Spatial Diversity Solutions for Short Range Communication in Home Care Systems using One Antenna Element

Markku J. Rossi, Jukka Ripatti, Fikret Jakupovic and * Reijo Ekman
Mikkeli University of Applied Sciences, Finland
** Turku University of Applied Sciences, Finland*
markku.rossi@mamk.fi

Abstract- ***It is becoming increasingly important for countries like Japan, Finland and Italy to enable as wide as possible home care for their elderly citizens because of the rapidly changing age structure of the population and high hospital costs. Wireless sensors hidden in furnishings (as a reference to a Finnish ongoing project) can provide necessary information for the high quality planning of home care visits. The relative positions of the radios are now fixed because of their relations to the furnishings. When conductive or metallic walls, floors or objects are found in the apartment, an antenna can hit a radio fade caused by shadowing or the summing up of waves. The Link Quality Indicator of a ZigBee® receiver can vary by up to 50 units within a short distance because of the floor, compromising the radio range. This paper describes the principles of a radio construction which is able to move the antenna element inside the enclosure of the radio unit along an X-shaped path along the major mechanical plane of the radio unit. Two electrical motors dynamically optimise the location of the internal antenna element to fit the current radio propagation environment. The paper also describes the feasibility and cost factors associated with the new structure. The achieved effect is a useful countermeasure against shadowing and multipath in the 2.44 GHz band but provides only a partial solution to the problem in the 868 MHz band, due to the space limitations in a typical radio unit. A prototype of the Diversity Adaptability radio was built and the capability to remarkably enhance the received power in difficult fading conditions was verified in an anechoic chamber. The observed side effects to the directional pattern of the radio were analysed to be removable by carefully selecting the route of the coaxial cable from the radio unit to the moving antenna element.***

Keywords-home care; short range radio; sensors; ZigBee; shadowing; fading; spatial diversity; avoiding gain minima; diversity adaptability

I. INTRODUCTION

Mikkeli University of Applied Sciences (MiUAS) is situated in the South-Eastern district of Finland that has one of the most challenging predicted demographic structures for the 2020s in Europe. The eastern part of the district is expected to have 44700 inhabitants in 2020, 2130 of which will need daily care, 1580 because of memory disorders . The age structure of the population can be characterised by calculating what proportion of the population is children and of over 65 years old, divided by the number of people that are in the working age. The fresh population forecast gives a ratio 75,3% for Eastern Finland for 2020 /17/ . The situation will be more challenging for Eastern Finland than to the whole Finland. In Finland the ratio is caused by the unusually high birth rates in 1945 – 1955 and in Italy and Japan by the low birth rates after 1980. The forecasted population structures of these countries show challenges in financing the health care for the elderly [18].

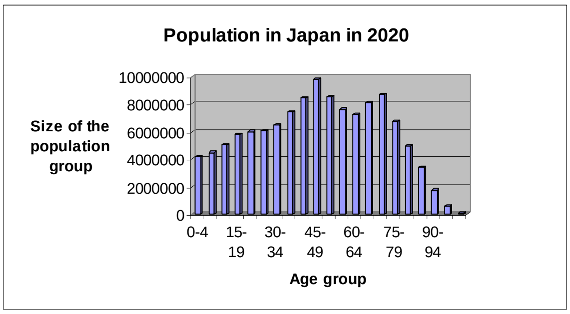

Figure 1. A forecast of the population structure of Japan for 2020 [18].

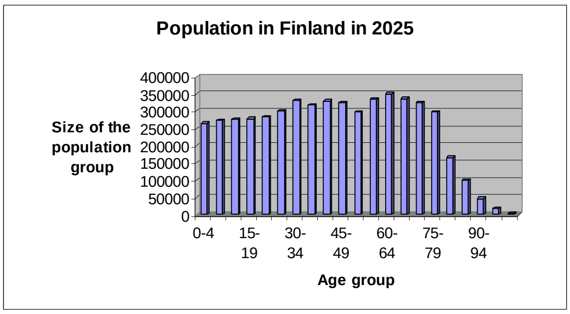

Figure 2. A forecast of the population structure of Finland for 2025 [18].

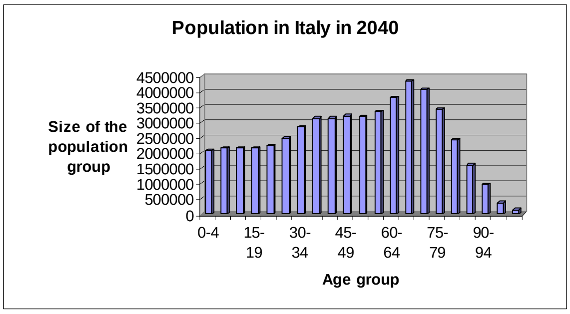

Figure 3. A forecast of the population structure of Italy for 2040 [18].

Data communication from homes has become feasible due to GSM and Flash OFDM (at 450 MHz) WWAN networks. Wireless communication has also become feasible at homes due to low cost short range radios such as ZigBee ®. The MiUAS generated an initiative to send to the hospital district home care visit recommendations generated at a call centre and based on real time event messages sent wirelessly from the homes of the elderly [14]. The project is now financed by the ERDF instrument of the European Structural Fund (ESF) and governed locally. The project built 37 test homes in 2 cities, 2 towns and 2 municipalities. We are aiming at 40% reduction in hospital days for a selected group due to increased home care, with corresponding cost savings. The main result will be the new work process. Recommendations of action based on real time sensor data have not been used in planning of home visits before. The decision rules for extracting recommendations of action from sensor data will also be new. The main technical challenges are how to maximise the time between replacing batteries to the sensor that detects motion in the living room and by providing countermeasures to the effects of RF shadowing and fading. Otherwise the ZigBee technology is already quite field proven, e.g. in the U.S. networks that read kWh-readings of consumed electricity from homes. The first challenge is related to different tactics to keep the receiver circuitry of the sensor device on as little as possible. The second challenge is related to the situation when the transmitter of the device is transmitting sensor data in an environment with shadowing. The battery life aspect was addressed in [2].

