth's network topology and protocol is more complex. The major problem with the Bluetooth network is that the devices must always be on to maintain the link whereas ZigBee devices can go to the sleep mode [20]. A Bluetooth radio consumes 47mA in receive mode [13] thus exhausting the 1000mAh battery in less than 24 hours without beaconing. The Bluetooth link betters ZigBee with a better data transfer rate (Bluetooth 1 Mbps, ZigBee 20-250 kbps). Nonetheless, the ZigBee network's data rate is sufficient, for example, to track simultaneously simulated real time ECG data from up to 80 nodes [21]. Thus ZigBee was selected to be the HF protocol of the RFID system.

The LF-receiver was selected in a previous study [22]. The receiver has three inputs to adapt a 3-dimensional (3-D) antenna so that even signal strength is obtained regardless of the orientation of the tag in an inhomogeneous magnetic field.

d. Location accuracy tests

In the system scenario the prevailing NFI location system is used as the primary location reference. The RFID system adds the identification to the basic location data. The location data may, however, comprise of locations of several persons and the system should be able to identify the right one. To resolve the persons, some location capability is needed in the RFID system. The system sends an LF-signal that contains a wake-up header and 8 bits of data to each antenna. Each antenna transmits a unique data byte which is transmitted by the HF link back to the system for location reference. All the data bytes are linked to a table with coordinates $[x_i, y_i]$. For example, 0x01 means in this case, coordinates [20 cm, 32 cm], 0x02 [20 cm, 81 cm], etc. Usually, the tag receives the location data from several antennas in one scan. The location estimate $[x_A, y_A]$ is calculated from the received values $[x_i, y_i]$ using:

$$x_A = \frac{\sum_{i=1}^{N} x_i}{N}, \quad y_A = \frac{\sum_{i=1}^{N} y_i}{N} \qquad (1)$$

The aim is to have a location error of less than 2 meters which is about the loop coverage area. This is the minimum requirement for the location system, because the tag has to be at least within one antenna's coverage area. Normally the tag is in the area of two or more antennas and by combining this data a more accurate estimate is achieved.

RESULTS

a. System

The RFID tag consists of a Texas Instruments CC2430 system-on-chip (SoC) [23] and an Austria Microsystems AS3931 LF transceiver [24]. The LF antenna is a Premo's 3D ferrite coil antenna [25] that has one ferrite coil in each of the three coordinate axes. With a 3D antenna maximum signal amplitude can be received from the magnetic field regardless of orientation of the tag.

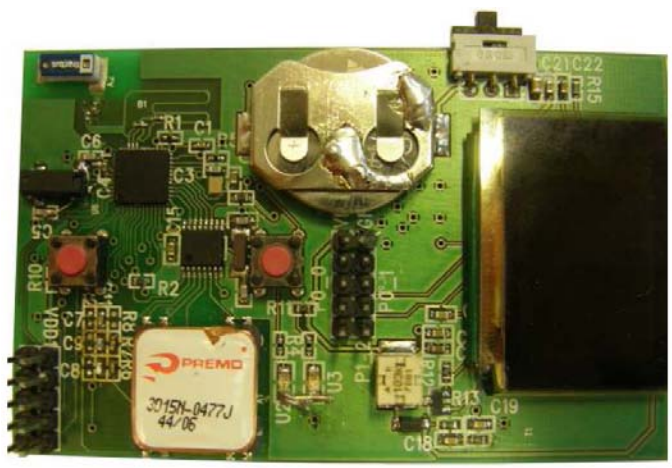

Figure 4. Tag is the same size as a normal credit card (8 cm x 4 cm). It consists of a CC2430 SoC, AS3931 LF-receiver, two buttons, and an OLED-display.

Texas Instrument has two different already designed antenna systems to be used with the CC2430: a folded dipole antenna and a chip antenna that is matched with a balun [26,27].

