

Bandwidth Dependence of CW Ranging to UHF RFID Tags in Severe Multipath Environments

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Abstract— In this paper the impact of the signal bandwidth on the performance of frequency modulated continuous wave (FMCW) radar based ranging to ultra high frequency (UHF) radio frequency identification (RFID) tags is investigated. The analyses are based on ultra-wideband (UWB) channel measurements performed in a warehouse portal, which is a severe multipath environment. It is illustrated that the available bandwidth of the usual ISM bands at 900 MHz, 2.5 GHz and 5.8 GHz is only sufficient for a precise RFID tag localization if moderate or low multipath conditions are given. However, in severe multipath channels the ISM bands are unsuited and UWB signals are needed. The results can be considered a lower bound for signal time of flight (TOF) based localization approaches that utilize Fourier or correlation methods for the signal travel time estimation.

Keywords—UHF RFID, multipath channels, channel sounding, FM radar, distance measurement.

I. INTRODUCTION

The increased reading range of modern UHF RFID systems comes along with an increasing uncertainty of the actual spatial and situational context during the reading event. This stimulates an increasing interest in distance measurements to RFID tags and direct range bounding.

The basic principles to identify and localize a cooperative target such as an RFID backscatter transponder with the use of secondary radar have been known for a long time [1]-[3]. In [4] and [5], several CW secondary radar based transponder systems are presented that allow localizing and tracking amplitude- or phase-modulated backscatter transponders by phase or frequency evaluation of the radar beat signal. The principles of single-carrier CW, multi-frequency or stepped-frequency, and FMCW radar systems and their related evaluation approaches can be found in the above mentioned publications. Recently, several research groups have utilized these CW approaches for the UHF and microwave RFID tag localization problem and extended them by new features or established new applications [6]-[10].

The application of a CW radar system for UHF RFID localization is attractive because the design of RFID reader and backscatter tag required for ranging is very similar or even identical to general UHF RFID systems. Merely the tag

modulation, the RF synthesizer, and the reader signal evaluation have to be adapted.

Even though passive UHF RFID is now a widespread technology, reliable positioning in real-life scenarios is a feature that is not yet available. Beside the constraints of the power supply, the reading range, and the system complexity, also the bandwidth limit of the UHF RFID frequency band poses a major challenge. The channel sounding in a warehouse portal [11] has shown that UHF RFID channels are often dominated by indirect (non-line-of-sight, NLOS) paths and not by the direct (line-of-sight, LOS) path. This leads to large ranging errors and biased distance estimates for narrowband radar signals, since an extraction of the LOS signal is rarely possible with low bandwidths. Ultra wideband (UWB) systems have the potential to overcome this problem and make accurate ranging in dense multipath environments feasible [12], [13], but have strict power emission limits and a considerably higher system complexity.

In a preceding measurement campaign ([11,14]), a representative set of the UWB channel transfer functions in a UHF RFID warehouse gate has been acquired. These measurements are utilized in this paper to analyze the impact of the chosen signal bandwidth on the ranging uncertainty in multipath channels. The analysis covers bandwidths ranging from narrowband to ultra-wideband.

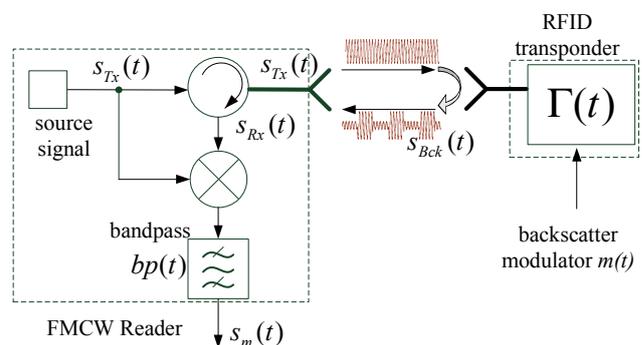


Figure 1. Setup of the FMCW radar based RFID localization system.

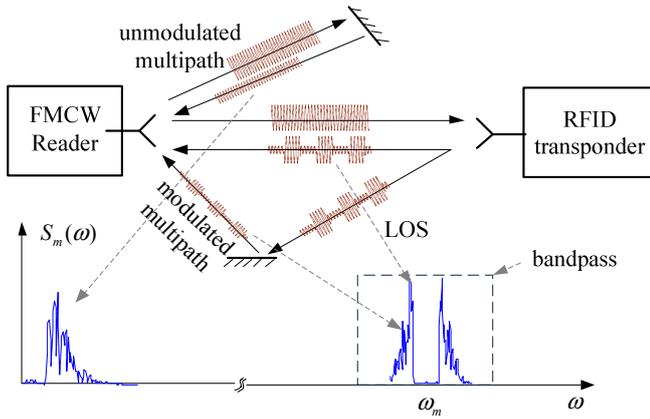


Figure 2. Exemplary radar echo profile of a FMCW secondary radar measurement to a RFID backscatter transponder in a multipath environment.