II. MOBILE CARE IN EASTERN FINLAND PROJECT

The Mobile Care service will produce three kinds of products: alarms, emergency voice calls and recommendations of actions, like home care visits. The operators generating recommendations can view the following events:

- usage of a selected electrical appliance , such as a microwave oven
- motion in the living room
- pressure distribution on the bed
- whether the main door is opened or shut
- usage of the electrical cooker
- verification of taking medication pills out of a smart pill box
- whether the inhabitant is inside / outside of the apartment.

The homes have VoIP handsets with one button call initiation. The Central Unit has both a WWAN radio and a WLAN base station in addition to ZigBee. This also enables IP cameras. A ZigBee wrist device with an alarm button completes the set [14]. The recently founded company IsCom Oy continues the work of Riihonlahti Services Ltd in the project. The project started a field test with 37 homes in October 2009. The final project report is expected in April 2010.

A plan for the next phase includes a project that takes UML descriptions of the decision rules of creating action recommendations out of sensor data (a result of the current project) and develops an expert system that will deliver recommendations semi-automatically under the supervision of a nurse. MiUAS is now also a partner of a funding proposal to the EU COST programme for deep co-operation between organisations that have similar goals than MiUAS in the field of Smart Homes oriented to Health. The proposal was filed in September 2009 by Coventry University.

III. RESEARCH NEEDS FOR REACHING THE REQUIRED LEVELS OF RELIABILITY

The error control methods: error control coding and retransmissions operate on a single wireless channel and add redundancy to the data packets to improve reliability. Their usefulness is however sometimes compromised over real fading RF channels. If the packet transmission both starts and passes the packet deadline in a deep fade, the methods mentioned before are usually not successful in delivering the packet [8].

The former reference is convinced that the incorporation of the spatial diversity approach into error-control is a very promising approach.

In the Mobile Care Eastern Finland concept some of the sensors can be invisibly embedded into furnishings. This eliminates the possibility of moving the sensor radio slightly so that heavy shadowing or a heavy slow fading can be avoided. We then decided to study spatial diversity to achieve as high as possible reliability in delivering the measurement results of the sensors. This is particularly important with the bed pressure distribution sensor. The later applications of this sensor can include e.g. an analysis of the breathing parameters during sleep.

IV. RADIO PROPAGATION ENVIRONMENTS RELATED TO USAGE AT HOMES OF THE ELDERLY

A typical home where we are expecting to use the Mobile Care service in Eastern Finland is a wooden single family house. Typical dimensions for this house type are: floor area 8 x 8 m, a second floor with narrower rooms 2.7 m above the first floor and a fireplace downstairs built of bricks. The radio propagation here through the structures at 2.4 GHz has a fairly low level of shadowing. The findings in [7] support this conclusion. The metal casing above the stove and by the chimney typically cause some effects.

Another frequency available in Finland is 868.3 MHz according to the standard EN 300 220-1, with a longer range than for the ISM band with a 1 mW transmit power.

It is however also common that the inhabitant lives in a block of flats with steel reinforced concrete walls and floors. There is some heavy shadowing and reflections present particularly due to washing machines, water pipes and dish washers.

The reference [4] examined an office space of 30 x 15 m and found that the attenuation caused by a 0.14 m thick concrete wall was in the order of 5 dB.

The reference [5] uses the parameter Link Quality Indicator LQI to describe propagation effects. The LQI was interpreted there to represent well the chip error rate. In the case of a floor consisting of wood and polystyrene, sharp variations in LQI , 50 units out of the total range of 255 units along a 0.25 metre section of the propagation path were detected. The dielectric constant of polystyrene at 1 MHz is of the order of 2.75 [9]. The bending of radio waves is heavily correlated with the dielectric constant. It is evident that more studies would be needed on the effects of floor coverings made of different dielectric plastics materials.

In [6] measurements of RSSI (Received Signal Strength Indicator) were performed up to a distance of 32 metres in an indoor scenario. The Packet Error Rate (PER) was found to be low until the distance reached 25 metres. Severe degradation of 802.15.4 was however detected in the active space of a 802.11b/g (WLAN) base station, if the WLAN channels and the SRR (Short Range Radio) frequencies overlapped. There are however at least 4 pieces of 802.15.4 channels not severely overlapping with the 802.11b/g channels. The WLAN usage is at the moment very common in Finnish blocks of flats.

The rationale to study a solution that can move the antenna element to various positions inside the device is based on the characteristics of current two-element diversity antennas. These antennas have two elements at fixed positions from each other. The reference [3] points out that when the distance between the edges of the antenna elements is e.g. 41.7 mm (very suitable for our purpose), the gain of the combination has gain minima -22 dB .. -18 dB deep on the horizontal plane as can be predicted from the theory of antenna arrays. We want to avoid the existence of these gain minima.

V. THE SPATIAL DIVERSITY SOLUTION

The design parameters of the 802.15.4 are well suited to our usage scenario because our expected required ranges as such are nearly always less than 25 metres. The challenge is mostly related to slow fading caused by the summing of the signals related to a direct path and reflections from metal surfaces.

The fitting of the sensor/radio devices discreetly into furnishings usually prevents the moving of the device with a built in antenna element which is required to avoid a deep fade. We decided to study the possibility of arranging spatial diversity that would be internal to the device and be arranged with only one antenna element to minimise antenna, signal division and cabling costs in addition to avoiding gain minima at certain angles. No prior art studies about antenna elements moving inside the enclosure of a device, in connection with sensors for home care were found.

The typical device dimensions of a combined sensor, logic and RF circuitry are 50 x 50 mm without the battery compartment [10]. Willig [8] mentions that antenna movements of even a few centimetres are adequate to change the value of the spatial autocovariance function. The half wavelength in the ISM band is around 62 mm. If we move the antenna element along a path with a 45 degree angle to the sides of the enclosure, the available movement is of the order of 70 mm in an enclosure also housing a typical 2500 mm2 printed circuit board.