Minimizing the space the HF-antenna needs a chip antenna instead of a folded dipole. The tag also has an organic light-emitting diode (OLED) display for the alarm purposes (Figure 4).

The tag receives the LF signal's preamble bits with AS3931. After successful reception of the preamble byte, AS3931 sends an interrupt from the wake-pin to the microcontroller which, decodes the data, adds its own identification (ID) number and, furthermore, sends it all back to the system using ZigBee network (Figure 5).

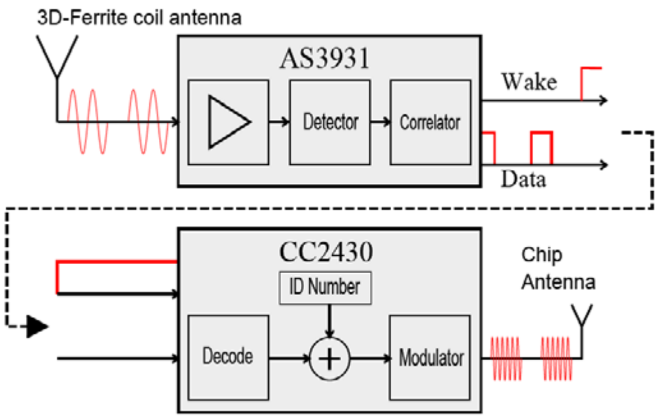

Figure 5. Block diagram of the receiving system.

The location system is built around the existing NFI system. All the quad antennas and multiplexers were already placed in the room. The antenna loops are driven by a 30-mA rms current which is the maximum for the used ADG706 multiplexers [28]. The coverage volume of one antenna was measured to be 1.78 meters high which allowed testing the system properly.

The 125 kHz loop signal is modulated with a version of FM0 keying. The carrier frequency and modulation is produced with the microcontroller. The AS3931 identifies a 16 half-bit binary coded data pattern, which is ASK keyed on a LF carrier [29]. The proper functioning of the receiver AS3931 requires that the DC component of the keyed signal is 0. Thus Manchester keying or similar should be used. FM0 is used for coding because the microcontroller can decode it more effectively. Manchester code relies on transition directions, while FM0 is defined by the time between transitions. Figure 6 shows how the keying works. A logical '0' is half the length of logical '1' and in both cases the carrier frequency is first off and then on. Note that using FM0 the signal length depends on the data, the more 1's in the byte the longer the signal.

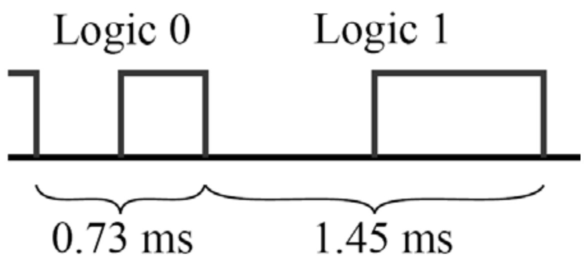

Figure 6. Used FM0-keying.

The transmitted location signal consists of a preamble burst and the location byte. The preamble is about 9 ms long. Hence, in the best case with 8 bits of data, one transmission to one antenna takes (9 ms + 8*0.73 ms =) 14.8 ms (0x00) and in the worst case (9ms + 8*1.45 ms =) 20.6 ms (0xFF). Switching the transmissions to different antennas takes negligible time compared to the transmission.

The test room has a 7x9 matrix of numbered loop antennas that the RFID system can use to transmit LF data (Figure 7). Every number is translated to the related coordinate in the central unit. The dimensions of the test area are 4 m x 4 m. The test room is located in the Department of Electronics, Aalto University, Espoo.