II. CW RADAR BASED UHF RFID TAG LOCALIZATION

A. System Setup and Localization Approach

The setup of the considered FMCW radar based RFID localization system is depicted in Fig. 1. The radar unit emits a transmit signal $s_{Tx}(t)$ that will be reflected by the RFID transponder and additional passive objects located in the environment. If we assume that the transponder reflectivity $\Gamma(t)$ is a periodical modulation with a period $T_m = 2\pi/\omega_m$, where $1/T_m$ is the modulation frequency and let φ_m denote the phase shift, we can write:

$$\Gamma(t) = \Gamma_0 \cdot \cos(\omega_m \cdot t + \varphi_m). \quad (1)$$

Note that this analysis concentrates on the effects of the channel, hence the modulation is assumed to be stable, i.e., the frequency variation is assumed to be negligible inside the measurement window. For simplicity, we also presume a frequency-independent reflection coefficient.

The radar will receive two kinds of echoes from the channel: a) the echoes of the passive objects that are the time delayed replicas of the transmitted signal and b) the echoes caused by the transponder that are delayed and superimposed by the amplitude modulation given by (1). Both kinds of echoes can either be transmitted directly over the LOS path or via multipath reflections. In a FMCW radar, the frequency of the down-converted radar beat signal $s_m(t)$ is proportional to the signal roundtrip-time-of-flight (RTOF) of a given echo. The modulation (1) shifts the complete echo profile related to the backscattered transponder signal from the center frequency $\omega = 0$ to the radian modulation frequency $\omega = \omega_m$, i.e., to larger distance values well separated from the echoes of the passive objects. A typical echo profile is shown in Fig. 2. Since the transponder signal components are amplitude modulated, we obtain an echo profile with two sidebands centered around ω_m . In [4]-[6] and [8] it is shown that the RTOF of a transponder echo can be determined by the frequency and/or phase difference between the two spectral lines – which are symmetrically located around ω_m . By identifying the LOS echoes, i.e., the two spectral lines with the closest distance to

the left and right of ω_m , the distance between the reader and the backscatter RFID tag can be determined.

B. Range resolution

The minimal width of an echo and thus the range resolution δ_{rad} quantifies the ability of a FMCW radar to separate two closely spaced echoes. It is directly linked with the radar signal bandwidth B via

$$\delta_{rad} \approx \frac{c_0}{2B}, \quad (2)$$

where c_0 is the free space RF signal phase velocity.

C. Transmission model

For identical up- and downlink channel impulse responses $h(t)$ and given a transmit-signal $s_{Tx}(t)$ the measured beat signal $s_m(t)$ is given as follows:

$$s_m(t) = \left(\left(\left(s_{Tx}(t) * h(t) \right) \cdot \Gamma(t) \right) * h(t) \right) \cdot s_{Tx}(t) * bp(t), \quad (3)$$

This transmission model is applied for the investigation below.

III. IMPACT OF THE SIGNAL BANDWIDTH ON RANGING ACCURACY

A. Experimental Setup

Our investigation is based on (3) and on a measurement campaign that yielded a set of channel transfer functions in a UHF RFID warehouse gate.

The modulation and band-pass are known and assumed to be ideal. The modulation frequency was set to 320 kHz and the band-pass / IF filter was adjusted to the expected distance range of the FMCW radar beat signal (see Fig. 2). The selection of the modulation frequency has no effect on the ranging uncertainty provided that the backscattered signals are well separated from the echoes of passively reflecting objects. For this scenario, 320 kHz is sufficient to achieve this separation.

The transmitted radar signal is assumed to be a linearly frequency modulated signal and given as:

$$s_{Tx}(t) = A_{Tx} \cos\left(\omega_c t + \pi \cdot \frac{B}{T} \cdot t^2\right) \quad \text{for } 0 < t < T, \quad (4)$$

where A_{Tx} , ω_c , B and T denote the Amplitude, the RF center frequency, the sweep bandwidth, and the sweep duration, respectively (s. [4]-[6]). The RF center frequency was set to 800 MHz, and the sweep duration T was set to 1 ms. The bandwidth B of the transmitted signal, and thus the bandwidth of the measurements, are varied in the range from 10 MHz to 500 MHz.

