Combining of Redundant Signal Strength Readings for an Improved RF Localization in Multipath Indoor Environments

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Abstract—Multipath signal fading is a fundamental problem when using received signal strength (RSS) readings as sensor for a range-based indoor localization. Redundant RF transceivers with a simultaneous use of spatial and frequency diversity enable a compensation of multipath fading effects for more precise distance and position estimations. A novel maximum probability combining technique for a sensor fusion of the RSS readings of up to eight redundant and decorrelated RF channels is proposed. Experimental results on a one-dimensional motion test track are used to evaluate the improved localization performance compared to a maximum signal combining and the accuracy of a position estimation without redundancy.

Index Terms—Indoor Localization, Multimodal Diversity Combining, Multipath Fading Compensation, Object Tracking, Real-Time Positioning, Received Signal Strength.

I. INTRODUCTION

The latest research activities regarding indoor local positioning systems (ILPS) for the tracking and navigation of people and objects show a variety of applied sensor technologies (cf. Fig. 1). The use of directional sensors like infra-red (IR), ultrasound or optical systems are limited to line-of-sight (LOS) scenarios. Systems with artificial quasi static magnetic fields are more robust in multipath environments, although the high power consumption of coil-based magnetic fields limit the field of application. Due to the latest advances in micro-electro-mechanical systems (MEMS) the use of an miniaturized inertial navigation system (INS) seems interesting for an ILPS. The main issue of an INS is the limited long-term stability of MEMS-based localization systems.

Hybrid localization systems with a sensor fusion of different types of sensors are able to overcome the specific drawbacks of a single system. The fusion of RF-based systems with an INS is a common solution which offers both, a good short-term accuracy and a good long-term stability. An overview of the latest positioning systems with a comparison of their specific coordinate accuracy and coverage is given in [1]. A more general taxonomy of localization systems can be found in [2].

Range-based systems with an evaluation of the received signal strength (RSS) of narrow-band RF signals are commonly used for obstructed environments with many non-line-of-sight (NLOS) conditions, although they are known to be error-prone in multipath environments.[3],[4] The characteristics of fading channels inside a factory building are discussed in [5] and [6]. The multipath propagation due to reflection, diffraction and scattering leads to signal interferences at the receiver. Thus, the RSS is affected by strong variations and frequent signal drop outs which make it challenging to find a relationship between the RSS and the distance between transmitter and receiver.

One solution to overcome multipath signal fading is the use of an ultra-wide band (UWB) technique. The short signal pulses lead to a relative low sensitivity to multipath fading effects. Otherwise, UWB has a limited communication range and needs expensive transceiver hardware. A possibility to compensate fading with the use of narrow-band RF signals is the implementation of multiple-antenna techniques. The spatial multiplexing of different antennas is primarily used to increase the data rate of RF communication systems, like it is implemented in the IEEE 802.15.4n WLAN standard with MIMO channels and multiple frequency bands.

Diversity with a combining of redundant and decorrelated RF channels can be used to compensate signal fading and enhance the link reliability [8]. Thus, multiple-antenna techniques are not only exploiting the capabilities of data communication, but also can be used in indoor localization systems to reduce the error of the RSS-based distance estimation and increase the accuracy of the associated position estimation.

Time diversity with a repeated transmission often is not an acceptable solution – especially when a real-time local-

Fig. 1. Taxonomy of localization techniques according to the used sensor, the signal processing and the location estimator (cf. [7]).
ization is required. With an a priori limited transmission delay the simplest possibility to get redundancy into the radio transmission is the so-called spatial diversity. Therefore the RF signal is transmitted and/or received using two different antennas which are placed in a certain distance to each other. In order to compensate the effects of multipath fading and especially the influences of noise from external interferers, the same signal might also be transmitted using two different carrier frequencies. Therefore, two channels of the same frequency band or even of different frequency bands can be used. Our latest research investigations focus on low-cost redundant transceiver solutions with spatial and frequency diversity and efficient signal fusion strategies for redundant RSS measurements to reach an improved position estimation in obstructed indoor environments. The application of several antennas with different radiation patterns and polarizations is interesting for the localization with angle of arrival (AOA) measurements and therefore is not considered in the following.

