Smart Communication and Relative Localization System for Firefighters and Rescuers

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***Abstract*—This paper presents a smart communication system for simultaneous data reception and direction of arrival estimation for firefighters, rescuers, and other emergency personnel. The system consists of a passive six-port microwave interferometer which transforms the challenge of an accurate phase measurement for direction estimation to a relative power measurement. This can be easily realized by the readout of the received signal strength indicator of low-cost commercial off-the-shelf transceivers which are simultaneously used for communication. Due to the differential IQ structure the robustness of the system is enhanced, even for severe disturbance and interference, where it still can provide a relative angle of emergency team members to each other.**

***Index Terms*—direction of arrival, relative localization, communication, phase measurement, RSSI, six-port, interferometer**

I. Introduction

Firefighters and other emergency forces often risk their lives in critical situations to help others. Especially smoke, vapor and dust may limit their vision and orientation with possible fatal consequences. A report from the US National Fire Protection Association (NFPA) has identified "lost inside" as one of the three major traumatic injuries to firefighters [1]. As commonly used location systems based on the global positioning system (GPS) are not reliable inside buildings, there is a huge demand for technical solutions, especially for localization and tracking systems [2]. Infrastructure-based localization shows promising results in terms of absolute positioning accuracy but requires pre-installed beacons that are not preset everywhere [3]. Inertial sensor-based indoor localization requires only a small device worn by the first responder, however, the biggest challenge of this concept is the sensor drift that integrates the position error over time [4]. Although ad-hoc relative localization can only obtain angular information between several targets this can already be a major relief for emergency forces, e.g., when a building is filled with smoke and a group of firefighters tries to locate a nearby colleague who needs help. Main advantages of this concept are the robust system, that the user can easily understand, and that neither pre-installed infrastructure is necessary nor does a sensor drift integrate the error over time [5]. Thus, this paper presents a smart and reliable communication system with a new concept for simultaneous data reception and direction of arrival (DOA) estimation using a six-port microwave interferometer and low-cost commercial off-the-shelf (COTS) transceivers. The system can be easily integrated, e.g., into a firefighter helmet and provides the relative position (angle information) on a head-mounted display or by a spatial hearing impression using a stereo headset.

II. System concept

The fundamental idea of six-port based relative localization is a DOA estimation realized by a path delay induced phase difference measurement of the input signals of two receiving antennas [6]. The six-port structure was historically known as a reflectometer but is nowadays used for a much wider range of microwave and mm-wave communication as well as measurement applications [7], [8]. Main reasons are the passive structure, the high phase resolution and a low-cost system with simple signal processing [8]. The block diagram of the system concept is depicted in Fig. 1.

The two antennas are placed in a well-known distance d to each other, ideally spaced apart equal to half the wavelength of the operating frequency to avoid ambiguities [6]. Each antenna is connected to one of the two input ports of the six-port structure. Depending on d and the angle of arrival α a phase difference $\Delta\phi$ will occur between the two received signals (P_1, P_2). This phase shift can be easily evaluated by the six-port interferometer that superimposes the two input signals under four different relative phase shifts of 0°, 90°, 180°, and 270° using four passive microwave couplers: A power

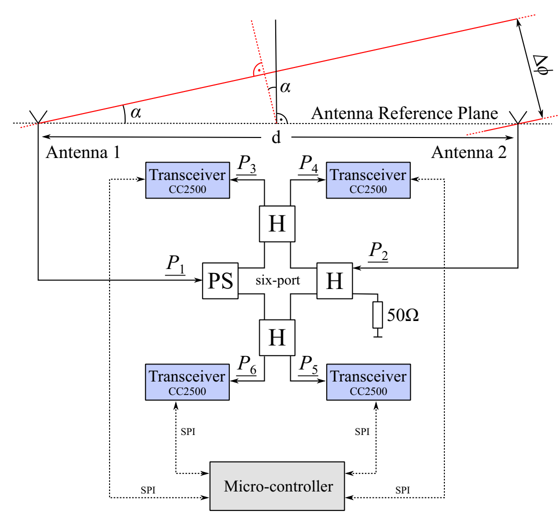


Fig. 1. Simplified block diagram of the receiver's system concept.

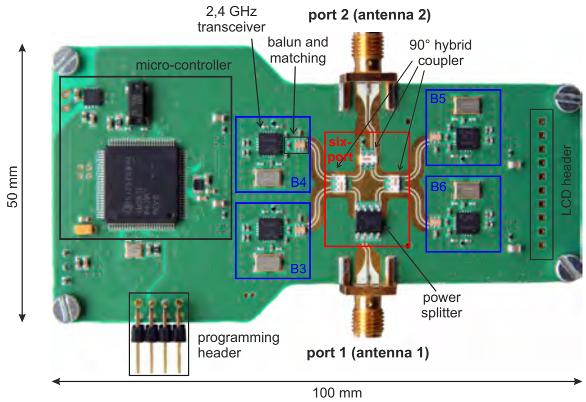


Fig. 2. Photo of the receiver unit featuring a 2.4 GHz six-port interferometer, four low-cost COTS transceivers and a low-power micro-controller.