Benefits found in printed circuit antennas include: narrow bandwidth, mechanical strength, low cubic volume and low cost. A modern antenna design is presented in [3]. The bandwidth of a Hilbert inverted-F-antenna (IFA) for 2400 MHz is 3.3% or 80 MHz. This fits well with a scenario where we would use the 5^{th} and the 10^{th} channel of 802.15.4 so that they fall in between two wider WLAN channels. The WLAN channels are however this narrow only in the U.S., and in Europe wider WLAN channels are admitted, bringing more spectral overlapping to ZigBee and WLAN. These particular ZigBee channels are separated by 25 MHz. The Hilbert IFA would then reject the major parts of two WLAN channels and amplify only WLAN channel 6 and the two selected ZigBee channels. The dimensions of this Hilbert IFA are 2.7 x 5.6 x 1.5 mm and the gain is 1.0 – 1.5 dBi.

The mechanical construction consists of a plastic board with the movement route holes above the circuit board, with the flexible antenna coaxial cable attached to the centre of the circuit board.

Springs are attached to the 90 degree and 270 degree corners of the plastic board. Opposite to the springs there are two miniature electric motors. The Kysan Electronics FF-K10WA-5Z215 miniature motor has an 11.5 mm long chassis. It provides 0.06 mN/m torque at 14000 rpm and 0.09 W [11]. If the used pulley has a diameter of 3 mm, the required spooling for a 70 mm displacement is 7 full turns and the spooling time is 30 milliseconds. The other dimensions of the motor are: 6 x 8 mm. The antenna element slides along the X-shaped path drawn by one of the motors at a time. Whenever one motor is moving the antenna sledge the other motor is idle.

The antenna sledge is attached to both springs and both motors via lines. The basic orientation is with the sledge at the crossing of the two paths. The force against the spring is 0.04 N and the desired spring constant is 0.1 N/m, slightly less than the motor can stretch. The small pulleys for the motors can hold the line attached to the sledge.

When the antenna diversity module is 60 x 60 mm, the routes (2) of the sledge at 45 degree angles can be 70 mm long each, forming together an X-shaped movement area. This means that the length of the route from one end of the route to the centre is 35 mm and the maximum additional movement to any of the remaining three corners is also 35 mm .

When the sledge is moving, the motor that is not pulling the line, is releasing a maximum of 70 mm of line. The springs are capable of overcoming the sliding friction of the sledge. Therefore the sledge has also a micro sized servo in it to stop the movement wherever this is needed.

An example of a state-of-the-art servo is the Pico from GWS [12]. The dimensions are: 22.8 x 9.5 x 15.5 mm and the axle turns 60 degrees in 0.12 seconds. The activated servo will lock the sledge at the desired position against the pull of the springs.

When used together with the frequency of 868.3 MHz, the ratio of the dimension of the path of the antenna movement to the wavelength is only 0.2. It is then uncertain that the maximum improvement in the field strength would be as high as if operating at 2.44 GHz.

VI. EFFECTS ON THE SENSOR DEVICES FROM THE ADDED DIVERSITY ADAPTABILITY FUNCTION

The coupling of the interference (EMI) from the digital circuits to the antenna is considerable in relation to the reception. The sharp edges of digital signals generate interference energy at high frequencies. The nonlinearities of the receiver can leak this energy into the received signal due to nonlinear mixing results. A sensitive receiver with fast digital circuits nearby is therefore usually a result of an iterative designing and prototyping process.

Now as we are moving the antenna unit above the logic circuits, the design of the electronic module is more challenging than ever. The complexity of the circuitry is however much lower than in a 3G cellular phone with fast processing and a GPS receiver.

Because of the Diversity Adaptability function the cubic volume of the wireless sensor device grows bigger. The effect from the empty space in between the electronics board and the plastic board is 36 cm3 if we allow 10 mm vertical space for the flexible coaxial cable for movement during the optimisation of the reception. The two motors consume 1.1 cm3 of space and the servo 3.4 cm3. The required space for the antenna sledge compartment can be estimated to be 18 cm3. This can be compared with the volume of an AA sized primary battery, 8 cm3. Because our advanced device is now larger than a standard device, it is more difficult to hide it in certain kinds of furnishings.

The additional cost is: two motors 4.9 € , servo 10.8 € and cables plus additional mechanical gear and a larger enclosure 1 €, bringing the additional cost to 16.7 €. This means roughly doubling the component cost of the wireless sensor device. When compared to the new ability to dynamically minimise the packet error rate of ZigBee in changing propagation environments, the extra cost can sometimes be acceptable.

VII. CONCLUSIONS FOR THE THEORETICAL CONCEPT

The critical nature of delivering sensor measurement results reliably in a service assisting the planning of medical home care visits generated a concept where one single antenna element is moving inside the wireless sensor device to minimise the packet error rate. The optimisation can adapt to a changing environment such as the later positioning of new home appliances in or out of the line-of-sight paths between the radios.

The concept shows theoretical promise to help in situations where the location of the sensor devices is fixed and cannot be fine tuned to avoid fades. The component cost of the device is doubled as is its cubic volume when compared to a conventional device.

A clear benefit of the solution compared to a competing scenario, the two-element diversity antenna, is the absence of gain minima at certain angles, associated with the pair of antenna elements.

I also recognised the need for more study on the effects of dielectric floor coverings to ZigBee propagation due to the possible bending of waves in the floor coverings.

VIII. DESIGNING A PROTOTYPE FOR THE DIVERSITY AVAILABILITY (DA) FUNCTION

The design of the prototype was based on the principle presented at the 3rd International Conference on Sensor Technologies and Applications /1/ , (FIG 4).

This article describes a real transceiver pair designed and built according to the concept from [1] and about its measured performance. From the wide selection of commercial ZigBee modules we chose devices from the product line of Dresden Elektronik Ingenieurtechnik GmbH in Germany. The unit providing an interface to the PC and to an external antenna is called the Sensor Terminal Board (STB). The dimensions are 100 x 75 mm. It has connectors for the actual radio board. The radio board is called the Radio Controller Board RCB230SMA. It has horizontal dimensions of 53 x 52 mm coming very close to our previous size assumptions.