In section II, a survey of the related work regarding multiple-antenna techniques for an improved RSS-based position estimation is given. The used system model for the RF propagation in multipath indoor environments and the principles of diversity combining are presented in section III. The system architecture of the used RF diversity transceiver hardware is described in section IV. The proposed maximum probability combining algorithm for up to eight diversity channels is described in section V. Results from a path loss measurement are used to evaluate the combining process in section VI, the position estimations using different combining techniques are compared by experimental results of a dynamic tracking measurement on a one-dimensional motion test track. In the last section VII, the results are discussed and investigated in terms of an outlook for further system developments.

II. RELATED WORK

A localization in wireless sensor networks with a combination of temporal and frequency diversity is presented in [9]. With a switchover between two different channels in the 2.4 GHz WLAN band the rms error of the position estimation in an office building is reduced by about 30%. For the signal combining the results for the maximum, average and minimum RSS are compared without showing significant differences. In [10] the RSS values of two consecutive RF transmissions in two adjacent frequency bands (868 MHz, 915 MHz) using the same antenna are averaged to detect outliers and reach a more precise localization. According to the Jakes model [11] the redundant channels are not completely decorrelated due to the low frequency separation. Also the signal combining with an averaging of the redundant RSS is not an optimum solution for multipath fading channels.

In [12] an indoor location estimation and tracking based on a selection combining of a 433 MHz and 2.4 GHz RSS measurement is proposed. With the large frequency separation the channels can be assumed to be decorrelated. The results show better distance approximations for 2.4 GHz in LOS scenarios and for 433 MHz in NLOS environments.

For all related techniques an additional time diversity is effective since there is a time lag between the transmissions with different carrier frequencies. With the mingling of different diversity techniques the redundant channels can not be assigned as decorrelated. Thus, the results might only be relevant for a position estimation of stationary devices but not for a localization and tracking of moving devices.

In [13] we propose a multimodal diversity transceiver platform with the simultaneous use of spatial and frequency diversity. A digital selection combining of up to four redundant RSS indicator (RSSI) values is used to compute the maximum RSS and achieve a high available and precise two-dimensional localization in a factory hall. A miniaturized platform with chip antennas and tracking results for a one-dimensional setup are proposed in [14] together with a detailed path loss analysis of eight redundant RF channels.

III. SYSTEM MODEL

A. Multipath Fading Channel

To find a relationship for the distance-dependent RSS and to evaluate the impact of diversity in multipath fading environments, it is necessary to have a look at the indoor signal propagation model for a single channel. Without any disturbances (free space propagation) the distance-dependent path loss shows a logarithmic dropping of power with a linear increasing distance according to the log-distance path loss model. With (1) the average path loss $PL(d)$ (in dB) over a distance $d$ is given by the reference path loss $PL(d_0)$ over a reference distance $d_0$ of eight redundant RF channels.

$$PL(d) = PL(d_0) + 10n \log \left( \frac{d}{d_0} \right).$$ (1)

The value of $PL(d_0)$ is influenced by the effective radiated power (ERP) of the RF transmitter and the gain of the transmitting and receiving antenna. The value of $n$ is influenced by the specific environmental propagation conditions and the used frequency. In [6] and [15] values for $n$ between 1.8 and 3.2 are given for frequencies between 900 MHz and 4.0 GHz in obstructed indoor environments where not only NLOS conditions but also multipath signal fading affects the RF signal propagation.

The distance dependent path loss from (1) is an average value and therefore not suitable to entirely describe a real channel. For obstructed indoor environments the log-normal shadowing model (LNS) is used. A zero-mean Gaussian random variable $X_{\sigma}$ with standard deviation $\sigma$ is added to the average path loss according to (2).

$$PL(d) = PL(d_0) + 10n \log \left( \frac{d}{d_0} \right) + X_{\sigma}$$ (2)

To investigate the path loss in fading environments we have carried out an indoor measurement with proprietary 2.4 GHz RF modules. The measured RSS over a distance of 11 m is shown in Fig. 2 where the small-scale fading due to the multipath propagation is pointed out. The determined reference
path loss $PL(d_0)$ at a distance of $d_0 = 1\, m$ between TX and RX antenna is $-67\, dBm$ for the used IEEE 802.15.4 compliant 2.4 GHz RF transceiver with an output power of $+10\, dBm$. The resulting path loss coefficient $n = 2.62$ is a typical value for fading environments. The destructive interferences of different multipath signals lead to abrupt signal dropouts where the signal sometimes even falls below the receiver’s sensitivity level $S_{\text{min}}$ and the transmitted information gets lost.

