Study of BLE6 Ranging Performance in a Utility Basement

Tim Ulsamer, Christian Mazur and Stefan Knauth*

Faculty for Computer Sciences, Mathematics and Geomatics, HFT Stuttgart – University of Applied Sciences, Schellingstr. 21, Stuttgart, Germany

Abstract

The paper explores the Channel Sounding (CS) method introduced in the Bluetooth Low Energy 6 (BLE6) specification with a focus on its evaluation under difficult adverse radio conditions in an utility basement employing BLE6 hardware. Two measurement series were conducted, one for reference and calibration in open ground, and one in the utility basement of an university building. Multiple distance estimation algorithms are assessed. In addition to the standard algorithms implemented in the evaluation board, namely Inverse Fast Fourier Transform (IFFT), Slope, and Round Trip Time (RTT), some enhancements for the IFFT-based method have been implememted and tailored for improved robustness and precision. Experimental results indicate that Channel Sounding remains effective even in complex and obstructed environments, with the proposed algorithm outperforming the default implementation.

Keywords

Channel Sounding, BLE6 ranging, phase based ranging

1. Introduction

The new Bluetooth (BT) Low Energy 6 (BLE6) standard introduces a novel method for distance estimation: Bluetooth Channel Sounding (CS). The method itself is of course well known, but new to BT. This feature is expected to be integrated into many smartphones in the near future, enabling a wide range of new use cases for indoor positioning.

The signaling protocol and measurement procedures of Channel Sounding are defined in the BLE6 specification. CS employs a two-way measurement scheme: the initiator, which seeks to determine its position, transmits a test signal to a responder, in BLE6 “reflector”. The reflector measures the carrier phase of the received signal and returns this information to the initiator. This bidirectional approach compensates for oscillator frequency deviations, and in addition to the carrier phase, the round-trip time (RTT) of the signal is also measured.

Distance estimation in CS is based on evaluating the phase shift of the received radio signal as a function of the carrier frequency. The test signal is transmitted sequentially over multiple frequencies with a fixed frequency spacing. The BLE6 CS specification utilizes nearly all of the 79 channels available in the BLE standard. This results in a distance-dependent phase pattern from which the propagation distance can be estimated with high precision. The underlying principle is illustrated in Fig. 1. It should be noted that the Bluetooth SIG defines the physical channels and procedures for CS, but the actual distance calculation algorithm is left to the application layer. An overview of BT and CS may also be found in [1] and [2].

In this paper, we evaluate the accuracy of CS and RTT under challenging radio conditions, specifically those found in an underground utility basement using available BT6 CS evaluation boards. Besides using the default algorithms supplied with the firmware of the board, we propose and evaluate an enhancement for the IFFT (inverse Fourier transform) based algorithm employed in the firmware of the chip.

In [3] a comparable work is described. The surrounding there is not as special as our utility basement, and the reported performance seems to be below what we obeyed. The authors of [4] describe a mobile

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*Corresponding author.

stefan.knauth@hft-stuttgart.de (S. Knauth)

phone application scenario, but as BLE6 has not yet found its way into real smartphones, it is based on simulation. A car key fob scenario is investigated by [5]. In [6], Parametric Neural Networks are employed to achieve reasonable results. Also the MOSAIC algorithm [7] will solve the distance estimation problem in an optimal manner. Support vector regression is reported to adopt well to multipath ([8]). Nonetheless, our focus lies on a more lightweight approach suitable for execution on constrained embedded systems.

2. Algorithm

To support the discussion of results, the employed algorithms are reviewed in greater detail: The RTT algorithm is already present in the vendor-supplied firmware and directly interfaces with the hardware to determine the signal round-trip time for each individual transmission. In contrast to CS algorithms, it would work already with one single channel.

The Slope– and IFFT algorithms are also part of the default firmware. Both operate on IQ values representing the measured phase differences for the channels, which are provided by the hardware/-firmware. The Slope algorithm estimates the distance by evaluating the slope of the unwrapped phase differences over the frequency, which is ideally a line. The IFFT algorithm performs an inverse fourier transformation (IFFT) on the phase function. The index of the IFFTs peak value is proportional to the signal's propagation distance. As the index is an integer, the accuracy is limited. Therefore a more accurate value is obtained by parabolic intepolation of values around the index of the maximum value.