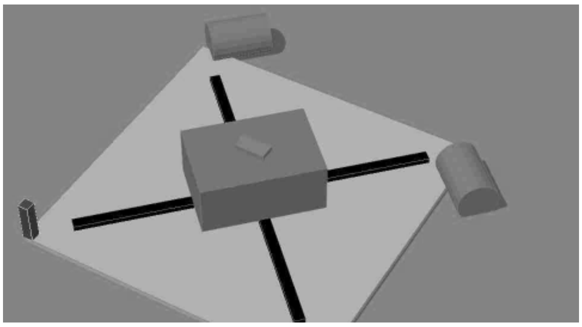

Figure 4. DA realised with two motors pulling a sledge against springs. The sledge has a servo for braking and an antenna element on it.

The radio Controller Board is capable of transmitting at +3 dBm. The transceiver chip is the Atmel AT86RF230. The board manufacturer gave us great co-operation and programmed the two STBs to use a constant frequency of 2,44 GHz and a transmit power of -10 dBm. These parameters would be suitable for the later tests in an anechoic chamber. In addition, the STB that would be selected to be the network device and receiving continuous temperature measurement data from the coordinator device was capable of outputting its own RSSI (Received Signal Strength Indicator) measurement results continuously and at suitable 1 second intervals to the USB connector.

The prototype of the network device uses a flat chip antenna instead of a higher quarter wave stub as originally planned. Samples of the interesting Hilbert IFA [3] are not available anymore so we selected a very small chip antenna from the manufacturer Yageo Corporation. Again, we received excellent co-operation and got samples of the Yageo 3216 PIFAs (Planar Inverted-F) antennas. Instead of the 2,7 x 5,6 mm dimensions from the original plan we now moved to the 1,6 x 3,2 mm range. The mean effective gain for Yageo is +0,14 dBi, slightly less than for the Hilbert IFA of [3]. The directional pattern is not perfectly omnidirectional as the maximum gain to a space angle is +3,7 dBi [13].

We then built the printed circuit board for the PIFA exactly according to the manufacturer's recommendations (including the matching components) and connected the antenna unit to the SMA coaxial connector of the Dresden RCB used as a network device with a 50 ohm cable of the type RG 178 B. The structure of the prototype network device can be seen from FIG. 5. A good feature of the construction is the 20 x 30 mm printed circuit board for the PIFA, having a large ground plane visible on the picture against the electronics situated underneath. For the measurements the antenna unit was turned 180 degrees vertically compared to this picture.

The servo is the same unit as selected earlier, the GWS Pico [12]. The motors of the prototype are Motraxx K10WAs from Motraxx Elektrogeraete GmbH. The specifications are very close to the ones from Kysan [11].

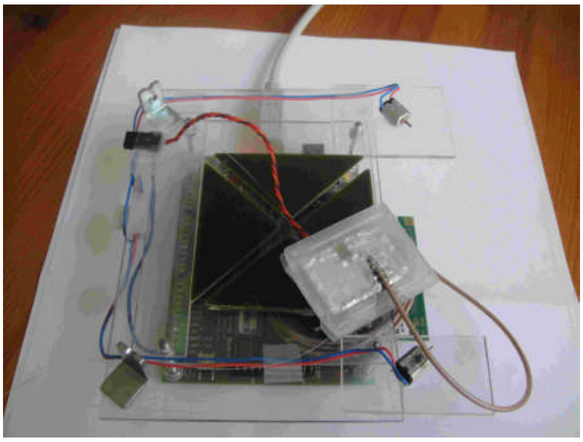

Figure 5. The DA antenna construction on Dresden RCB. The two motors are visible. The servo for the braking function is underneath the board which has the X-shaped hole.

IX. LABORATORY TEST ARRANGEMENTS FOR THE PROTOTYPE

After investigating different service providers for anechoic chambers we selected the Turku University of Applied Sciences' chamber. Their facility is situated in SW Finland and uses a RFD-FA-100 room by ETS-Lindgren. The internal dimensions are : 6,4 m x 3,44 m x 3,0m (h). The level of internal reflections compared to the direct wave is -20 dB. The overall appearance of the anechoic chamber can be seen in FIG. 6.

The distance between the transmitter and the DA receiver was chosen to be 3,27 m. The height of the transmitter antenna from the floor was 1,15 m and 1,00 m at the receiver. The slight angle of 2,6 degrees for the line connecting the antennas compared to horizontal does not affect the received power. The transmitter antenna was an omnidirectional quarter wave stub from Dresden Elektronik.

The room has a non-reflective turning table that can be remote controlled from outside the chamber.

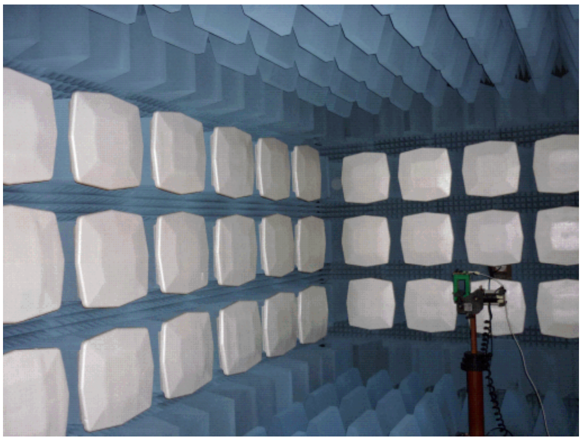

Figure 6. The anechoic chamber in Turku.

X. LABORATORY TEST RESULTS

The simulated condition of a severe signal minimum caused by multipath was created with one 0,6 x 1,2 m aluminium plate hanging vertically and at a 90 degree horizontal angle compared to the signal path. The achieved weakening of the signal was 17dB.

The ZigBee radio working as a coordinator is seen in FIG. 7.