In Fig. 2 the multipath fading becomes apparent by a significant short-term variation of the RSS values in the case the TX antenna is moved in the order of the wavelength (e.g. a few centimeters). The experimental path loss shows deep fades of about $25\, dB$, according to [15] even larger dropouts by more than $40\, dB$ have to be assumed. In general, a Rayleigh distribution of the RSS is assumed for NLOS conditions. When there is also a LOS component reaching the receiver the fading is modeled with a Rician distribution. The probability density function (PDF) of the Rician distribution is given by

$$f(x, \nu, \theta) = \frac{x}{\theta^2} \exp \left( -\frac{x^2 + \nu^2}{2\theta^2} \right) I_0 \left( \frac{x\nu}{\theta^2} \right),$$  \hspace{1cm} (3)

where $\theta$ is the amplitude of the superimposed RSS from all multipath components and has a scaling functionality. The parameter $\nu$ is the peak amplitude of the LOS component. For $\nu = 0$, the Rician distribution reduces to a Rayleigh distribution. Thus, the Rician distribution is a generalization of the Rayleigh distribution. For $\nu \to \infty$ the distribution reduces to a Gaussian distribution.

The ratio of the LOS component compared to the superimposed signal can be expressed by the Rician K-factor according to (4).

$$K(dB) = 10 \log \frac{\nu^2}{2\theta^2} dB \hspace{1cm} (4)$$

The environment-specific values of $\nu$ and $\theta$ can be evaluated with an empirical analysis of multiple path loss observations using a two moment-based estimator as described in [16].

A typical variation of the RSS values for the path loss in multipath environments with a dominating LOS component is shown in the histogram in Fig. 3. The values are taken from the path loss measurement from Fig. 2 using proprietary 2.4 GHz RF transceivers. The variation of the RSS around the average value is modeled with the shown Rician distribution using $K \approx 17.7\, dB$ which completely specifies the Rician distribution. In Fig. 4 the distribution of the RSS values for a 868 MHz path loss measurement and the corresponding Rician distribution with $K \approx 20.0\, dB$ are shown.
B. Diversity Channel Correlation

As statistical model for the correlation coefficient envelope $\rho$ of redundant channels in a diversity configuration we use the Jakes model [11] according to

$$
\rho = \frac{J_0^2 (k_0 v \tau)}{1 + (2\pi)^2 S_{\tau}^2 (f_2 - f_1)^2},
$$

(5)

where $J_0$ is the zeroth order Bessel function, $k_0$ is the wavenumber, $v$ is the velocity, $\tau$ is the temporal separation, $S_{\tau}$ is the rms delay spread and $f_2 - f_1$ is the frequency separation. For the used Jakes model some assumptions need to be made, including the validity of the wide sense stationary uncorrelated scatterer (WSSUS) model and omnidirectional antennas with isotropic power distributions.

Any correlation between the fading of the channels reduces the improvement of diversity. If $\rho$ is below a certain threshold the channels are assumed to be “effectively” decorrelated [17]. This can be reached by large frequency separations or large spacings between the antennas. Since the place on a transceiver module is limited and the Bessel function has certain minimum values, the spatial separation with the minimum optimal antenna spacing is of interest and will be discussed in detail in the next section.

C. Optimum Antenna and Frequency Separation

The requirements of a small correlation coefficient between two radio channels are a large frequency separation or a large spatial antenna separation (at RX and / or TX). A large antenna separation might not be possible on a miniaturized hardware platform. Since $J_0$ has more than one local minimum the hardware design goal should be a preferably small correlation coefficient with respect to the limited spatial hardware expansion.