In addition to these 3 default algorithms implemented in the vendor firmware, the authors propose-and implemented a modified IFFT algorithm "IFFT2". This algorithm currently works offline. For this purpose, the firmware was modified to transmit raw IQ values alongside the distance estimates generated by the firmware via a serial interface to the connected PC in real time. The proposed offline algorithm "IFFT2", which is analyzed in this paper, also relies on an inverse FFT. Distinctive features of this approach include:

- Neglecting of the signal amplitude by normalization of the IQ values.
- Interpolation of missing data points on the unit circle, taking into account the direction of the phase rotation.
- Zeroing of missing data points which are at the beginning- or end of the frequency range

The final peak is determined by applying a parabolic approximation around the maximum of the transformed signal, as also performed by the original IFFT algorithm.

3. Experiment

The Experiments are employing Nordic nRF54L15 Development Kits (DK), which are equipped with the corresponding BLE6 Bluetooth System-on-Chip (SoC). This chip supports BLE6 Channel Sounding. An SDK provided by the manufacturer is available for the development kits, including example code for CS devices. These examples already provide distance estimates for both CS and Round Trip Time (RTT). Two CS algorithms are implemented by default: Inverse Fast Fourier Transform (IFFT) and Slope. For our experiments, we modified the initiator firmware to extract also the raw data which constists of the quadrature (IQ) values from the 75 acitve measurement channels.

The DK modules were mounted on tripods, with the feedpoint of the vertically oriented antenna positioned at a height of 1.20 meters above ground level. The RF modules use a PCB antenna ($\lambda/4$ monopole), connected to the chip via a 5 mm short transmission line. The reflector does not require any I/O connections and starts operation immediately upon battery connection. The initiator outputs measurement data via a serial interface using a USB converter, and a connected laptop is used for data acquisition.

A complete channel scan is performed approximately every 0.5 seconds. The IQ values from each scan are averaged already in the firmware. Every 5 seconds, an aggregated dataset (comprising typically

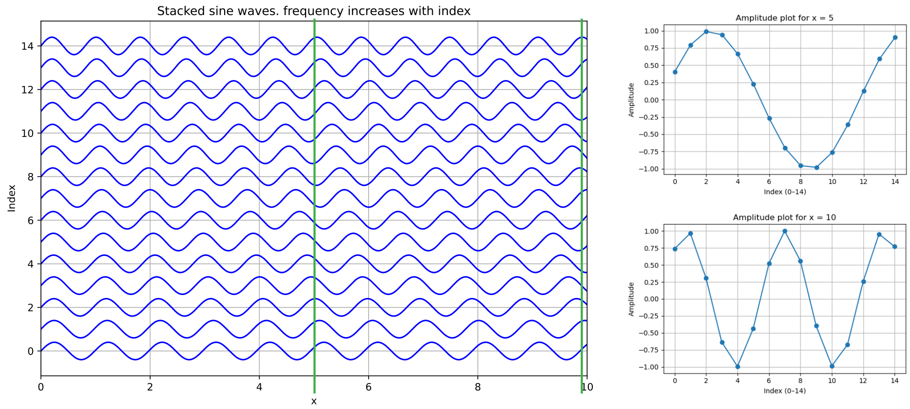

Figure 1: Principle of BLE CS: (left) Waves propagate from location x=0 to the left (in practice not at the same time). The frequency increases from index 0 to index 14 (Y-Axis). The two green lines (x=5 and x=10) indicate distances, for which amplitude values are plottet on the right for particular time t. As it can be seen, the plots each have a characteristic frequency, which is proportional to the distance x. In the plots, the amplitude refers to the real part of the received signal. In practice, I and Q are recorded and named "phase slope function". A higher "frequency" in these functions indicate a larger distance to the sender.

10 averaged scans) is sent to the PC via the serial interface, comprising averaged IQ data, along with the firmware-computed distances.

The actual measurement procedure for each position was as follows:

- Adjusting of the devices to the forseen positions
- Performing of 50 seconds of measurement which gives typically 10 measurement results.
- Recording of measurement label and the set of results to allow for offline evaluation of mean value and standard derivate for each position.

To validate and calibrate the setup and to evaluate the algorithms under more or less ideal conditions, initial measurements were conducted in open field conditions (see also Fig. 2). This was carried out on a grassy area in a public park (see photograph). Ground truth distances were established using a surveying tape. The ground truth accuracy, estimated by repeated bidirectional tape measurements, was determined to be well below 5 cm. Measurements were taken over a distance range of 1..40 meters, with the initiator remaining stationary while the responder was repositioned for each measurement.

