Characterisation of the NLOS Performance of an IEEE 802.15.4a Receiver

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***Abstract*—Range and outlier probability of the underlying ranging technology are important system parameters for RTLS system architects. Analogous to the traditional receiver sensitivity level, this paper introduces the concept of first path sensitivity, defined as the minimum first path signal power required for the receiver to be able to detect it. A simple two-path measurement set-up yields both first path sensitivity and outlier probability. As an example, the test is applied to DecaWave's DW1000 ScenSor IC. NLOS first path sensitivity is shown to be much better than what pure LOS communications sensitivity would suggest. Both frequency offset and strong reflections that cause gain control to adjust, negatively affect first path sensitivity. By tuning the IC's parameters and increasing the preamble length, first path sensitivity can be increased.**

I. Introduction

In order to provide accurate positioning, the underlying distance measurements need to be as good as possible. Ultra-wideband (UWB) ranging is a natural fit for indoor real time location systems (RTLS). The large bandwidth allows for accurate time-of-flight measurements and high resolution channel impulse response estimation in dense multipath environments.

Accurate ranging and positioning were one of the main motivations behind the IEEE 802.15.4a standard. A UWB physical layer was selected, which in 2011 was integrated in the main 802.15.4 standard as the UWB PHY [1]. Recently, commercial implementations of the standard have become available, in the form of DecaWave's DW1000 ScenSor integrated circuit (IC) [2].

The reliability of the communications performance of the chip is characterised by the receiver sensitivity. However, in order to design an RTLS system, the ranging performance is an equally important characteristic. In many scenarios, particularly non-line-of-sight (NLOS) ones, multipath reflections may provide enough signal strength to maintain the communications link even though the first path may have been attenuated below detectable levels. Therefore, analogous to receiver sensitivity, this paper introduces the concept of first path sensitivity, defined as the minimum first path signal power required for the receiver to be able to detect it.

Unlike receiver sensitivity, first path sensitivity will depend on the scenario. In pure line-of-sight (LOS) cases, first path sensitivity will be equal to receiver sensitivity, for the simple reason that if the devices are not able to communicate, they cannot range either. However in NLOS, stronger multipath components may allow the communication link to be established and the first path sensitivity can be much lower since it is now determined by the first path detection algorithm and the noise in the system.

In a threshold based ranging system, first path sensitivity could probably be improved by lowering the first path threshold. Obviously, this will come at the cost of increased false, early first path detection triggered by noise and interference artefacts. The probability of these outliers is another important metric for the RTLS system designer. If they occur often, some higher layer outlier or motion filtering probably needs to be implemented to maintain acceptable system performance.

In this paper, a simple two path test is proposed to measure both first path sensitivity and outlier probability. Combined with [3] and [4], RTLS system designers can use the results of this new test to readily estimate the performance of their system in NLOS conditions. As an example, the NLOS performance of DecaWave's DW1000 ScenSor IC is characterised.

The remainder of this paper is structured as follows. The next section first presents the ranging provisions in the IEEE 802.15.4a standard. Then threshold based time-of-arrival ranging as implemented in DecaWave's DW1000 ScenSor is discussed. Next, the two path NLOS characterisation test is introduced and applied to the DW1000 IC. It will be shown that frequency offset and, perhaps counter-intuitively, strong signal, degrade first path sensitivity. The trade-offs of preamble length, first path sensitivity and outlier probability are also discussed and evaluated.

II. IEEE 802.15.4a Ranging Provisions

The IEEE 802.15.4a standard, approved in 2007, was originally an amendment to the 802.15.4 standard, to complement it with increased range, better mobility, enhanced coexistence and precision ranging capability. In 2011, it was integrated as the UWB PHY in the main 802.15.4 standard [1].

UWB was a natural choice given the objectives of the amendment. The wide bandwidth allows for short pulses with steep rising edges. This enables the receiver to distinguish the various multipath reflections arriving with different time delays. Unlike narrowband systems which suffer from multipath fading, UWB receivers can combine the multipath energy to increase the communication range and reliability. At the same time, the steep rising edges enable high resolution channel impulse response estimation supporting superior time-of-arrival ranging.

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The standard cleverly exploits these UWB benefits. Every frame starts with a preamble consisting of a train of isolated pulses with perfect periodic autocorrelation properties. The receiver is therefore able to estimate the channel impulse response by accumulating the results of the correlation of the incoming samples with the expected preamble sequence. A leading edge detection algorithm uses the channel impulse response estimate to accurately determine the arrival time of first signal energy within the channel impulse response.

In the context of RTLS, a standard compliant device provides all the necessary PHY and MAC capabilities to perform precision time-of-flight measurements. Using its capability to accurately determine transmission and reception times, the standard supports two-way ranging (TWR) between two devices, allowing them to determine the distance between them without any other infrastructure. Alternatively, a set of reference anchors can use time-difference-of-arrival (TDOA) to determine the position of a transmitting node.