For a moving communication participant the spatial diversity is mathematically equivalent to the temporal diversity. Assuming a stationary transmitter, the distance $d$ which a mobile receiver moves between the first transmission and its repetition is equal to the distance of two spatial separated antennas at a stationary receiver. For spatial diversity with $\Delta f = (f_2 - f_1) = 0$, the envelope of the correlation coefficient from (5) can be written as

$$
\rho(d/\lambda) = J_0^2 \left( \frac{2\pi d}{\lambda} \right),
$$

(6)

where $d$ is the spatial antenna separation. The envelope is shown in Fig. 5 for the correlation of frequency and spatial diversity channels.

For frequency diversity the correlation coefficient decreases with larger frequency separations. Thus, a maximum of possible separation should be used. The minimum optimal distance for spatial diversity can be derived from (6). The first root of $\rho(d/\lambda)$ at $d/\lambda \approx 0.38$ gives the minimum optimal antenna spacing. For a frequency of 2440.2 MHz this value of $d/\lambda$ is reached with $d \approx 4.67$ cm.

![Fig. 5. Envelope of the correlation coefficient as a function of antenna and frequency separation (normalization to $d/\lambda$ and $2\pi\Delta f S_{\tau}$ for spatial separation and frequency separation, respectively). Source: [17]](image)

IV. DIVERSITY TRANSCIEVER ARCHITECTURE

For our new signal combining approach we use our latest multimodal RF platform (cf. Fig. 6) which consists of a MSP430 16-bit MCU and four proprietary RF transceivers, two operating at 868 MHz (T1, T3) and two operating at 2.4 GHz (T2, T4). Both transceivers use the TI Chipcon RF stack (CC1101 for 868 MHz, CC2500 for 2.4 GHz) and are connected via SPI to the MCU. The distance between the two antennas of a frequency band is $d = 5$ cm. According to the Jakes fading model and Fig. 5 the distance is near the optimum for the 2.4 GHz band ($f_g = 2440.2$ MHz, channel #36). For the 868 MHz band ($f_g = 868.3$ MHz, channel #0) the theoretical minimum optimal antenna spacing is $d \approx 13.13$ cm. This distance can not be realized with a miniaturized hardware platform, thus we accept a higher correlation coefficient $\rho(d/\lambda) \approx 0.65$ for the 868 MHz band.

![Fig. 6. Miniaturized diversity module (right) and schematic communication structure with eight diversity branches (left).](image)

In the following, the progress of a redundant RSS sampling will be described in detail. First of all, the transmitter MCU splits up the signal into four packets which are sent to the RF transceivers. In the first step, the RF packet is transmitted over T1 and T2 at $t = t_1$ simultaneously. Of course, the other two RF transceivers (T3 and T4) have two be hold in IDLE mode for the duration of the first transmission to prevent the platform from receiving its own RF packet. Immediately afterwards these two transceivers send out a packet at $t = t_2$ and the
remaining transceivers are hold in IDLE mode. The time gap respectively temporal separation from (5) between the first and the second transmission is \( t_2 - t_1 = 1 \text{ ms} \). For the dynamic behavior of the mobile platform we assume a maximum speed of \( 2 \text{ m} \cdot \text{s}^{-1} \). Thus, there is a spatial misalignment of \( 2 \text{ mm} \) between the two transmissions. For both frequencies, this distance is much lower than the corresponding wavelength and thus, the time difference can be neglected. The receiver uses the same hardware as the transmitter. Since two RF packets are received for each transmission, overall eight packets can be analyzed for their RSS values.

V. Advanced RSS-Based Combining

In addition to our previous selection combining algorithm we use the information of all RSSI values of the same frequency – especially their statistical distribution – to get another improvement of the system’s accuracy. The combining logic which runs on the MCU at the RX is a two-stage processing according to the principle from Fig. 7.