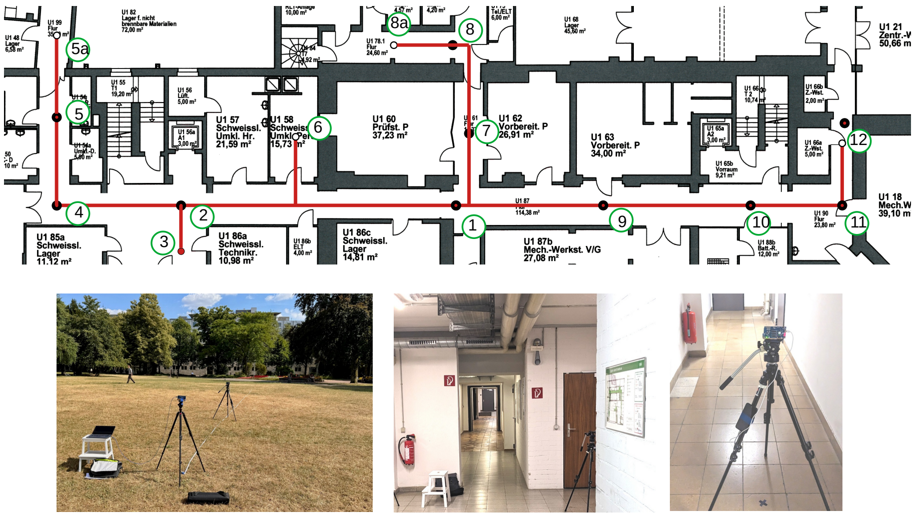

Figure 2: Top: Scenario in the basement. Red lines connect the indicated measurement points. The red line from label 4 to label 11 has a length of 46.2 meters. Bottom: left: free field scenario. Middle and right: impressions of the utility basement

The measurements in the basement were conducted in the same manner (see photo). The building dates back to around 1910. The walls are partly made of brick and partly of concrete, while the ceilings are entirely constructed from concrete. The measurement points and corresponding distances are marked on the building plan. The metal doors in the corridors were left open during the measurements, as performance through closed fire doors would have been very poor.

4. Results

Table 1
Summary of ranging results in the outdoor environment, including 23 measurement points with distances in the range from 1..40 meters.

	IFFT2		IFFT		Slope		RTT	
	Delta	SD	Delta	SD	Delta	SD	Delta	SD
Mean	0.13	0.01	0.21	0.23	0.98	0.23	0.35	0.26

Table 1 presents a summary of the results of the outdoor measurements. For each of the four methods ITTF2, IFFT, Slope and RTT the mean distance error (Delta) and the standard derivative (SD) for 10 successive measurements is given. Table 3 (at the end of the paper) presents a detailled view on the measurements for each position. The Fourier-based methods demonstrate high accuracy in outdoor environments. Notably, for the proposed IFFT2 method, the standard derivative reveals exceptionally low variation within individual distance measurements typically within a few centimeters.

The results were calibrated with an offset: each method exhibited a constant distance offset, sometimes on the order of meters, which was subtracted for the phase-based methods. These offsets (calculated from the mean deviation from ground truth) were 0.93 m for IFFT2, 0.46 m for IFFT, 1.91 m for Slope and 3.78 m for RTT. Such a constant offset could, for example, be caused by antenna cable length; however, in our setup, the antennas were mounted directly on the chip. The antennas themselves, especially near their resonance frequency, might exhibit a frequency-dependent phase response that is influenced by their quality factor. There is already a compensation factor considerered in the firmware, but it did not perfectly match the given antenna configuration.

Table 2
Ranging results utility basement. Label a->b with respect to fig. 2. True ground dist. given as Manhattan and Euclidian. Dist.: measured Distance , SD: standard deviation, Delta: measurement error.

