Evaluation of wireless sensor technologies in a firefighting environment

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***Abstract*—In firefighter environments navigational support could help to reduce casualties. While exact indoor localization is still a research problem, an alternative may be a bread crumb based approach in which not the exact localization but the recovery of laid out wireless sensor nodes is crucial. Recovery, however, can be enabled using sensors typically employed for indoor positioning in wireless sensor networks (WSNs). Such sensors include infrared, ultrasound and radio.**

Only little information is available on the behavior of these sensors under the influence of a firefighter environment. In this paper first a report of the evaluation of these sensor technologies under the harsh conditions in a firefighting training facility is given. Secondly, tests considering received signal strength in respect to firefighter equipment, postures, movement patterns and antenna positions are presented. Third, two potential antenna configurations are evaluated. We show that the evaluated sensor technologies and antennas may be used to realize the envisioned navigation tool. We conclude that antenna placement is crucial and propose the front side of the helmet as optimal location for a directional antenna.

I. Introduction

Firefighting today still remains a dangerous job. Especially in indoor environments numerous accidents may be avoided by providing better tools for orientation. Various location systems for firefighters based on WSNs have been previously developed but they either require a fixed infrastructure [1] or have high computational demands [2] making them hardly practical. In contrast, we aim to develop a WSN as proposed by Ramirez et al.[3]. Therein the idea of an ad hoc WSN is proposed whose nodes are deployed by the firefighters themselves to improve node localization and increase the relevance of node position. In an emergency firefighters may traverse the laid out nodes to find the exit. To deliver such a tool a mandatory information is the direction in which the node is located. This is an information which may be acquired using technologies commonly employed in WSNs such as infrared light, ultrasound and radio. In this work a report on the evaluation of these sensors in a firefighter environment is given. The paper is structured as follows: In chapter 2 the influence of fire fighting conditions on the above mentioned sensor technologies is reported. In chapter 3, the effects of antenna location, receiver direction, distance and firefighter movement patterns on the received signal are explored. And in chapter 4 two different antennas are evaluated considering their employment for radio localization of sensor nodes. In chapter 5 follows the discussion and related work. The paper is closed in chapter 6 with the conclusion.

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The work presented in this paper was in part supported by the Federal Ministry of Education and Research of Germany through the landmarke project.

II. Sensor technologies under firefighting conditions

As previously stated the most widely implemented technologies for node localization in WSNs are ultrasound, radio frequency and infrared. Considering these technologies for employment in a navigation support system raises the question if the harsh environmental conditions of a firefighter operation influence these sensors. In order to develop a navigation support system for firefighters, these sensors must be evaluated under the constraints of their possible environment of employment. Our partner the fire brigade of the City of Cologne department Chorweiler provides a training facility in which firefighters can practice mission tasks under the stress of high heat and smoke developed by a real fire. This facility seemed suitable for a first sensor evaluation.

A. Sensor hardware

In addition to the suggested sensor technologies, temperature, humidity and smoke sensors were integrated into the sensor nodes. This was done in order to monitor the environmental conditions in the facility. The sensor hardware and temperature depended operating range is shown in table I.

TABLE I
Sensor/actuator hardware selected for the test

Type	**Hardware**	**Temp.range**
Ultrasonic	Transducer: SRF02	-30..50°C
Short wave infrared (940nm)	Emitter: TSAL7200	-40..85°C
	Receiver: TSOP36236TR	-25..85°C
Ambient light	Emitter: LM520A	-40..85°C
	Receiver: TSL2550	-25..85°C
802.15.4 2.4 GHz radio	Jennic JN5139	-20..70°C
Temperature, Humidity	SHT75	-40..125°C
Smoke detector	Kidde Model 0915	4..38°C

B. Setup and test scenario

Following the described idea of a WSN based navigation tool a specific mission scenario was created together with the firefighters. In this scenario a firefighter has reached the source of fire. While exploring the scene of action he has deployed sensor nodes. Hence, in this scenario the firefighter is closest to the fire source while the nodes lie further behind. In the simulated scenario it was chosen to deploy the nodes closer to the firefighter as they would be on a real mission (all nodes lay within 6 meters from the firefighter node). This was done in order to get a higher resolution of the sensor behavior and to allow a finer monitoring of the environmental changes. Five nodes (1-5) without housing and a 802.15.4 coordinator node in housing were laid out in the training facility. The coordinator node was equipped with all of the above mentioned actuators (infrared emitter, ambient light emitter, ultrasonic transceiver, radio transceiver) but no sensors. For this reason node 1 was placed directly next to the beacon. Both nodes were placed 0.5m above the ground and 0.9m away from the fire source as their functionality may be integrated into the firefighters clothes. Nodes 2-5 were placed on the ground in the container and in 1m, 3m, 5m and 6m distance from node 1, respectively. Node 1 had not ultrasound transducer and ambient light sensor, node 2-4 had all sensors and node 5 had not smoke detector. Another node (6) which was only equipped with a radio transceiver was placed outside the facility and connected to a notebook computer. In figure 1 the test container is shown.