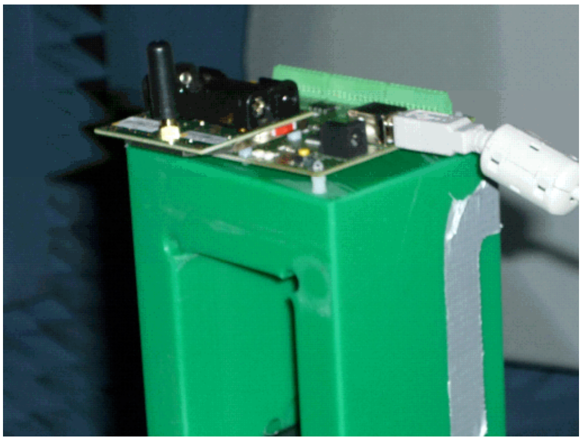

Figure 7. The ZigBee coordinator radio in the anechoic chamber.

The DA effect was achieved by selecting 8 adaptation positions for the DA antenna unit that is capable of moving along the X-shaped path. The direction "North" was at the receiver directly away from the transmitter antenna. The DA positions were named as NE ½ , NE1, SE ½ , SE1, SW ½ , SW1 , NW ½ and NW1. The positions " ½ " were halfway from the centre of the X towards the ends of one of the four 35 mm long DA paths. The positions " 1 " were 35 mm away from the centre of the X.

The results of the test for achieving escape from the fade are in TABLE 1 :

Measurement no.	DA position	RSSI (dBm)
DA0	middle of the X	-78
DA1	NE ½	-67
DA2	NE1	-70
DA3	SE ½	-64
DA4	SE 1	-63
DA5	SW ½	-59
DA6	SW1	-67
DA7	NW ½	-79
DA8	NW1	-62
DA9	middle of the X	-74

Table 1. The RSSIs when using the DA function. The unrotated RSSI before providing the back reflector was -59 dBm.

The elapsed time between DA0 and DA9 was 10 minutes. The usage of only one reflector caused a hysteresis of 4 dB during the DA test (-74 dBm - -78 dBm).

The DA function was able to raise the RSSI by at least 15 – 19 dB. The best position for this test setting was the DA position SW ½ . The rotation of the antenna element during the linear movement was negligible and as we can see from the second measurement described below, the angular response at the angles close to the angle used in the test above was nearly flat.

The second test was the examination of the directional pattern of the DA unit antenna gain against the horizontal rotation angle.

The ZigBee network device on the electrically rotatable measurement table can be seen in FIG. 8.

The measurements were taken every 5 degrees, rotating clockwise when seen from above the DA unit with the starting point RSSI-0 pointing directly away from the transmitter antenna. The average RSSI over 72 measurements over the angles was -62,3 dBm. The average of the standard deviations of the powers at angles was 0.45 dB when the sample size at every angle was 20 samples. The dBm-readings were then rounded to the nearest 0.5 dBm reading to the table, because the radio gave the individual readings to the terminal emulation software only at a resolution of 1 dBm. The typical 90% confidence level of the power readings at the angles from the t-distribution with the sample size 20 is + - 0.78 dB.

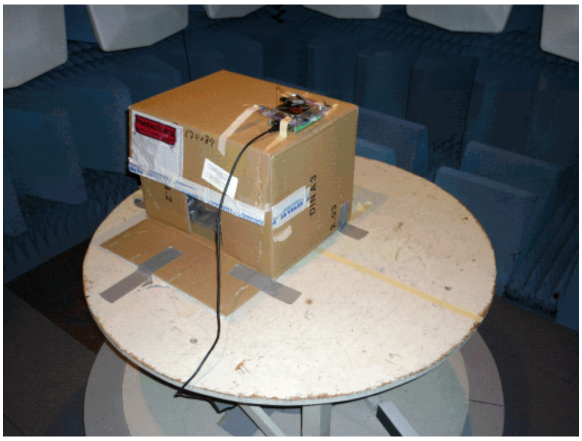

Figure 8. The ZigBee network device on the electrically rotatable measurement table.

The results of the measurement of the horizontal angular response of the prototype are in TABLE 2 :

rotation angle, degrees	received power, dBm	**std deviation, dB**	rotation angle, degrees	received power, dBm	**std deviation, dB**
0	-59	.497	185	-66	.51
5	-58	.497	190	-64	.384
10	-58	.357	195	-64	.447
15	-56	.384	200	-62	.384
20	-55	.447	205	-61	.384
25	-55	.447	210	-61	.384
30	-54.5	.49	215	-60	.384
35	-54	.6	220	-59	.316
40	-54	.477	225	-58	.384
45	-54	.316	230	-58	.384
50	-54.5	.497	235	-59	.384
55	-55	.384	240	-58	.447
60	-58.5	.49	245	-58	.436
65	-61	.447	250	-59	.447
70	-66	.548	255	-60	.384
75	-70	.775	260	-58	.384
80	-67	.632	265	-58	.384
85	-65	.539	270	-58	.218
90	-63	.316	275	-60.5	.497
95	-61	.316	280	-61	.477
100	-61	.384	285	-61.5	.589
105	-62.5	.49	290	-62.5	.592
110	-64	.447	295	-64	.384

115	-67	.316	300	-64	.436
120	-70	.539	305	-64	.6
125	-82	.853	310	-62	.384
130	-74.5	.589	315	-62.5	.477
135	-67	.447	320	-64	.497
140	-67	.316	325	-67	.548
145	-69.5	.654	330	-64	.316
150	-67	.384	335	-62.5	.477
155	-64	.384	340	-61.5	.583
160	-66	.384	345	-61	.384
165	-67	.384	350	-61	.477
170	-67	.51	355	-61	.384
175	-70	.624	360	-59	.316
180	-66.5	.497			

Table 2. The RSSIs of the DA prototype at different horizontal rotation angles.

These results can be seen also in polar format on FIG. 9.

The diagram shows the numbers of the rotation measurement stops from RSSI-0 to RSSI-73 with RSSI-0 and RSSI-73 at the same angle.