III. First Path Detection in the DW1000 IC

DecaWave's DW1000 ScenSor IC is the first commercially available implementation of the 802.15.4a standard aimed at wireless sensor networks and real-time localization systems [2]. By fully exploiting the benefits of UWB, it is able to take advantage of multipath propagation to reliably detect signals more than 20 dB below the noise floor. It has a range up to several hundreds of metres in line-of-sight conditions and is able to overcome severe non-line-of-sight conditions. Thanks to the time-of-flight based ranging, it is able to range down to centimetre level even in severe multipath and obstructed-line-of-sight scenarios.

During preamble, the perfect periodic autocorrelation properties are exploited to build an estimate of the channel impulse response. When the start-of-frame delimiter signals the end of the preamble, the integrated circuit starts its leading edge detection algorithm. This finds the minimum noise region in the channel impulse response, assuming that the first path must be located between this minimum noise region and the peak of the channel impulse response. A noise-based threshold is set according to the characteristic of this minimum noise region.

Frequency offset between the transmitter and receiver results in a degradation of the perfect autocorrelation properties of the preamble codes.

Consider the situation where the incoming ternary code isn't aligned with the preamble code in the correlator. Without frequency offset and ignoring noise, a simplified system consisting of only 2 pulses P at t_1 and t_2 respectively would be combined such that

$$P_{t_1} - P_{t_2} = 0 \tag{1}$$

because the perfect autocorrelation properties of the preamble code combine to form zero when the codes are not aligned. With frequency offset however, the second pulse will have a phase offset $\Delta\phi$ compared to its idealized version above, such that when the pulses are combined in the correlator, they will no longer sum to zero but a small value depending on the size of the frequency offset:

$$P_{t_1} - P_{t_2} \times e^{j\Delta\phi} \neq 0 \tag{2}$$

Because this small rest term will be consistent throughout the preamble, it adds coherently in the channel impulse response and appears as a small replica of the main channel impulse response.

To take these replicas into account, a second threshold is derived based on the preamble code and the observed frequency offset. The final threshold used by the algorithm is the maximum of the noise based and the replica based thresholds.

The user of the DW1000 IC is able to tune both thresholds by programming respectively a noise threshold multiplier (NTM) and a replica threshold multiplier (RTM) register. This allows for optimisation and adaptation according to the expected usage and the rest of the RTLS systems components.

For example, if a system operates predominantly in NLOS conditions, the system architect should decrease the threshold multipliers in order to lower the threshold and increase first path sensitivity. However, this will come at the cost of increased probability of outliers, due to false first path detections at peaks in the noise or replicas. Further filtering in the higher layers of the RTLS system will be required to provide robustness against these outliers.

If, on the other hand, it is known that the system will be used mainly in LOS conditions, the system architect can increase the threshold multipliers and reduce the number of outliers. This in turn allows for the simplification of the overall design since the higher layers of the RTLS system could potentially operate without outlier filtering.

IV. NLOS First Path Sensitivity Test

Operational range and reliability are the main concerns for users of RTLS systems. In LOS conditions, operating range is easy to calculate from the traditional receiver sensitivity of the system. In NLOS, however, the system may still be able to communicate via a strong multipath component, while the first path may be attenuated to a level below the threshold. While the actual operating range depends heavily on the nature of the obstruction, a simple modification to the communications sensitivity test is proposed to extract a NLOS first path sensitivity figure.

To determine the conventional receiver sensitivity, a reference transmitter is connected to the receiver via an attenuator. The attenuation is then increased until the receiver error metric of interest drops below a certain level. The received signal power at which this occurs is the conventional receiver sensitivity level. For example, in [1], receiver sensitivity is defined as the power level where a 20 byte packet experiences a packet error rate of 99%.

To measure NLOS sensitivity, the set-up is modified to include a second, longer path, which will not be further attenuated. The energy from this path will arrive after the attenuated first path and ensure that communication between transmitter and receiver remains possible. The attenuation of the first path is then increased until its probability of correct detection drops below 90%. The signal power of the first path at this instance is defined as the NLOS sensitivity level. When combined with typical attenuation levels, as for example listed

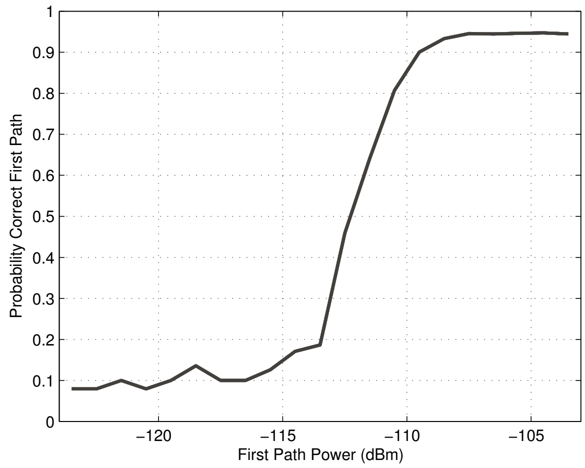

Fig. 1. First Path Sensitivity Measurement (preamble length 128, 0 ppm offset, noise threshold multiplier 7, replica threshold multiplier 3)