Our investigation is focused on the impact of a lifelike channel. Other system impairments such as receiver noise, phase noise of the RF synthesizer, instabilities of the

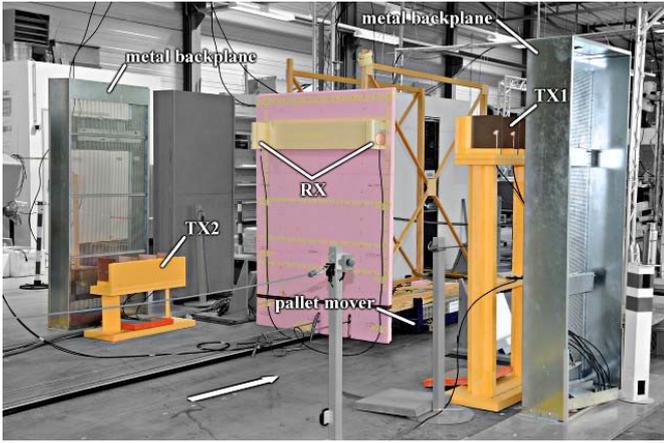


Figure 3. Photograph of the measurement setup for the “empty gate” measurements (EGM). The receivers are mounted on electromagnetically inert polyurethane slabs.

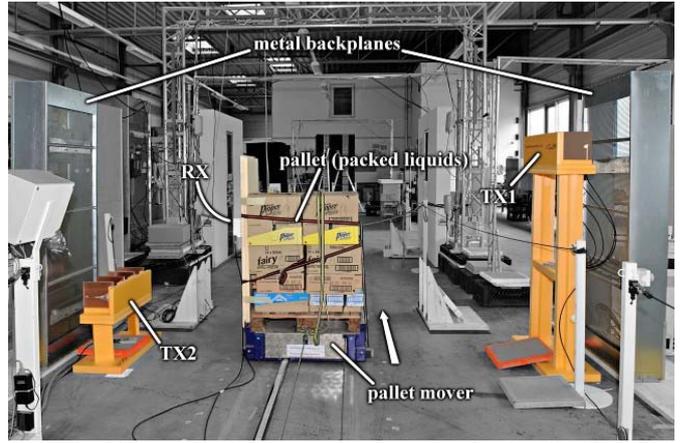


Figure 4. Photograph of the measurements setup for the “liquids pallet” measurements (LPM). Receivers are mounted on the left side of the pallet and move with the pallet, which contains mostly liquids and thus serves as a challenging example for ranging.

modulation, as well as phase and amplitude distortion of the antenna and the RF system were ignored. However, based on practical experience with CW radar based RFID localization [6,8,9,13,15], most of these distortions can be kept small by careful system design, so multipath propagation is very often the dominating cause for ranging errors. The channel inside a UHF RFID portal is a severe multipath environment, providing a challenge even for ultra-wideband localization, as will be shown below.

B. Channel Characterization

Passive UHF RFID is mostly used in logistics, with main applications in supply chain management and product tracking. Consequentially, typical application environments are industrial, i.e., constructed of highly reflective materials. A common supply-chain scenario employing UHF RFID are portals registering tagged objects while they are moving through. These portals are often constructed with metal surfaces for mechanical stability and in order to concentrate energy to the interior of the portal. In combination with the unavoidable backscatter nature of passive UHF RFID, this creates a severe multipath scenario.

The presented investigations use channel impulse responses recorded in such a portal. The recordings were taken in NXP’s Application and System Center, a large hall with corrugated metal walls and ceiling, and a steel-reinforced concrete floor. The portal itself was constructed using two bare steel portal chassis, forming the metal backplanes behind the transmitter antennas (“reader”). The receiver antennas (“tags”) were mounted on pallets and hauled through the portal by an automated pallet mover. Photographs of this setup are shown in Figs. 3 and 4.

Channel impulse responses were recorded in a frequency range of 0.5-1.5 GHz for two scenarios: An empty gate simulated by an electromagnetically inert pallet (Fig. 3), and a challenging product pallet containing packed liquids (Fig. 4). These two scenarios are denoted EGM (empty gate measurement) and LPM (liquids pallet measurements) below. A detailed description of the measurement setup has been

published in [11], and an in-depth channel analysis w.r.t. ranging can be found in [14].