When compared to the specification of the Yaego 3216 PIFA which itself is not perfectly omnidirectional, we observed one new gain minimum caused by the construction of the DA unit prototype. The gain minimum corresponding to the rotation angle of 125 degrees caused an RSSI of -82 dBm. With the rotation angles of 120 and 130 degrees, the gain was already more than 10 dB higher.

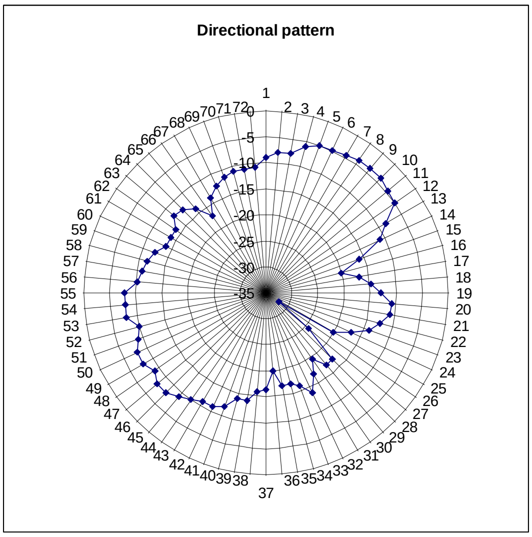

Figure 9. The directional pattern of the DA unit. The reference level 0 dB corresponds to an RSSI of -50 dBm.

The average received power was at -62,3 dBm. When the parameters :

- Tx transmit power -10 dBm
- Tx antenna gain 0 dBi
- average Rx antenna element gain +0,14 dBi
- distance between the Tx and Rx antenna elements 3,27 metres
- frequency of 2,44 GHz

are applied to the Friis free space equation

$$P_{received} = P_{transmitted} * G_{Tx} * G_{Rx} * \lambda^2 / (4 * \pi * r)^2$$

we get $P_{received}$ = 923E-9 mW = -60,3 dBm .

When also taking into account the loss in the RG 178 B coaxial cable between the Dresden RCB and the Yaego antenna element of 1,6 dB, we notice that the received power was only 0,4 dB less than the theoretical prediction. Actually the received power was the same as the predicted power within the measurement accuracy of the Atmel radio chip.

XI. ADDITIONAL MECHANICAL PRINCIPLES

In addition to the current approach with one movement plane with one X-shaped path, the function can be realised with two movement planes. The lower plane has one straight hole in the horizontal direction of 45 degrees and is attached to an upper plane. The whole lower plane can move around a knob situated below. The second, upper plane has a corresponding straight hole at an angle of 135 degrees and can move along the hole that is at a 90 degree angle with the lower hole.

The hole can also be circular in shape, e.g. from an angle of 3 degrees to 357 degrees. The antenna element would be attached to a pole corresponding to the hand of a clock. The hand is attached to only one motor that is situated at the centre of the circle.

If the original one-plane with two motors construction is used, one additional release mechanism is needed close to one of the springs. This mechanism selects the required one of two possible directions at 90 degree angles to what the spring is pulling the antenna sledge.

For practical control of the position with good long term stability, a measurement of the position of the sledge would be required for control feedback. The measurement can be optical, with an LED on the lower side of the sledge and photodiodes attached to the radio board under the movement plane.

XII. ENERGY MINIMISATION ASPECTS AND SHADOWING

The main addition to the energy consumption in this concept compared to traditional solutions is during the running of the two Motraxx electrical motors one at a time. The usual starting position of the antenna sledge is from the centre point of the x-shaped antenna path. The efficiency of the motors is at a maximum with a 3.0 V supply voltage and with a 0.12 A current, providing rotation at 13800 RPM. The maximum distance travelled by the sledge during the measurement phase is 4 times 70 mm, or 280 mm. After this, the sledge simply moves to the most optimal measured position in terms of the packet error rate. The average distance travelled then is 17.5 mm. The end stage of the motor driver circuit is a switching transistor with a high efficiency.

With the planned pulley each 10 mm sledge movement takes one turn of the axle and lasts for 4.3 ms. The length of the steps is 10 mm. To find a new optimum antenna position would take an average of 30 steps. The duration of the whole procedure is dominated by the time to measure the new Received Signal Strength or the packet error rate and not by the movement periods of the antenna sledge.

The energy consumption of the motors during one position search is 3.0 V * 0.12 A * 30 * 0.0043 s = 0.046 Ws. This can be compared to a typical battery configuration with two pieces of CR123A Lithium primary batteries containing 9.0 Wh or 32400 Ws of energy. The position optimisation procedure is usually not a significant factor in the overall energy consumption.

Instead, the key question when designing a ZigBee radio network is the co-operation mode between the coordinator and the device of a star network. With the beaconed mode, the device can be asleep until the active period begins after a selected inactive period. During the inactive period the device can be asleep and only providing power to a low power real time clock. The power consumption of e.g ZigBee devices is nearly the same during a reception operation and a transmission operation. If the beaconed mode is used the energy consumption can be predicted quite well.

To reduce the energy consumption further the unbeaconed mode can be selected instead. Now the device can be asleep until it detects itself new sensor data to be reported, wakes up and performs a carrier sense operation. If no other device in the network is transmitting at that moment, the device can then send the sensor report.

In the case the service however wants to receive sensor reports on demand, a novel principle was introduced in [2]. If the beaconed mode is used and the inactive period is very long the coordinator cannot get sensor reports according to the needs of the higher system. Instead of keeping the device in the beaconed mode with periodically turning on the receiver circuitry, the waking up of the device is now arranged via an UV detector that has a negligible energy consumption. The coordinator emits bursts of UV light to wake up the device via an interrupt line of the sleeping microprocessor. This concept needs an optical path from the coordinator to the device.