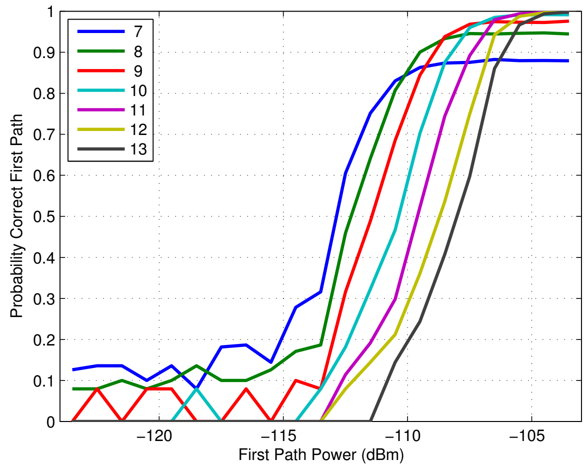

Fig. 2. First Path Sensitivity Measurement, varying noise threshold multiplier (preamble length 128, 0 ppm offset, replica threshold multiplier 3)

in [3] and [4], this figure allows an RTLS architect to estimate the operating range of his system for a given NLOS scenario.

The same test set-up is used to measure outlier probability. At very low attenuation, the receiver should always detect the first path, unless an earlier noise spike or replica triggers a false first path detection.

The actual test set-up performs two-way ranging. Since a two way ranging measurement is based on three time of flight measurements, all three measurements need to be correct to result in a correct range:

$$P_{correctTWR} = (1 - P_{wrongTOF})^3 \tag{3}$$

and the probability of correct time of flight measurement becomes

$$P_{correctTOF} = \sqrt[3]{P_{correctTWR}} \tag{4}$$

It is the latter that will be used to derive first path sensitivity and outlier probability in the next section.

V. NLOS Sensitivity Of The DW1000 IC

Figure 1 shows the result of a NLOS sensitivity measurement using DecaWave's DW1000 ScenSor IC. The frequency offset between transmitter and receiver was tuned to be 0 ppm, while the noise and replica threshold multiplier were configured to 8 and 3 respectively. Note that since there was no frequency offset, the actual value of the replica threshold multiplier is irrelevant. The packet used had a preamble length of 128 symbols and a data rate of 6.81 Mbps. Previous tests have shown that the receiver sensitivity level (90% packet error rate, 20 byte payload) for this configuration is -94 dBm. However, the sensitivity for the first path is 16 dB better, at 110 dBm for a 90% correct detection level.

At higher signal powers, there is about a 5% outlier probability. In order to deal with this frequency of outliers, the RTLS architect has two options. At the level of the DW1000 IC, the noise threshold multiplier could be increased. Table I and figure 2 show the drop in outlier levels, but this comes

TABLE I. Changing noise threshold multiplier (preamble length 128, 0 ppm)

Noise Threshold Multiplier	First Path Sensitivity (dBm)	Outlier Probability
7	-	12.09%
8	-109.5	5.55%
9	-108.9	2.41%
10	-108.2	0.86%
11	-107.4	0.25%
12	-106.7	0.11%
13	-106.1	0.02%

at the cost of reduced first path sensitivity. At system level, filtering could be introduced to reduce the effect of outliers.

Figure 3 demonstrates how increasing the preamble length can recover the first path sensitivity even with an increased noise threshold multiplier; this time at the cost of increased transmit power and air time. Every doubling of the preamble length results in 3 dB gain in first path sensitivity, such that a noise threshold multiplier 13 with preamble length 256 is able to obtain a first path sensitivity of -109 dBm. Doubling the preamble length again to 512 results in a first path sensitivity of -113 dBm, outperforming the original first path sensitivity of figure 1 and with hardly any outliers.

Figure 4 shows the effect of frequency offset on first path sensitivity. For this plot, the noise threshold multiplier was set to 13 while the replica threshold multiplier was kept at 3. The frequency offset between transmitter and receiver was tuned from -35 ppm to +35 ppm in steps of 5 ppm. The DW1000 IC detects the frequency offset and increases the threshold to keep away from replicas, resulting in a reduced sensitivity. In order to avoid this sensitivity loss, the DW1000 IC provides the ability to trim its crystal oscillators so that the frequency offset between devices can be minimized.