In essence, the entire setup can easily be characterized as the worst case with respect to ranging. The high attenuation of backscatter radio requires highly sensitive receivers. At the same time, signal-to-interference ratios can reach -70 dB and below [14]. The relatively small dimensions of the gate cause major reflections to be spatially close to the LOS component. Large signal bandwidths are required to resolve these multipath components and separate them from the LOS. Tags are also often mounted on reflecting materials such as liquids, thus creating multipath components that are within a few cm of the LOS and thus mostly inseparable. These conditions make the LOS-detection and thus ranging quite challenging.

Moreover, reader antennas used in such portals are directive (cf. Fig. 5), with the main-lobe pointed at the opposite side of the portal. This creates massive reflections at the gate’s walls, while at the same time causing a weak LOS path if the

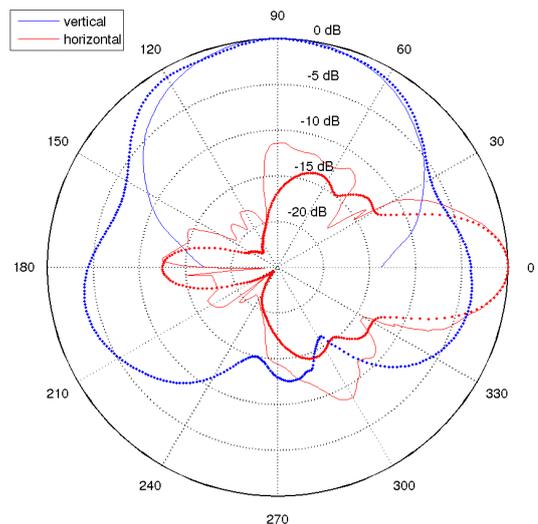


Figure 5. Gain pattern of the used transmitter arrays (dots) compared to an Intermecc 1A39B UHF RFID portal antenna (line). The UWB gain pattern of the transmitter array is averaged over 500 MHz bandwidth around the center frequency of 800 MHz.

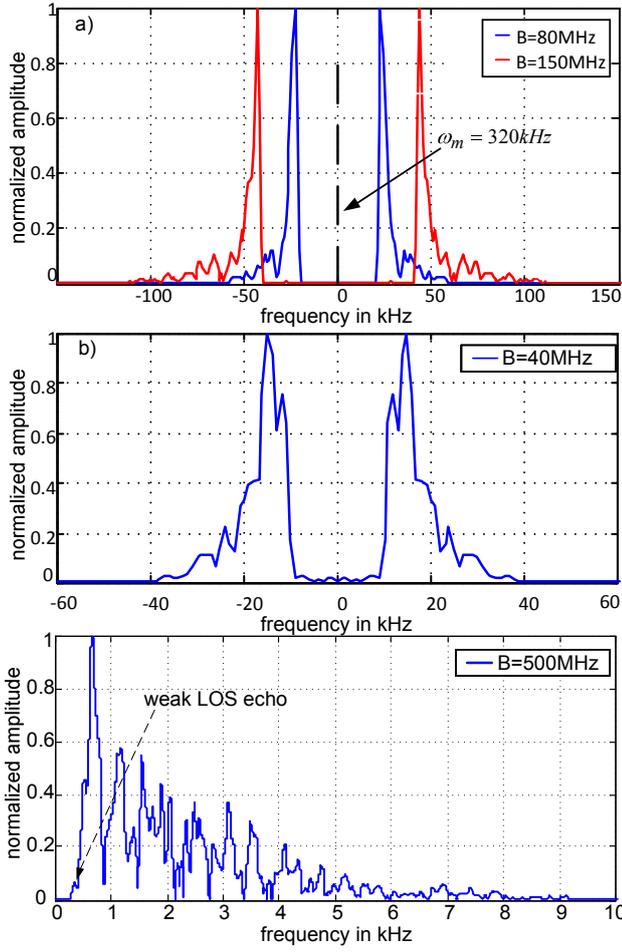


Figure 6. Example echo profiles: a) low multipath distortion, b) considerable multipath components, but strong LOS, c) weak LOS in zoomed profile.

tag is outside the main-lobe (see [16] for an RFID-specific analysis of this portal).

C. Results

In the presented analysis, the ranging accuracy is quantified via the root mean square error (RMSE):

$$\sigma_r = \sqrt{\frac{1}{M} \sum_{m=1}^M (d'_m - d_m)^2}, \quad (5)$$

where d'_m and d_m denote the measured and true distance between the RFID reader and tag.