The Diversity Availability system presented in here can run into problems in the energy consumption if there is a lot of movement of shadowing objects in the path between the coordinator and the device. When using the 2.4 GHz band the wavelength is of the order 0.13 metres. From the Limits of Exposure to RF Radiation we know that the human body is not especially much absorbing RF energy in the exact 2.4 GHz band in general. That is why an external power density of 10 W/m2 is accepted in Finland at this band. However, the used frequency is indeed used for heating food in microwave ovens. The heat is produced by the vibration of the various dipoles of the molecules in the EM field. There is no sharp absorption band for the water molecule in this band against the common assumption and e.g. also 915 MHz is used for heating food.

Therefore the presence of a human body close to the device in between the coordinator and the device can be seen as a normal shadowing case. When the dimension of the body is of the order twice the wavelength, the scattering cross section of the body is remarkable, or approx. 0.3 – 1 times the body dimension. When seen from the wave penetration point of view, the skin depth of a 2.4 GHz plane wave into the muscles and organs of a typical human body is close to 1 cm. This means that severe shadowing is experienced when a human is standing close to a ZigBee device.

The effect to the energy consumption is dependent on the frequency of the human movement related to the antenna position optimisation cycle. Because many RSS measurements are needed for each optimisation cycle, the cycle lasts at least 20 seconds. The cycle should be started only when shadowing has been observed for at least 20 seconds. The worst case would then be that the human changes the position in front of the device slightly every 40 seconds. A remarkable negative effect to the operational time would be observed if 20% of the battery energy would have been consumed to the mere continuous optimisation of the position of the antenna sledge. The dominating factor would be the need to keep the receiver on during the optimisations, not the energy used by the motors. The continuous receiver-on status would consume 20% of our battery energy in just 3 hours. This should clearly be taken into account when selecting the position of the sensors at homes.

To optimise the overall combination of the data transmission quality and energy consumption in a star network one should analyse the needs of the higher system using the services of the sensor network. The energy consumption coming from the active usage of the receiver circuitry is important in the overall energy consumption [16]. The power consumption of the example transceiver IC, Atmel AT86RF230 is 46 mW when the receiver is on and the transmitter is off. The difference between the power consumptions at the RF output powers +3dBm and -17 dBm (the whole range that can be controlled by sw) is in comparison only 21 mW.

The key question is how often does the higher system need new sensor data. If sensor data updates are needed at any moment according to the demand, long periods of inactive time cannot be realised in the beaconed mode. The inactive period must be set to a lower value than the maximum permissible delivery time for a sensor data report. An alternative to this is to use an optical turn-on activation principle together with unbeaconed mode for the receiver, presented in [2] with an erratum in [1]. This principle minimises the time with receiver on.

When active, the IC can usually provide functions that can be used to minimise the used energy. The main functions are the RSSI measurement, the ED (Energy Detection) calculation and the LQI (Link Quality Indicator) calculation. RSSI indicates the received power of an individual data frame. The ED calculates an average of several RSSIs. These are related to the received power only. The LQI studies what the estimate for the PER (Packet Error Rate) is from analogue parameters. The LQI then takes into account also errors generated by possible RF interferers. The higher the PER is, the more often we must retransmit the data, consuming energy in the process. When the LQI shows 150, the PER is around 0.1 and when LQI is 220, the PER is already negligibly small.

The DA functionality can be used to achieve the best possible energy consumption in a given geometrical configuration and multipath and interference environment. If the radio channel is selected first out of the 16 alternatives so that the LQI is maximised we have avoided the interferers, including our own sensors, as much as possible. After this, the DA function can be used to find the best position for the antenna inside of the sensor device. After that, the LQI can be used to drop the transmit power until the PER is still acceptable together with the retransmission rate following from it.

XIII. CONCLUSIONS FOR THE PROTOTYPE MEASUREMENTS

The capability of the Diversity Adaptability function to increase the received signal power was verified by measurements. The DA unit won extra link margin for home care and other similar applications where the position of the receiver cannot be chosen at the level of +17 dB. If the sharply shaped space with high fading would have had even deeper fading, even more benefit could be possible. Here the depth of the fade was limited by the characteristics of the anechoic chamber.

The observed new minimum at the directional pattern requires some examination. The coaxial cable from the Dresden RCB runs in a horizontal position beside the Yaego antenna element. The incoming field was amplified less than with other angles, when the first motor was at an angle of 195 degrees from the Tx-antenna line. The starting angle of the first motor before rotation was +70 degrees. The horizontal coaxial cable started from the angle +30 degrees. It was at 155 degrees when the minimum was detected.

The interaction with both the horizontal coaxial cable and the first motor caused a strong deformation to the angular response. The direction to the transmitter antenna was 180 degrees when related to the set null of the rotation experiment. There was deformation of the field due to the shield of the coaxial cable whose potential is close to the potential of the reference electrical ground and which was now in the path between the transmitter and the receiver antennas.

The second motor was respectively first situated at -60 degrees from the Rx antenna element. It was between the Tx and the Rx antenna elements at the rotation angle of 240 degrees. The angular gain of the antenna construction was however good (RSSI = -58 dBm) in this case, at the rotation angle of 240 degrees. The mentioned angles take into account the fact that the Yaego element was not in the middle of the printed circuit board of the antenna element.

The horizontal coaxial cable is the main cause for the drop in sensitivity at the rotation angle of 125 degrees, corresponding to the measurement angle no 26 on the diagram. A motor alone did not remarkably disturb the field. The diameter of the motors is only of the order 7 mm.

To overcome this side effect, the coaxial cable should be led through the centre of the sledge when designing an operational product. We concluded that when this principle is applied, the observed gain minimum will disappear. To verify this postulation, we selected later, after the chamber measurements an open field with low ground conductivity to test a modified device. Because the RSSI function of the radio does not work with powers lower than -91 dBm and the notch detected at the rotation angle 125 degrees was 20 dB deep, we selected 7.0 meters to be the antenna distance in the field test. The free space power expected with this arrangement is -69 dBm overall and -89 dBm at the rotation angle of 125 degrees.

The measured power was -65 dBm indicating some reflections from the ground. The receiver was again rotated to find the notch angle. The notch was found at the expected angle and the depth of the notch was now 18 dB.