The influence of gain control on first path sensitivity is shown in figure 5. Unlike the other results in this section, it is based on a simulation of packets with a preamble length of 128 symbols. As above, the noise threshold multiplier is set to 13 and the replica threshold multiplier to 3. Along the x-axis, the second path power refers to the signal strength of the second, non-attenuated path in the test.

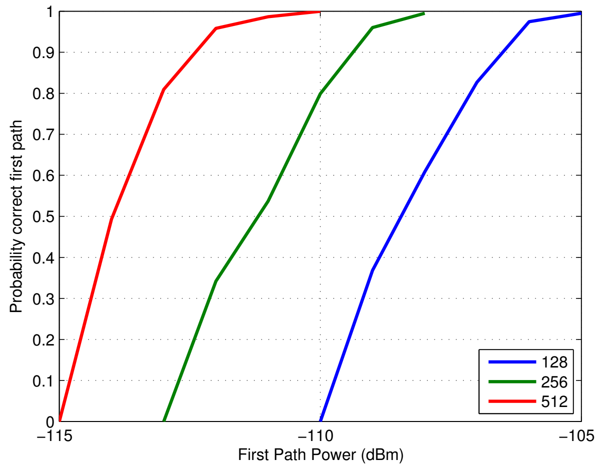

Fig. 3. First path sensitivity versus preamble length (0 ppm, noise threshold multiplier 13, replica threshold multiplier 3)

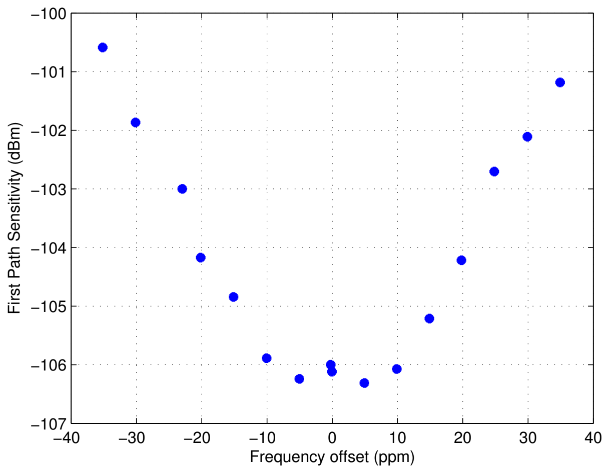

Fig. 4. First path sensitivity versus frequency offset (preamble length 128, noise threshold multiplier 13, replica threshold multiplier 3)

The scenario in figure 5 is quite artificial, in the sense that in most real world scenarios, NLOS goes hand in hand with low received signal levels. However, if the reflections are strong enough to force gain control to adjust, it can be seen that the reduced gain in the front end negatively affects first path sensitivity. Besides adjusting the noise threshold multiplier or extending the preamble length, the perhaps counter-intuitive solution in this case could be to reduce transmit power, which would also benefit battery life.

VI. Conclusion

Range and outlier probability of the underlying ranging technology are important system parameters for RTLS system architects. This paper proposed a simple adaptation of the receiver sensitivity level test to yield a first path sensitivity metric and outlier probabilities, which, together with [3] and [4], can be used to predict RTLS system performance.

The test was applied to DecaWave's DW1000 ScenSor

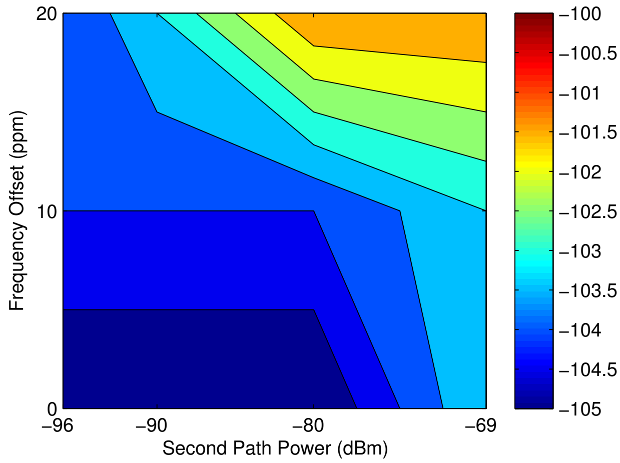

Fig. 5. First path sensitivity versus frequency offset (preamble length 128, noise threshold multiplier 13, replica threshold multiplier 3)

IC. It was shown how lowering the noise threshold multiplier improves NLOS range at the cost of increased outliers. Similarly, increasing the preamble length improves first path sensitivity by 3 dB per doubling of the length. Frequency offset has a negative influence on first path sensitivity but can be mitigated by crystal trimming. Finally, in those unlikely scenarios where NLOS is combined with powerful reflections, gain control reduces first path sensitivity levels. However, in all cases, the NLOS first path sensitivity is much better than pure LOS communications sensitivity would suggest.

References

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