As depicted in Fig. 6a, the echo profiles $S_m(f)$ are located around the modulation frequency ω_m . We took the frequency difference of the sidebands for RFID ranging (cf. [4]-[6]):

$$d = \frac{\Delta f \cdot T \cdot c_0}{4B}. \quad (6)$$

In Fig. 6a the echo profiles were not notably disturbed by multipath propagation. Thus, the distance estimation of (6) even with an 80 MHz bandwidth matched the true distance

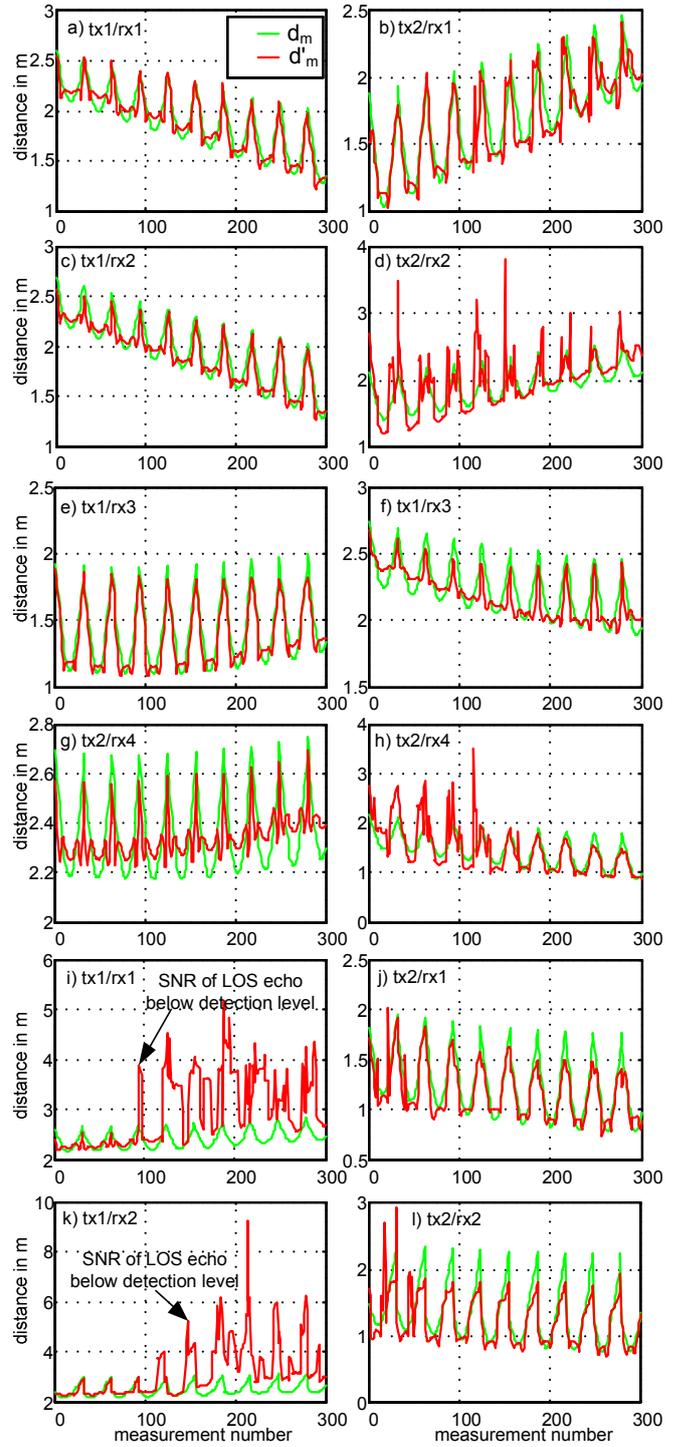


Figure 7. Ranging results calculated from the measured channel transfer functions for multiple passes of the receivers through the portal. The measurements are from different receiver positions in situation EGM (a-h) and LPM (i-l). The FMCW sweep bandwidth here is 500 MHz.

well. However, in most other cases the measured channel transfer functions and the resulting echo profiles were strongly corrupted by multipath distortions.