Label	Ground truth		IFFT2			IFFT			Slope			RTT		
a->b	Manh.	Eucl.	Dist.	SD	Delta	Dist.	SD	Delta	Dist.	SD	Delta	Dist.	SD	Delta
1-2	15.0		15.306	0.164	0.306	15.309	0.153	0.309	15.666	0.819	0.666	18.84	0.463	3.84
1-4	23.0		29.334	2.652	6.334	8.797	8.775	-14.203	34.312	0.874	11.312	44.31	1.944	21.31
1-3	17.5	15.2	17.907	1.53	0.407	15.901	1.08	-1.599	19.663	0.781	2.163	21.78	0.958	4.28
1-5	28.0	23.5	28.687	0.104	0.687	13.607	3.431	-14.393	29.777	0.856	1.777	34.27	0.449	6.27
1-7	3.8	3.55	6.384	0.306	2.584	5.889	0.519	2.089	7.199	0.683	3.399	10.12	0.597	6.32
1-8	10.4	8.8	14.592	2.961	4.192	9.851	1.712	-0.549	14.318	1.271	3.918	17.8	1.549	7.4
1-8a	13.7	9.4	18.587	0.0	4.887	14.607	0.0	0.907	19.809	0.0	6.109	24.13	0.0	10.43
1-9	9.4	9.4	14.905	6.061	5.505	12.085	3.72	2.685	15.801	4.234	6.401	17.58	4.837	8.18
1-10	18.0		23.42	3.815	5.42	14.854	2.927	-3.146	23.386	3.357	5.386	25.56	2.644	7.56
1-11	23.2		23.409	0.036	0.209	23.419	0.129	0.219	22.938	0.188	-0.262	27.01	0.155	3.81
4-11	46.2		46.383	0.041	0.183	46.27	0.094	0.07	46.896	0.218	0.696	50.47	0.218	4.27

In contrast to the very reliable and accurate results outdoors, the situation in the basement is significantly different. Table 2 lists the corresponding indoor measurement results. The pairs of numbers in the first column indicate the measurement points between which the distance was recorded. Two types of ground truth distances are provided: Manhattan and Euclidean. The Delta values were computed relative to the Manhattan distance. The mean standard deviation is 1.61 m for IFFT2, 2.05 m for IFFT, 1.21 m for Slope and 1.25 m for RTT.

The performance of CS is noticeably degraded in the utility basement corridors, likely due to multipath propagation and signal shadowing. Positions 5a, 6, 8a, and 12 could not be reached from the initiator positions 4 and 1 used in the measurements.

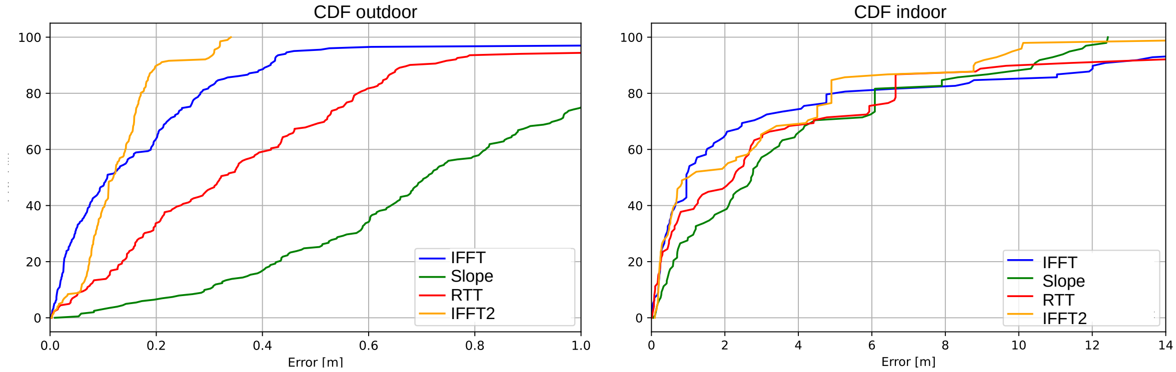

Figure 3: CDF Plots of the measurement results for different algorithms. Left: Outdoor scenario, x-scale: 0..1 m. Right: uitility basement scenario, x-scale 0..14 m

The CDF plots (Fig. 3) confirm the discussion: Outdoors, reasonable accuracies have been reached: Looking for example at the 80. percentile, CS with the FFT methods show good performance. IFFT2 is below 0.2 meters, IFFT about 0.3 m. Slope can not hold up and is above one meter. Even RTT, which has relaxed requirements on channel availability, reaches 0.6 m.

Indoors, trhe situation is worse. The IFFT variants reach 80% only close to 5 meters of error. IFFT2 error is below 9 m for 95% of the measurents, others at or above 11 m.