The receiver was now modified so that the coaxial cable comes to the antenna unit directly from the down direction. The receiver was again installed on the field and it was rotated to find out if the notch was still existent. The lowest detected power was now - 73 dBm instead of the -83 dBm with the coaxial cable oriented horizontally. The received power was still around the level -65 dBm at most of the angles indicating the performance of the antenna unit was now the same but more even than before the modification.

The hysteresis experienced with the back reflector arrangement suggests that very local and deep fades might not be very common in practical situations.

Also another phenomenon could at least theoretically reduce the number of situations where DA would be mandatory in practical systems. This phenomenon is the limited cross-polarisation ratio CPR of commonly used antennas. CPR is the gain of the cross-polarised component divided by the gain of the copolarised component /15/. For a short vertical dipole the CPR is larger (less perfect) at large elevation angles than at small angles. The CPR ranges commonly around -20 … -10 dB and is caused especially by the physical thickness and slight mechanical errors of the constructions. After polarisation changes due to interaction with conductive obstacles in the apartment a part of the signal will leak into the receiver antenna also via the polarisation that was not the original design criteria for the antenna.

To study the level of probability that a DA receiver would be mandatory in apartments a large simulation set up could be arranged. Another possibility would be to compare conventional and DA receivers in a real and demanding multipath environment.

ACKNOWLEDGEMENTS

We wish to thank Mr. Mike Ludwig of Dresden Elektronik for providing the embedded software that sent the RSSI measurements from the radio chip to the USB port.

We wish to thank Mr. Remco Hollemans of Yaego Corporation for sending samples of their small Planar Inverted-F antennas.

We wish to thank Mr. Elmar Bernhardt of the Elektroniikan 3K-tehdas of the city of Savonlinna for designing and building the printed circuit board for the Yaego antenna element.

REMARKS

ZigBee ® is a trademark owned by ZigBee Alliance, Inc.

REFERENCES

[1] Rossi, M.J. **,** *Spatial Diversity for Short Range Communication in Home Care Systems using one Antenna Element.* SENSORCOMM 2009. The 3rd International Conference on Sensor Technologies and Applications, IARIA , 2009. 978-0-7695-3669-9/09 , IEEE 2009 , DOI 10.1109/SENSORCOMM.2009.35 .

[2] Rossi, M.J. **,** *Energy Efficient Motion Detection of Elderly Living at Home.* SENSORCOMM 2008. The 2nd International Conference on Sensor Technologies and Applications, IARIA , 2008.

[3] Azad, M.Z. and Ali, M., A New Class of Miniature Embedded Inverted-F Antennas (IFAs) for 2.4 GHz WLAN Application.. IEEE Trans. on Antennas and Propagation, Vol. 54, No. 9, 2006, pp. 2585 – 2592.

[4] Lee, J. et al. , *RF Propagation Simulation in Sensor Networks.* The 2nd International Conference on Sensor Technologies and Applications. IEEE , 2008.

[5] Machedon-Pisu, M. et al. , *Efficient Data Propagation Techniques and Security Concerns in Low Rate Wireless Personal Area Networks in Outdoor and Indoor Scenarios.* Optimization of Electrical and Electronic Equipment - OPTIM 2008. IEEE , 2008.

[6] Petrova, M. et al. , *Performance Study of IEEE 802.15.4 Using Measurements and Simulations.* WCNC 2006 Proceedings. IEEE , 2006.

[7] Tang , L. et al. , *Channel Characterization and Link Quality Assessment of IEEE 802.15.4-Compliant Radio for Factory Environments.* IEEE Transactions on Industrial Informatics, Vol. 3, No. 2, 2007. pp. 99 – 110.

[8] Willig, A. , *Recent and Emerging Topics in Wireless Industrial Communications: A Selection.* IEEE Transactions on Industrial Informatics, Vol. 4, No. 2, 2008. pp. 102 – 124.

[9] *Electrical Properties of Plastic Materials. Professional Plastics Inc.* http://www.professionalplastics.com/professionalplastics/ ElectricalPropertiesofPlastics.pdf , *accessed in Feb. 2010.*

[10] *Rihotec Detector with ZigBee Communication. Personal communication, Pertti Harju, Riihonlahti Services Ltd., Puumala, Finland, 2008.*

[11] *DC Motor FF-K10WA-5Z215 . Data sheet. Kysan Electronics, Mountain View, CA, 2003.*

[12] *Sub micro sized Servo GWS Pico. Data sheet. Grand Wing Servo-tech Co., Ltd., Taipei, Taiwan.* http://www.gwsus.com/english/product/servo/sub%20micro.htm , *accessed in Feb. 2010.*

[13] 3216 *Ceramic Chip Antenna in PIFA Mode for Bluetooth/WLan Application. Preliminary. Yageo Corporation, Taiwan, 2009.*

[14] Rossi, M.J., Pärnänen, A. and Luukkainen, S. , *Mobiilihoiva turvallisen kotihoidon tukena. Täydennetty projektisuunnitelma.* Project Plan to the ERDF funding programme, Mikkeli University of Applied Sciences, August 2008, in Finnish.

[15] Yau, K.S.B. **,** *Ionospheric Propagation , The Experimental System.* http://digital.library.adelaide.edu.au/dspace/bitstream/2440/ 50413/4/03chapter4.pdf , *accessed in October 2009.*

[16] *AVR Low Power 2.4 GHz Transceiver for ZigBee, IEEE 802.15.4 , 6LoWPAN, RF4CE and ISM Applications. AT86RF230 Data Sheet. Document 5131E. Atmel Corp. , 2009.*

[17] Population Projection 2009-2060, *Statistics Finland,* http://www.tilastokeskus.fi/til/vaenn/2009/vaenn_2009_2009-09-30_tie_001_en.html, *accessed in Feb. 2010.*

[18] International Data Base, *U.S. Census Bureau,* http://www.census.gov/ipc/www/idb/informationGateway.php , *accessed in Feb. 2010.*