After deployment the sensor nodes were activated and a beacon-enabled 802.15.4 peer-to-peer network was formed. The beacons were modified to contain the coordinator time allowing the nodes to constantly synchronize their clocks. After activation the coordinator started emitting infrared light and ultrasound pulses at fixed intervals. The ambient light led was switched on. Using the beacon time the test nodes (2-5) estimated the distance to the coordinator node by utilizing the SRF02 fake ranging mode. All sensor values were logged to the internal flash of the nodes and broadcasted to the 802.15.4 network. The data was received by node 6 outside the facility and logged on the notebook computer.

Fig. 1. The training facility of the fire brigade of the City of Cologne.

C. Test events

During the test various events were tripped by the firefighters. Thereof some events ("small events") were not expected to have a great impact or occurred to frequently to protocol them adequately (e.g. test facility door open/closed). In contrast, "big events " were expected to have a considerable impact on the sensors. Therefore the beginning of such events was documented and the length was estimated. In the case of personnel entering the facility the entry time was documented. The sequence of "big events" for node 2 is shown in figure 2.

D. Results

The test lasted three hours which was longer than expected and the internal flash was full after 75min. Hence, data over the complete duration of the test is only available from the packets received by radio (for this reason the missing measurements shown in figure 2 only indicate an impaired radio reception of the protocol node outside the container). During the test

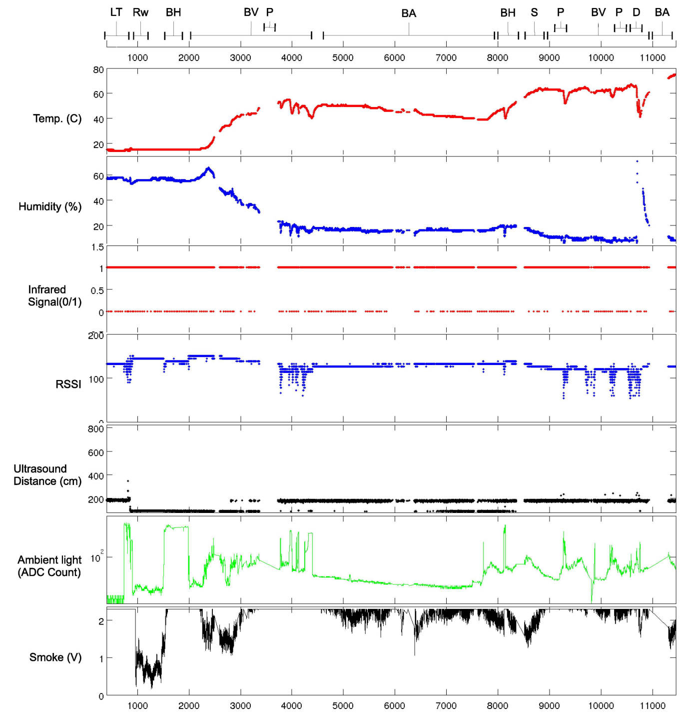

Fig. 2. Node 2 measurements as received outside container by node 6. (Abscissa is labeled with the test events. LT: empty container, Rw: dense white smoke, BH: fueling with untreated wood, BV: fire burning, BA: fire dying out, S: burning household material, P: personnel in facility. D: extinction test with water).

the maximal measured temperature was 75°C at node 2 while minimal temperature was 14°C. Five of six sensor nodes survived the test i.e. continued to send radio packets over the complete test duration. Node 1 lost its radio after about 45min at which also the SHT75 connected to this node stopped working. The only other failure was the TSOP on node 4 which stopped receiving signals after 63min.

For the investigated sensor technologies the following behavior was observed:

- In dense white smoke (temp.class 1 (<20°C), density class D (sight <30%, <2m), type 1 (white smoke) following [4])
  - no infrared reception at 5m (reception possible at 3m using TSOP)
  - no ambient light detected at 3m (although infrared is also detectable using TSL it seems not as sensitive as the TSOP)
- In normal fire smoke (temp.class 2-3 (20 to >50°C), density class B-C (>30%, 22-2m), type 5 and 6 (plastics and wood) following [4])
  - no influence
- During vapor test
  - no direct influence on radio is detectable (although radio reception from node 2 to node 6 is lost for a short time after the test, all other nodes constantly reported receipt of coordinator beacons)

In general, all "big events" were detected using the sensor measurements of the nodes. In addition, the representation of the spatial distribution of the sensors was found in the measurements, i.e. comparing measurements of nodes closer to the source of fire showed a gradient in the sensor measurements.