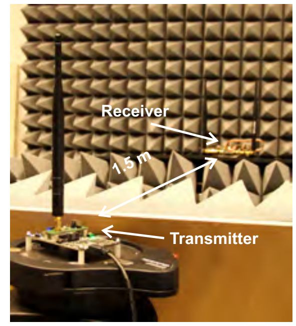
splitter (PS) as well as three 90° quadrature hybrid couplers (H). Depending on the relative phase between the input signals constructive or destructive interference takes place so that the original phase difference is now represented as a power ratio at the radio frequency (RF) output signals ($P_3 \ldots P_6$). At this point, typically diode-based power detectors perform a direct conversion to DC [8]. However, for the proposed novel system concept low-cost COTS communication receivers featuring a received signal strength indicator (RSSI) are used instead. This way the input power can be easily determined but, furthermore, all the benefits of modern monolithic microwave integrated circuits can be used: They feature an excellent receiver sensitivity, have a compact and low-power realization as well as media access control capabilities, packet orientated transmission, cyclic redundancy check, and error correction. The RF power measurement is simply performed by digital readout of their RSSI registers. Using the measured power values ($P3 \ldots P6$ in linear representation) and the knowledge of λ as well as d the DOA angle α can easily be calculated as described in [6]:

$$\alpha = \sin^{-1}\left[\frac{\lambda}{2\pi \cdot d} \cdot \operatorname{atan2}\left(\frac{P3 - P4}{P5 - P6}\right)\right] \qquad (1)$$

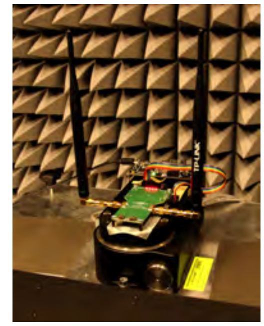
To avoid ambiguities the distance should be chosen to half the wavelength of the operating frequency [6]. Alternatively, a dual six-port system can be used: With evaluation of the difference function the unambiguous range can be significantly enhanced [9].

III. Hardware Demonstrator

A hardware demonstrator in the 2.4 GHz industrial, scientific and medical (ISM) frequency band has been built up and evaluated. Fig. 2 depicts a photo of the receiver unit and the assembled components. The six-port structure was realized by compact lumped components from Mini-Circuits (power divider: BP2U+ and 90° hybrid coupler: QCN-27+) interconnected by grounded coplanar waveguides on a 0.254 mm Rogers RO4350B high frequency substrate. A realization with planar microwave couplers, like shown in [10], would also be possible and even be more cost efficient, but requires considerable more board space. Low-cost 2.4 GHz transceivers (CC2500 by Texas Instruments (TI), unit price US$ 1.40) have been selected for data reception and RSSI power measurements. They are suited for audio and speech transmission, support different modulation formats (OOK, FSK, MSK) with a data rate of up to 500 kBit/s and show a very good RSSI linearity from -20 dBm down to -100 dBm with a resolution of 0.5 dB. They are connected by a standard serial peripheral interface to a low-power micro-controller (MSP432 by TI) which performs the data reception and RSSI readout.



(a) Transmitter (static) with the receiver in the background



(b) Receiver with two antennas, mounted on rotary stage

Fig. 3. Photo of the experimental measurement setup.

IV. Experimental Setup and Measurement Results

An experimental setup using an automated rotary stage has been built up (Fig. 3) to evaluate the proposed system concept. The inter-antenna distance at the receiver (Fig. 3b) was approximately 14 cm (1.12 λ). This is above the desired distance of 0.5 λ so it limits the unambiguous measurement range, but investigations showed that a closer antenna distance leads to an undesired mutual coupling between the currently used rod antennas. The ambiguity will map the precisely measured DOA back to the first period, i.e., for angles exceeding the ambiguity range a static offset characteristic for the respective actual period is missing. Optimized antennas or the use of a dual six-port system with two different antenna distances, as shown in [9], could be used to resolve this issue. The transmitter (Fig. 3a) was programmed to continuously send 20 MSK-modulated data packets per second to the receiver, which collected 100 of them at each angle to evaluate the precision and accuracy of the system. In total 40 different angles have been evaluated, with a step-size of 2.2° to fully cover one unambiguous measurement range, for different scenarios and emulated interference types.

The measurement results for a free space measurement with no intentional interference are depicted in Fig. 4. The IQ-diagram, calculated from the measured and delogarithmized power values (P3 ... P6), without any compensation, is a little distorted and the calculated DOA α shows some slight nonlinearities. Nevertheless, the coarse angle can be clearly identified, what is most important for the proposed use case. The measurement angluar precision σ was around 1° in average for a single measurement. The packet loss rate was

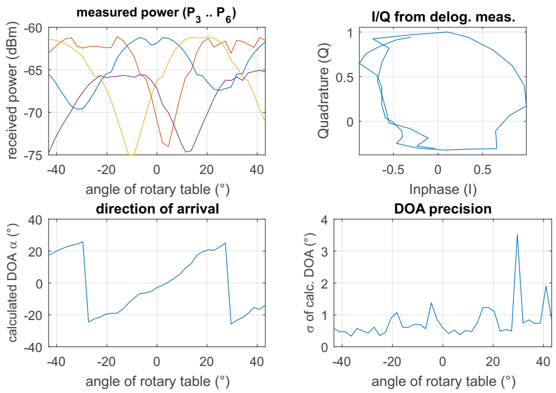


Fig. 4. Measurement results without intentional interference.