	1	8	15	22	29	36	43	50	57
	2	9	16	23	30	37	44	51	58
	3	10	17	24	31	38	45	52	59
Y	4	11	18	25	32	39	46	53	60
	5	12	19	26	33	40	47	54	61
	6	13	20	27	34	41	48	55	62
	7	14	21	28	35	42	49	56	63
					X				

Figure 7. Matrix of the loop antennas.

b. Demonstration of the location accuracy

The receiving antenna can be tuned with a parallel capacitor as:

$$C = \frac{1}{(2\pi f)^2 L}, \qquad (2)$$

where C is the tuning capacitor, f is the resonant frequency (125 kHz), and L the antenna inductance (4.7 mH). This gives a rough estimate of 330 pF for the tuning capacitor. However, when the resonant circuit is connected with the LF input of the AS3931 the additional reactive components require fine tuning, which was done using an Agilent 4395A impedance analyzer and small capacitors. The resulting resonance curve is shown in Figure 8.

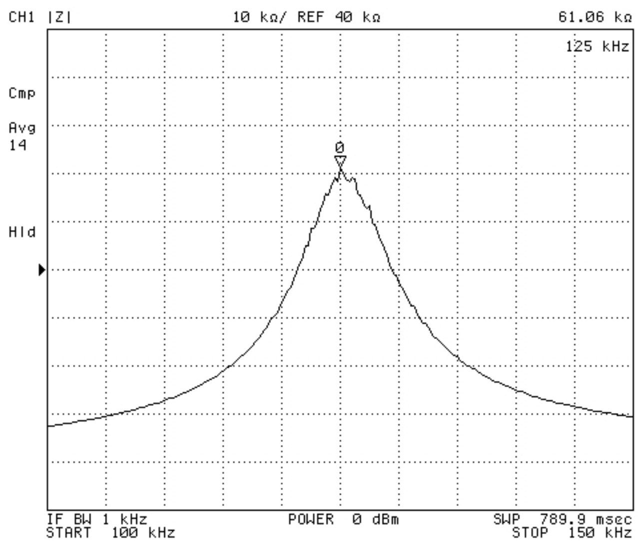

Figure 8. Measured impedance of the receiver circuit (scalar value)

The time taken for the system to go through all the antennas in Figure 7 was measured to be about 1.1 seconds.

To test the location accuracy of the RFID-system, the performance of the transmission was first tested. The magnetic field generated by each antenna in the room was measured by transmitting a pure carrier signal to each antenna and measuring the field strength above it with Rohde & Schwarz ESCS30 EMI test receiver. The measurement gives relative information of the antenna performance. Figure 9 shows how the normalized magnetic field varies in the room.

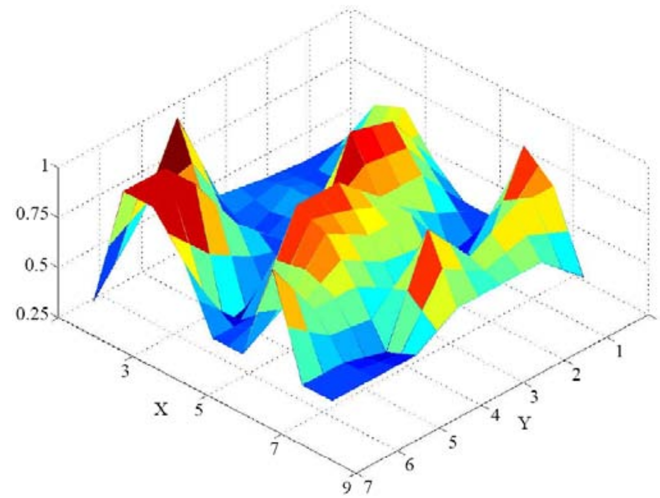

Figure 9. Normalized magnetic field strength in different parts in the room.