According to (2) it is known that the replicas of the echo profile with different time delays have the same width δ_{rad} as the LOS component. These multipath echoes can shift the

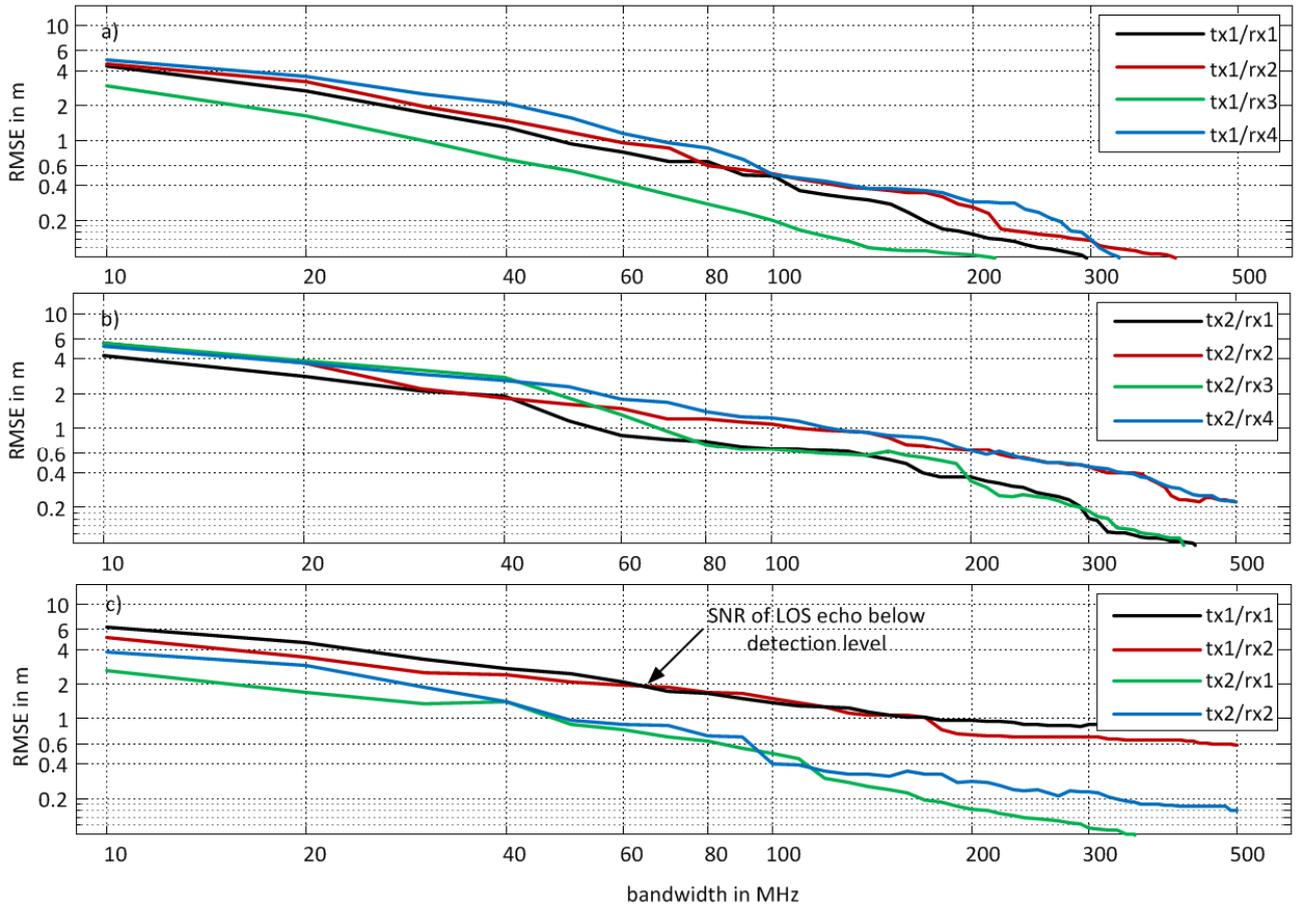


Figure 8. Logarithmic representation of the FMCW radar based ranging performance in the gate environment. In the data processing runs, the FMCW sweep bandwidth was varied from 10 MHz to 500 MHz. The measured channel transfer functions are taken from a) RFID reader tx1, b) tx2 of “EGM” and c) “LPM”.

maximum of the LOS echo, if they are close enough. Examples of echo profiles with strong multipath distortions are shown in Figs. 6b and 6c.

The results of the ranging experiments for each RFID reader and tag can be found in Fig. 7. The results in Fig. 7a-h match our assumption well that the distance of the passive UHF RFID tag can be determined accurately with wideband FMCW signals. The huge ranging errors – as depicted in Fig. 7d and 7h of “EGM” and 7i and 7k of “LPM” – were caused by a very weak LOS-component with an amplitude below the detection level. The system thus falsely identifies a reflected component as LOS, which causes large ranging errors. This is especially true for the LPM and tx1, where the pallet completely blocks the LOS path, but not the gate-reflection. It is obvious that a very good SNR is required to detect the correct LOS echo in such a scenario. If the LOS signal is masked by noise, a strong echo at a larger distance can easily be mistaken for the LOS echo and an erroneous distance is determined, as shown in Fig. 7d, 7i and 7k.