III. Signal strength measurements on the firefighter

This section focuses on radio direction finding as a possible technology for recovering wireless sensor nodes. Hence, its is investigated how antenna location, receiver direction, distance and firefighter postures affect the received signal strength (RSS).

A. Tested movement patterns and antenna positions

From our work with the firefighters two main postures in action could be observed: If sight permits and heat is moderate firefighters usually walk upright. If sight is limited and heat is up firefighters crawl (move on hands and knees). In respect to these postures different positions of a directional dipole antenna on the firefighter were evaluated on its influence on RSS. From discussions with the firefighters, the projects' integration expert and practical considerations two general locations for an antenna were identified: atop the left shoulder and on the left side of the chest. In both places, the firefighters of the fire brigade of the city of Cologne usually have no tools or equipment mounted which could interfere with the antenna or hinder the firefighter. The measurements were conducted in LOS between an JN5139 based sensor node and a equipped firefighter[1] with another JN5139 based sensor node connected to the dipole antenna. A summary is given in table II. Actions performed by the firefighters were approach and withdrawal to and from a node (A/W) in either standing or crawling position. As well as rotation (ROT) in either crawling or standing position.

TABLE II
Tested scenarios evaluated on a fully equipped firefighter

#	Posture	Dist. to node	Antenna pos.	Action
1	standing	3m	chest	ROT
2	crawling	3m	chest	ROT
3	standing	3m	shoulder	ROT
4	crawling	3m	shoulder	ROT
5	standing	8m	shoulder	A/W (1m per 15s)
6	standing	8m	chest	A/W (1m per 15s)
7	standing	8m	chest	2xA/W (continuous, ca. 10s per direction)
8	standing	40m	chest	A/W (continuous)

Action types are: ROT for a 360° rotation (45° every 15s) and A/W for approach and withdrawal to/from the node.

B. Results

Test 1-4 showed a strong dependence of antenna position and posture. I.e. if the antenna was either turned to the ground or to the ceiling RSS showed no significant trend. *Test 5 and 6* delivered a good RSS representation of the firefighters' movement independent of antenna location. *Test 7* showed a curve perfectly describing the action. *Test 8* showed a good representation of the firefighters movement when the firefighter was close to the node. In summary it is found that:

- position of antenna on firefighter is crucial
- orientation of antenna (directionality) is essential
- if antenna position and orientation fit posture then RSS reflects firefighters' actions
- a filter or classifier must be used to smooth RSS
- RSS influence due to ground reflection or other influences must be respected

[1] I.e. the firefighter was wearing a helmet, protective clothes, breathing apparatus and tool belt. He did however not wear his breathing mask.

IV. Antenna evaluation

In the following the type of antenna which might be used for localizing a specific sensor node of the network is considered. Various geometrical and mechanical designs of directional antennas exist. While size and directionality of the antenna depend on its type and the used frequency, directionality may be improved by shielding the antenna in one direction. Shielding can be realized by bonding the antenna onto a reflecting material. In discussion with the projects integration specialist and in respect to industry acceptance and availability two such reflector antennas were selected for this evaluation. Antenna A was a linearly polarized 53x27x5mm patch antenna in housing. Antenna B was a linearly polarized 70x50x15mm inverted f-shaped antenna without housing.

The test was focused on the front-to-back ratio (F/B ratio) of the antennas. The F/B ratio is a common measure to compare directional antennas and denotes the ratio of measured signal power at 0° to measured signal power at the antenna backside 180°. The higher the ratio the better the directionality of the antenna. To improve this ratio additional reflectors can be attached to the antennas. In this experiment the antennas were tested with three flexible wire grid reflectors: a small reflector of size 105x155mm (DIN A6), a medium reflector of size 155x225mm (DIN A5) and a large reflector of 210x300mm (DIN A4).

Firstly, signal level measurements were made with the unmodified antennas facing and turned away from the sender. Thereafter, measurements were conducted with the antennas bound to the reflectors. Table III gives a summary of the results.

TABLE III
Summary of the antenna measurements

Antenna	Additional reflector	Front to backside gain at 2.4 GHz
Patch	none	$-12dB$
	small	$-12dB$
	medium	$-18dB$
	large	$-20dB$
Inverted F	none	$-10dB$
	small	$-10dB$
	medium	$-17dB$
	large	$-22dB$
Attenuation	Human body	$-25dB$

Both antennas show very similar signal attenuations at 2.4 GHz. The attenuation of the unmodified modules is around $-10dB$. The small reflector delivers no significant additional attenuation with both antennas. The medium reflector provides an attenuation of $-7dB$ over the standard configuration, while the large reflector adds a total of $-8dB$ with the patch antenna and $-12dB$ with the inverted-f antenna. Hence, it should be considered depending on the type of antenna if the large reflector or the medium reflector has to be employed. The human body has a significant effect on the radio signal as it attenuates the signal by $-25dB$. Hence, in integrating the antenna close to the human body the total attenuation will increase considerably and should improve radio based direction finding.