5. Conclusion

This work investigated the performance of Bluetooth Channel Sounding (CS) and Round Trip Time (RTT) based distance estimation methods under both ideal and challenging radio conditions, employing stock BLE6 hardware. Particular attention was given to an underground utility basement environment, which introduces propagation effects like multipath and signal shadowing.

Outdoor experiments demonstrate that Fourier-based approaches achieve high precision, with intra-measurement deviations (StdDev) in the range of a few centimeters. Slight systematic errors were observed as function of the distance, which might be caused by constant phase offsets i.e. originating from antenna characteristics. These offsets were compensated to some extent during post-processing.

In contrast, the indoor measurements in the utility basement revealed significant performance degradation. The complex structure of the building with concrete ceilings and metal doors seemed to severely impact the signal propagation. Certain locations were unreachable, and the standard deviations of the distance errors increased substantially. However, the performance is still comparable to WiFi. Employing more reflectors at suitable places might help to overcome mentioned indoor issues.

Optimization of the IFFT algorithm lead to the proposed IFFT2 algorithm: The signal amplitude was normalized such that only the phase was considered. Missing data points were interpolated on the unit circle considerung also data points at the beginning- and end of the frequency range. IFFT2 outperformed IFFT under most conditions.

While reporting issues in complex environments, BLE6 CS showed a robust and, depending on the setting, very high ranging accuracy. When available at smartphones, we will propably see very interesting and helpful applications.

Declaration on Generative AI

During the preparation of this work, the authors used GPT-4 in order to perform Grammar and spelling check as well as for generating python code for data processing e.g. file parsing, averaging, conversions etc. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the publication's content.

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Table 3
Table of ranging results in the outdoor environment. S: Distance, IFFT2: optimized FFT algorithm, IFFT: embedded inverse FFT algorithm, Phase: embedded Phase slope algorithm, Diff: difference to ground truth

	IFFT2		IFFT		Slope		RTT	
Dist.	Delta	SD	Delta	SD	Delta	SD	Delta	SD
40.0	-0.12	0.02	-0.19	0.35	-0.6	0.15	-0.48	0.13
38.0	-0.15	0.01	-0.01	0.09	-0.15	0.3	-0.53	0.12
36.0	-0.14	0.01	0.0	0.1	-0.49	0.17	-0.33	0.14
34.0	-0.11	0.01	0.06	0.03	-0.54	0.14	-0.26	0.16
32.0	-0.17	0.01	-0.02	0.04	-0.5	0.23	-0.53	0.15
30.0	-0.15	0.02	-0.13	0.21	0.08	0.31	-0.26	0.25
28.0	-0.15	0.02	-0.18	0.45	-0.38	0.28	-0.24	0.26
26.0	-0.18	0.01	-0.11	0.19	0.98	0.41	-0.44	0.25
24.0	-0.07	0.01	-0.14	0.51	3.72	0.38	-0.03	0.68
22.0	-0.04	0.03	-0.85	1.57	4.53	0.55	2.52	1.01
20.0	0.2	0.02	0.18	0.11	1.33	0.36	-0.24	0.52
18.0	0.09	0.01	0.21	0.04	-0.49	0.11	0.23	0.28
16.0	0.09	0.01	0.23	0.05	-0.89	0.14	0.01	0.2
14.0	0.14	0.01	0.3	0.01	-0.7	0.13	0.01	0.16
12.0	-0.11	0.01	-0.78	1.23	0.6	0.51	-0.1	0.57
10.0	0.08	0.01	0.19	0.03	-0.79	0.14	0.33	0.14
8.0	0.08	0.01	0.21	0.02	-0.72	0.15	0.25	0.25
6.0	0.31	0.01	0.42	0.02	-0.7	0.09	0.51	0.12
5.0	0.32	0.01	0.42	0.02	-0.69	0.22	0.22	0.16
4.0	0.17	0.01	-0.0	0.19	-0.61	0.13	0.12	0.19
3.0	0.03	0.04	0.07	0.04	-0.9	0.16	0.0	0.16
2.0	-0.07	0.01	0.04	0.03	-1.08	0.08	-0.56	0.09
1.0	-0.01	0.01	0.08	0.04	-1.04	0.11	-0.22	0.07
Mean	0.13	0.01	0.21	0.23	0.98	0.23	0.35	0.26