The impact of the radar signal bandwidth on the ranging uncertainty is depicted in Fig. 8. In our investigation we calculated the ranging uncertainty based on 300 measured channel transfer functions of EGM and LPM for each chosen radar sweep bandwidth B , which was varied from 10 MHz to

500 MHz. Fig. 8a shows the ranging uncertainty of the RFID reader tx1 and tags rx1-4, while Fig. 8b corresponds to tx2. Our investigations illustrate that the FMCW radar based ranging uncertainty in this severe multipath environment is around 1 m for the 80 MHz ISM bandwidth. Not considering the NLOS cases, which may have arbitrary errors per definition, this meets the expected ranging resolution of $\delta_{rad,80MHz} = c/\nu/2B = 1.9$ m. From the results in Fig. 8 we conclude that the ranging uncertainty in the severe multipath channel is about half the minimal width δ_{rad} of an echo – if the low SNR situations in Fig. 8c are not considered. As visible, the ranging uncertainty is inversely proportional to the radar sweep bandwidth B . This assumption provides a lower bound of the RFID ranging error in severe multipath environments, because many possible error sources such as phase noise of the RF synthesizer, phase noise of the modulation oscillator and phase and amplitude distortion of the antenna and the RF system have been ignored.

In Section III.D we present a theoretical justification of this assumption. According to this assumption, the ranging uncertainty should be around 0.5 m in the shown severe multipath environments when using the 5.8 GHz FMCW radar based UHF RFID system with a bandwidth of 150 MHz. The results in Fig. 8 matched this estimation well. We can also conclude that accurate ranging in the cm-range is not possible

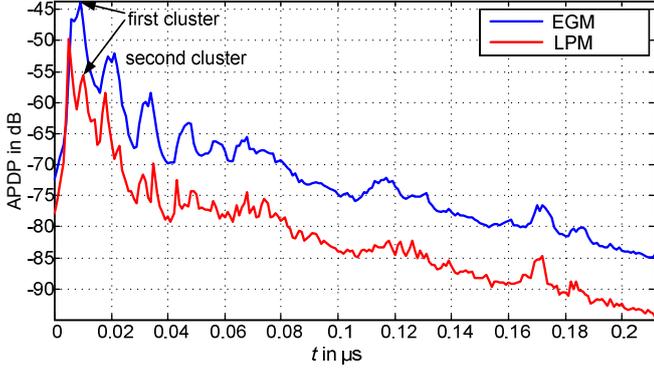


Figure 9. The average power delay profile of the measured channel transfer functions in [11].

with a 5.8 GHz ISM-band UHF RFID localization system in the given measurement scenarios. To improve the localization precision an increased bandwidth and/or diversity or synthetic aperture techniques (cf. e.g. [9, 20]) are required.

D. Interpretation of the Results

In our experiments we observed that the ranging uncertainty in severe multipath channels is inversely proportional to the bandwidth, provided that the LOS component can be correctly identified. Subsequently we want to present a qualitative theoretical justification of this identified behavior.

Provided that there is a discernable LOS component in the measured signal, we can conclude that the multipath reflection that has a RTOF that exceeds the RTOF of the LOS signal by more than the resolution limit can be resolved and does not disturb the range estimation. Based on (2) we can define this critical RTOF difference that is required to resolve the multipath reflections as:

$$\Delta d_c > \frac{c_0}{2B}. \quad (7)$$

Below this limit the LOS echo is superimposed by the echoes of multipath components and the ranging performance will be degraded. It is reasonable to assume that this degradation will be increased with an increasing number of multipath reflections and increasing amplitudes of the reflections. For the sake of simplicity we don't consider the phase effects in the subsequent derivation, even though they are crucial for the precision of each individual range measurement in multipath scenarios. Our assumption is that the phase constellations are randomly distributed for a larger set of measurements taken for arbitrarily distributed distance between reader and tag and that the amplitude consideration is sufficient for a qualitative, averaged /statistical consideration.