V. Related work and discussion

Apart from the general physical characteristics of electromagnetic waves (attenuation depends on frequency and medium) and sound (speed of sound is reduced if temperature of medium increases), only few information on practical sensor tests are available. In [5] the authors report that while smoke and fire do not influence 802.11 link quality, signal throughput and range decreases in vapor. Our test results show similar results in that 2.4GHz signals are not affected by smoke and heat. Even during the extinction test most of the nodes showed no effect in RSS. Only node 2 lost its connection to the protocol node (6) after the test for a short time, possibly indicating a reduction in transmission range.

In [4] the authors define 4 smoke density classes, 6 types of smoke and 3 temperature zones using which they test various sensors. They report that only long-wavelength infrared was able to penetrate smoke of all density classes and over all tested distances (maximal tested distance 6m). They further report an influence of heat on their ultrasound measurements. We found a limit of short wave infrared of 3m in dense white smoke but found no influence of heat and smoke on the ultrasonic measurements which is probably related to the moderate test conditions in which most of the nodes reached a maximal temperature of 80°C. In contrast, the firefighting robot discussed in [4] must withstand up to 400°C. Further simplifications were made concerning distance, LOS between the nodes and accuracy of documentation. However, it could be shown that the use of commercial off-the-shelf (COTS) sensors is generally not denied in such a special environment.

Further investigations considered the influence of antenna location, receiver direction, distance and firefighter movement patterns on RSS. The test showed that RSS can reflect the action of a firefighter and that antenna position and orientation are essential for this function. It was further found that none of the two tested antenna positions is optimal in respect to the firefighters' posture. Possible alternatives are the front of the helmet, a flapping antenna (which moves depending on gravity) or a multiple antenna system. The helmet would further allow the direct association of direction of sight to the antenna measurements. As this test was conducted under LOS conditions further tests must be performed in obstructed more realistic environments. The noisy RSS after a certain distance is probably related to ground reflection. An effect which may be mitigated by increasing antenna height or narrowing the vertical radiation pattern of the antenna.[6] However, both of these options are hard to realize as the nodes have constrained dimensions and ought to be placed arbitrarily, while a reduced angle of the directional antenna may hide close nodes.

Lastly, two reflector antennas were revised considering F/B ratios. Measurements were conducted in LOS between sender and receiver at a frequency of 2.4GHz. While both antennas provided a good F/B ratio in their standard configuration the ratio was improved using wire grid reflectors. As the reflectors are flexible and can be easily scaled they are simple to integrate in the protective wear of the firefighters. Backside attenuation can be further improved if the antenna is carried close to the body. While our F/B measurement is not as precise as a sophisticated antenna analysis in an anechoic chamber, it nevertheless shows the antennas principal eligibility for radio direction finding. The performance of the antennas may further be improved by changing the antenna polarization to a circular polarization. Following this analysis, the antennas must further be evaluated on the firefighter as a location dependent influence is expected[6].

VI. Conclusion

In this work the influence of different aspects of a firefighting environment on sensor technologies was evaluated. It was found that ultrasound, infrared and radio sensors can be employed in such an environment. With the used COTS infrared sensor/transmitter range was limited in dense white smoke to 3m. It was further found that neither chest nor shoulder of the firefighter are optimal positions for a directional antenna. The front side of the helmet or a flapping antenna were proposed as alternatives but need to be evaluated. Lastly, it was found that available, integrable industry standard antennas in combination with flexible reflectors and the human body can significantly improve the directional capability of an antenna. Fusing this directionality information with a proximity measure and visualizing this information e.g. in the mask of the firefighter could provide an orientation in critical situations. This way the firefighter may possibly establish an augmented visual contact with the sensor node. Basing these information solely on 2.4GHz radio may not be practical due to typical effects. Therefore the combination with other tested sensors or lower frequency radio should be evaluated. Independent of the concrete realization of the system an evaluation in the firefighting training facility by the firefighters under increased heat, smoke and vapor should be conducted to ensure functionality.

VII. Acknowledgment

The authors would like to thank the firefighter brigade of the city of Cologne department Chorweiler for providing access to their training facility and test supervision. The authors further express their gratitude to all our project partners for the successful joint work.

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