![Fig. 7. Two-stage combining using spatial and frequency diversity channels, separate maximum probability combining (MPC) for each frequency and maximum signal combining (MSC) for the output fusion.](image)

In the first step a separated processing of the two frequency bands is realized. The maximum probability combining (MPC) unit computes an RSS value with the maximum probability according to a Rician RSS distribution of the spatial diversity channels with (3). For both frequencies, we use the Rician K-factor from the path loss measurement according to Fig. 3 and Fig. 4 \((K_{868 \text{ MHz}} = 20.0 \text{ dB}, K_{2.4 \text{ GHz}} = 17.7 \text{ dB})\). The two frequency-separated branches are combined in the second step by an additional MPC stage. In order to evaluate the performance of the MPC combining, we performed a path loss measurement on a motion test track (cf. Fig. 9).

In Fig. 8, the RF path loss for the different diversity branches of the MPC logic are compared with the path loss of two single channels of each frequency and the MPC output using all channels. The given values for the standard deviation are an indicator for the quality of an RSS-based distance approximation. Thus, the MPC approach \((\sigma = 1.84 \text{ dB})\) outperforms the MSC technique \((\sigma = 2.43 \text{ dB})\) and MPC will result in an increased accuracy of the RSS-based position estimation. Of course, MSC has a slighter path loss dropping than MPC \((n = 1.29\) compared to \(n = 1.66\)) but this might only be important for an optimization of the SNR at the receiver when the availability of the communication is the only criterion.

VI. Location Estimation Results

The test bed for the tracking measurements is shown in Fig. 9 on the left. The mobile blind node (BN) which should be located performs periodic movements on a motion test track according to the motion profile shown on the right. The

![Fig. 9. Measurement setup on a motion test track in an obstructed test hall (motion profiles show one A-B-A motion cycle, \(T = 60 \text{ s}\)).](image)
duration of one movement from position A to B and back to A is 65 s. Seven reference nodes (RNs) are evenly distributed next to the track with a distance of 2.0 m between two nodes. For an explicit multipath propagation we installed metallic reflecting walls next to the track. Since there is always a LOS between the nodes, a Rician fading channel is assumed.

In Fig. 10 the trajectories of the BN on the motion test track for a complete motion cycle (A-B-A) are shown. Like we have proceeded at the path loss measurement in section V, different configurations are compared to point out the influence of the diversity and combining on the localization accuracy.

A detailed comparison of the location estimation error (LEE) of different diversity and combining techniques is given using Table I and the cumulative distribution functions (CDFs) in Fig. 11. The MPC of the four spatial diversity channels reduces the error for both, the 868 MHz and the 2.4 GHz band. The improvement is slightly higher for the 2.4 GHz band which indicates a lower correlation coefficient according to (6). Looking at the CDFs, the performance of the MPC compared to the MSC algorithm gets emphasized. The MPC reduces the maximum error for the combining of all eight RSS values by more than 34 %. Even the MPC of four 2.4 GHz channels enables a more accurate position estimation than the MSC of all eight channels.

![Fig. 10. Estimated tracks for 868 MHz and 2.4 GHz measurements on a motion test track, qualitative comparison of different diversity and combining techniques.](image)

![Fig. 11. Cumulative distribution functions for the location estimation error (LEE) of a 9.6 m tracking measurement using different diversity and combining techniques.](image)

**TABLE I**

<table>
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<th></th>
<th>868_A</th>
<th>868_MPC</th>
<th>2.4_A</th>
<th>2.4_MPC</th>
<th>MSC</th>
<th>MPC</th>
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<td>1.56</td>
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</table>

**VII. CONCLUSION AND FUTURE WORK**

The tracking results show that RSS-based localization holds a lot of promise when redundant signal strength readings are used. Especially the path loss measurement indicates the good conformity of the MPC combining approach with the theoretical Rician RSS distribution in indoor LOS environments with multipath fading. The simultaneous use of spatial and frequency diversity channels shows a low inter-channel correlation and a good fading compensation performance. Although not shown, the use of multiple frequency bands leads to a more reliable localization in the presence of external interferer like WLAN, Bluetooth or other widespread RF standards.

For a more sophisticated evaluation of the tracking system we are going to introduce a further measurement with the controlled inclusion of external interferences to point out the influence of the frequency diversity. The tracking system should also be tested in more obstructed multipath environments to confirm the performance of the proposed MPC technique for an ILPS under real-life conditions.

**REFERENCES**