Based on the explanation above we define a multipath distortion measure $\sigma'_r(\Delta d_c)$ based on the average PDP (power delay profile) as:

$$\sigma'_r(\Delta d_c) = \sigma'_r(B) = \frac{\int_{\zeta=0}^{\Delta d_c} |P_{mp}(\zeta)| d\zeta}{P_{LOS}} = \frac{\int_{\zeta=0}^{c_0/2B} |P_{mp}(\zeta)| d\zeta}{P_{LOS}}, \quad (8)$$

where ζ denotes the RTOF difference of a multipath echo w.r.t. to the LOS signal. The power of the LOS signal is denoted as P_{LOS} . The integral sums up the power $P_{mp}(\zeta)$ of all multipath echoes with RTOF difference ζ that fall below the resolution limit (7) and disturb the LOS echo. Thus the definition of (7) describes a kind of signal to multipath distortion measure.

Many channel models assume an exponential decay of the multipath components in the PDP [18, 19]. The PDP of our measured channel transfer functions is shown in Fig. 9. The time delay of the first cluster is about 10 ns for this given profile.

If we provide such an exponential decay during the delay time interval defined by (7), we can write:

$$|P_{mp}(\zeta)| \cong P_{max} e^{-\frac{\zeta}{\gamma}}, \quad (9)$$

where the RTOF difference is denoted by ζ , the term γ is the delay constant of the channel and the amplitude of P_{max} is assumed to be the power of the strongest echo of the signal.

Now we insert (9) into (8), solve the integral and obtain the following relation:

$$\sigma'_r(B) \cong \frac{\int_{\zeta=0}^{c_0/2B} P_{max} e^{-\frac{\zeta}{\gamma}} d\zeta}{P_{LOS}} = \gamma \frac{P_{max}}{P_{LOS}} (1 - e^{-\frac{c_0}{2\gamma B}}). \quad (10)$$

Given a time delay constant of γ in the order of several nanoseconds and given a radar sweep bandwidth range from 10 MHz to 500 MHz and provided that the LOS echo is the strongest echo within Δd_c , expression (10) can be approximated by:

$$\sigma'_r(B) \approx \frac{c_0}{2B}. \quad (11)$$

As visible, the experimental results shown in Fig. 8 and (10) and (11) are congruent. Unsurprisingly, the relation of (11) equals the range resolution definition given in (2). Hence, both the FMCW radar range resolution and the ranging performance in severe multipath scenarios are approximately inversely proportional to the radar sweep bandwidth B .

Note that the presented rules of thumb (10) and (11) are only valid to estimate the effect of multipath distortions. Other possible error sources that may degrade the ranging results were not considered. On the other hand, a well designed system operating in an environment with low multipath distortion can provide a ranging precision that is much better than indicated by (10) and (11). An expression for the lower bound of precision in ideal situations, where multipath and all other

distortions except noise are negligible, can be derived from the Cramér-Rao Lower Bound (CRLB). The CRLB for a two-way ranging system is given as [21]:

$$\sigma_r'(B, E_s, N_0) \geq \frac{c_0}{2B} \sqrt{\frac{1}{\pi^2 E_s / N_0} \left(1 + \frac{1}{E_s / N_0}\right)}, \quad (12)$$

where E_s and N_0 denote the signal and noise power. Provided that the bandwidth is fixed by legal spectrum regulations, expression (12) shows that the signal-to-noise ratio is the limiting factor in ideal measuring conditions.

IV. CONCLUSION

In this paper the impact of the signal bandwidth on the performance of CW radar based ranging to UHF RFID tags was studied. It has been shown that the ranging performance in severe multipath scenarios is approximately inversely proportional to the radar bandwidth B as long as the LOS echo is detectable. The results are of course not only valid for the presented CW radar approaches but for all localization approaches that utilize Fourier or correlation methods for the signal travel time estimation. In a following step we want to verify our findings by measurements with a broadband FMCW radar based RFID localization system. Parallel to and in conjunction with these measurements the effect of other distortion parameters, e.g. noise, phase noise of the RF synthesizer and the modulation oscillator as well as phase and amplitude distortion of the antenna and the RF system, will be considered.

TABLE OF ACRONYMS

| | |
|------|---|
| CW | continuous wave |
| EGM | empty gate measurement test set-up |
| FMCW | frequency modulated continuous wave |
| ISM | industrial, scientific and medical (frequency band) |
| LOS | line of sight |
| LPM | liquids pallet measurement test set-up |
| NLOS | non line of sight |
| PDP | power delay profile |
| RMSE | root mean square error |
| RFID | radio frequency identification |
| CRLB | Cramér-Rao lower bound |
| RTOF | roundtrip time of flight |
| TOF | time of flight |
| UHF | ultra high frequency |
| UWB | ultra-wideband |

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