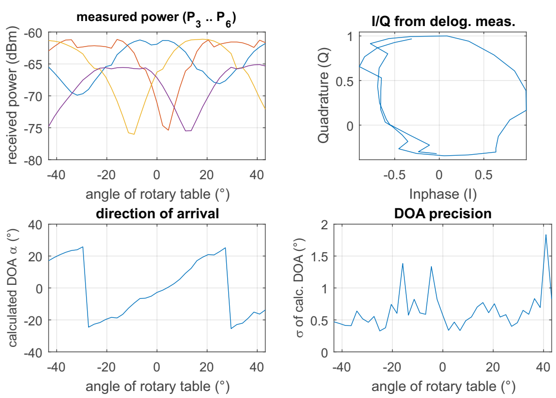


Fig. 5. Measurement results with interfering WiFi devices in neighbor channel.

about 0.05 % and is the reason for the peak in the measurement precision at around 30°, where some packets were lost randomly. For investigating the reliability of the system the same measurement has been performed with three active WiFi devices in an adjacent channel (Fig. 5), showing almost no difference: The random packet loss of 0.01 % was even a little lower, proving the good band selection within the receivers. To evaluate the system in a high interference scenario an RF signal generator has been used, transmitting a continuous wave (CW) interference signal, with equal power, directly at the carrier frequency of the communication with 50 % and 100 % duty cycle. The measurement results for the 100 % duty cycle interference are depicted in Fig. 6. A considerably higher packet loss (approx. 12 %) and worse precision (about 3.2° in average) of the DOA estimation could be observed. Depending on the angle of the rotary table it is sometimes even impossible for a single receiver to receive a valid signal at all, resulting in an RSSI measurement below the sensitivity limit (-104 dBm). But here the differential I/Q-structure of the six-port structure and the redundant receiver concept shows its advantages: Even though one receiver is completely distorted the others are still able to receive an useable signal and thus the DOA angle can be estimated, although, of course, with higher noise. Nevertheless, as these are random errors,

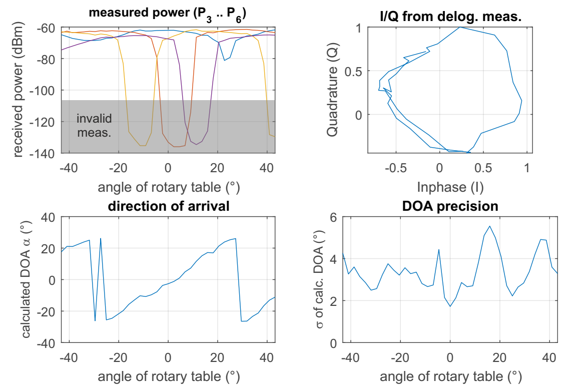


Fig. 6. Measurement results with a CW interferer (0 dB, 100 % duty cycle) directly at the carrier frequency.

TABLE I
SUCCESS RATE OF VALID RSSI DETECTION FOR DIFFERENT MEASUREMENT SCENARIOS

interference type	packet loss (%)	avg. precision
no intentional interference	0.05 %	0.77°
active Wi-Fi (adjacent ch.)	0.01 %	0.65°
CW pulsed interference (50 %)	6.37 %	2.82°
CW interference (100 %)	12.05 %	3.35°

the averaged angle calculations are still very close to the undistorted measurements, demonstrating the robustness of the proposed system concept even in harsh environments. Table I shows a summary of the measurement results and compares the packet loss as well as the measurement precision.

The presented demonstrator has been evaluated in a laboratory environment. As for any DOA and RSSI-based localization system indoor multipath propagation, which occur in real scenarios, can be a severe challenge. There are already several approaches to adress this issue based, e.g. on sensor fusion with inertial sensors and correlating RSSI measurements with data from a digital compass [11], [12].

V. Conclusion

A smart system for simultaneous data reception and direction of arrival estimation has been presented. The concept can be used to provide reliable communication and relative localization for firefighters and other emergency personnel also in harsh environments with limited visual range. With an integration, e.g., in the helmet and providing the angular information as a spatial hearing impression the concept can be simply used without any further user intervention. The system is based on a passive microwave six-port interferometer and low-cost COTS communication transceivers. A first demonstrator in the 2.4 GHz ISM band has been shown, providing a reliable DOA estimation and communication, even under severe interference, due to its differential IQ-structure that creates a diversity and redundancy in the system. Further enhancements can be made to remove the current angle ambiguities, e.g. by optimized antennas or a dual six-port [9] concept.

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