To test the tags' performance, a tag was placed 80 cm above the floor at ten randomly selected locations. This would be about the correct height if the tag was carried in a trouser pocket. The LF-scan was run 15 times at each spot and every time the location estimate was calculated. The results are shown in Figure 10. Blue triangles mark the spots where the measurements were made and the purple squares are the location estimates. The measured spot and its corresponding estimate are joined together with a black line. The calculated tracking error was [0.5 m, 0.9 m] on the x and y axes, respectively, with a standard deviation of ± [0.3 m, 0.7 m]. The calculated tracking error of the whole system was 1.1 m ± 0.5 m (S. D.).

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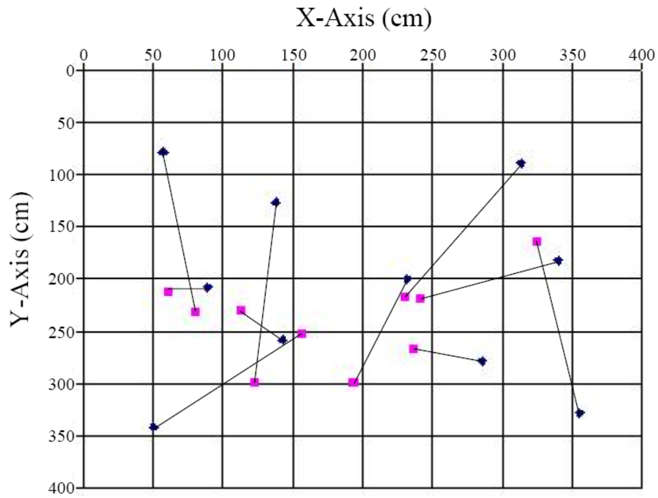

Figure 10. Location accuracy of the system. Blue triangles mark the spots where the measurements were made and the purple squares are the location estimates. The measured spot and its corresponding estimate are joined together with a black line.

IV. DISCUSSION

In the transmission test (see Figure 9) the strongest fields were measured around the [x=2, y=6] area. Also there was a large strong field area around [x=4, y=5]. This variation affects the calculated location values. The reason for the variations in the loop transmittance might be that the connection between the multiplexer board and the element installed under the floor is compromised. With a good connection the resistance of a connected antenna loop is at the most 50 ohms. However, with a bad connection the resistance can be up to a few kilo-ohms. When the magnetic field induced is directly proportional to the current in the loop such a drastic change in resistance lowers the current with disastrous effects. Another possible source of defect might be that the elements have two layers. In Figure 12, a schematic presentation of the wires on the floor sensor layout is shown. The antenna loops cross the signal wires on one layer. Wires on different layers are connected with laser cuts. When the elements have been in use it has turned out that the connections between two layers are quite fragile and the loops can break off. The loops were then measured with an ohm-meter to find out which antennas might be broken. Figure 11 indicates with a red 'F's the 12 out of 63 antennas that had gone off. When 19% of the antennas are dead it naturally affects the location accuracy. It also means that a new, more durable element structure is needed.

	1	8	15	22	29	36	43	50	57
	2	F	16	23	30	F	F	51	58
	3	10	17	24	31	38	F	52	F
Y	4	11	F	25	32	39	46	53	60
	5	12	19	F	33	40	47	54	F
	6	13	20	F	34	41	48	F	F
	F	14	21	28	35	42	49	56	63

X

Figure 11. Map of broken antennas. Broken antenna loops are indicated with a red F.

As can be seen from Figure 10 the calculated location values tend to concentrate on the center of the room. When located at the sides of the room, the tag receives the LF signal both from the side and center antennas. This moves the location estimate towards the center of the room. When the tag is in the middle of the room it receives the signals from every side and thus the estimate remains in the middle.

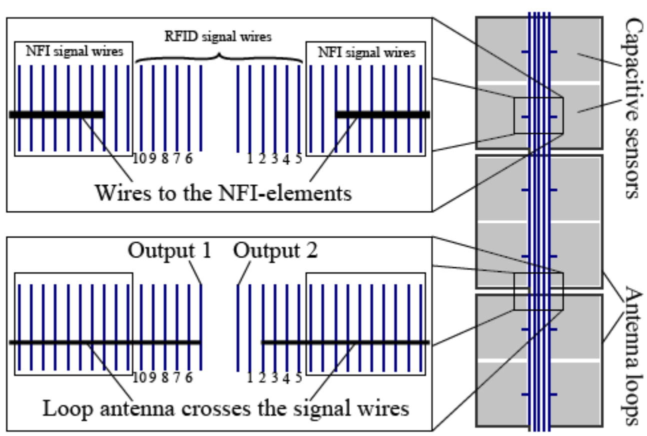

Figure 12. The structure of the NFI RFID laminate. The laminate has a fragile two-layered structure that is vulnerable to mechanical stress.

A reason why the location estimates tend to move down on the y axis could be crosstalk. As can be seen in Figure 12, the RFID signal wires 1-5 have a common output line (Output 1). Similarly, wires 6-10 have a common output (Output 2). The unused input is in a high impedance state. Thus the transmitting signal wire does not induce current in the other signal wires. When the signal lines are, in the worst case, 7 meters long and the signal wires are 1 mm away from each other, capacitive coupling has to be taken into account. The capacitance between two straight signal wires can be approximately calculated using the capacitance formula for round wires:

$$C = \frac{l\pi\varepsilon}{\ln \frac{\frac{h}{2} + \sqrt{\left(\frac{h}{2}\right)^2 - r^2}}{r}}, \qquad (3)$$

where l (=7m) is the length of the wires, ε (=4,6*8,85e-12 F/m) is the permittivity, r (=0.75mm) the radius of the wires and h (=1.3mm) the distance between the wire centers. However, the calculated capacitance is just 144 pF. At a frequency of 125 kHz the respective reactance is 8.8 kΩ. When the signal voltage is 5 V the coupled current is just 0.6 mA, which is insignificant compared to the transferred 30 mA.

When the system is installed on a second floor in a building there is a chance that the LF signal is received from the room below. Signal penetration through a normal floor, a 265 mm thick reinforced-concrete cavity slab, was measured. For a 100 mA rms current the measured field was -58 dBm 40 cm above the floor. Below the floor, the level of the measured field was below the noise level.

V. CONCLUSIONS

The accuracy results are quite comparable to other indoor location systems. For example the Horus WLAN location determination technique locates a device to within 1.4 meters [30]. Another WLAN system can locate to within 1.6 meters mean error, but then a dense network of access points is needed [31]. The ZigBee's own location systems' mean distance error is 1.8 meters [32]. The difference between location accuracy of the RFID system and the WLAN and ZigBee systems might not be so significant. However, the RFID system assures that the person is in a certain room. In most of position findings, some of the LF-signals were received from the center of the room. These signals cannot be received from the neighboring room due to the limited coverage area. With triangulation used by the WLAN and ZigBee systems, this verification is not possible. There are also systems with higher location accuracy. For example, systems that use ultrasonic pulses can achieve location accuracy of couple of centimeters [33, 34]. But if those are used a network of ultrasonic transmitters must be built next to the NFI-system.

An even more accurate location estimate could be possible by averaging from many samples or, for example, using Kalman filter [35]. However, the system monitors a moving person and the RFID scan is performed relatively seldom. Thus the measured movements appear to be quite random [36]. Hence the location estimate has to be measured from one single scan and the result must be updated when necessary.

Figures 6 and 8 show that either the transfer rate of the low frequency system or the sensitivity of the antenna can be further increased. At the moment the keying frequency is 1.4 kHz while the filter's -3dB band is 12 kHz wide. With a 125 kHz carrier frequency this means that the antenna's Q value is only 10.4. With a 1.4 kHz keying frequency the needed bandwidth is 2.8 kHz and thus the Q value can be about 44. Thermal noise power is flat relative to the bandwidth [37] thus with 2.8 kHz bandwidth the noise power would be 6.3 dB lower than with this current antenna.

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