A Flexible Real-Time Software-based Multi-Band Channel Sounder

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***Abstract*—We present a flexible real-time software-based multi-band channel sounder, which can flexibly be used in a variety of measurement campaigns, and fills the gap of expensive commercial channel sounders with limitations of operation frequency, sounding bandwidth, and ease of use. In general, channel sounding is a very valuable tool for designing wireless communication systems. Even though commercial channel sounders allow for thorough and detailed measurements, they are typically very expensive. In contrast, existing software-based solutions are often limited in scope and complexity of measurements. Our system closes this gap. Using GNU Radio and USRP radio front-ends, the system provides a high degree of freedom with respect to supported carrier frequencies and bandwidth. We also support features such as automatic spectrum-sweeping and transmitter gain management for dynamic channel characterization. We can use the system for both live visualization of the channel characteristics, e.g., Channel Impulse Response, Channel Frequency Response, Power Delay Profile, and Channel Phase Response, as well as for fully automated and repeatable experiments.**

I. Introduction

Understanding the behavior of a wireless channel in different environments is a fundamental requirement when designing robust radio communication systems. For this reason, channel characterization has been the focus of researchers for decades now [1]–[3]. Presently, the widely utilized sub-6 GHz spectrum is densely populated, and to meet the fifth generation (5G) requirements of considerably large bandwidth and low latency, the wireless communications now involve millimeter-wave (mmWave) frequency spectrum as well. Hence, the need for channel sounding and characterization still transpires, as in the case of mmWave spectrum, where, in comparison, the channel behavior is entirely different [4].

For the characterization of radio channel impairments, the typical sounding approaches include direct transmission of single tones, wideband sounding through multi-tones, frequency sweeping over the desired sounding spectrum, and transmission of spread spectrum sounding signals for a wideband channel characterization. The earlier narrowband/wideband channel sounding systems were strictly standard specific and required a lot of user involvement [5]–[8]. Moreover, the hardware used (e.g., wideband signal generator, spectrum analyzer, and vector network analyzer) was very expensive and/or specialized.

With recent technological advancements, a flexible channel sounding system which can easily adapt the evolving standards with least human intervention has become a research target [9], [10]. Thus, channel sounders now are often based upon Software Defined Radio (SDR) platforms. Using SDRs, i.e., freely programmable radios, channel sounders are not limited to specific standards and offer more flexibility in terms of implementation. SDR platforms are typically differentiated based on how the Physical (PHY) layer is implemented. The two most common SDR variants are based on Field-Programmable Gate Arrays (FPGA) and/or General Purpose Processor (GPP). In the recent literature [10]–[14], different SDR-based channel sounder implementations have been presented. Most of these designs have limitations in terms of operational frequency ranges, sounding bandwidth, dynamic channel characterization, and ease of use.

In this paper, we focus on filling these gaps and present a real-time channel sounder that offers more flexibility in terms of implementation and usage. We build upon our GNU Radio Orthogonal Frequency-Division Multiplexing (OFDM) implementation [15], [16] to realize the software part of our channel sounding system. In comparison to the state of the art, the presented channel sounder implementation processes a multi-tone wideband sounding signal and has the capacity to perform channel characterization of multiple bands in the available frequency spectrum with little human intervention. Additionally, the presented software implementation can be used with different variants of Ettus Universal Software Radio Peripheral (USRP) series, thus fashioning a channel sounding system that is not limited to any specific hardware or frequency spectrum. For the performance evaluation, we first validate the implementation in simulation mode under known channel conditions, then perform practical sounding experiments in an indoor environment, and finally utilize the sounding system for a real-world application in an industrial environment.

Our main contributions can be summarized as follows:

- We develop a real-time channel sounding system in the GNU Radio framework that allows live visualization of complete Channel State Information (CSI) in both time and frequency domain over multiple frequency bands.
- Our implementation offers features such as automatic

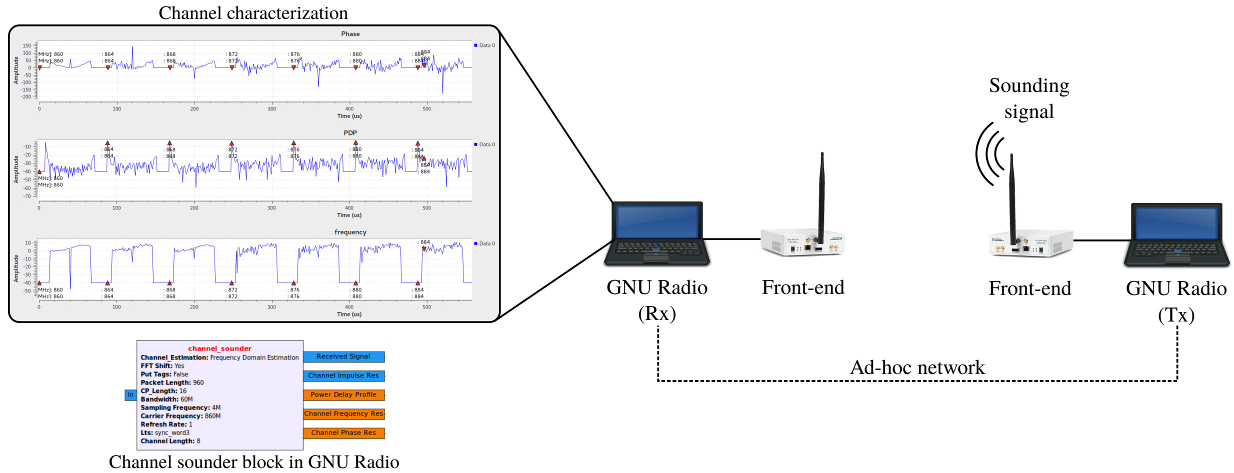


Figure 1. High-level description of our channel sounding system, also showing a screenshot of the corresponding GNU Radio implementation. The channel sounder is capable of sweeping through the given bandwidth to display real-time channel information in time and frequency domains.

spectrum-sweeping and transmitter gain management for dynamic channel characterization with minimal human involvement and, thus, reduced measurement errors.

- Using an automated car parking application scenario, we show that our channel sounding system can be used for live visualization of CSI as well as for automated measurements to conduct repeatable experiments.

II. Related Work

Channel sounding plays an essential role in characterizing a wireless channel in order to design robust communication systems. Earlier works on channel sounding required expensive hardware and were often application specific [5]–[8]. Hence, to make channel sounding more flexible, researchers started to focus on SDR-based implementations. In [13], a low-cost channel sounder is presented based upon an SDR using OFDM, however, only a single frequency band sounding is exploited. As a step forward, several recent works have considered multiple frequency bands [10], [17]. Moreover, advanced channel sounders with a particular focus on 5G communications have been developed [4], [9], [18]. Most of these works used FPGA-based SDRs because of their deterministic timing and low latency. However, these designs are rather inflexible, and it is often time consuming to modify and re-implement the complex signal processing algorithms, as these FPGA-based SDRs are not easily programmable in practice. In contrast, GPP-based SDRs support signal processing in software with high-level programming languages, such as C++ and Python, thus, making it particularly easy to use, modify, and debug [16]. Therefore, this work focuses on a GPP-based implementation making use of the GNU Radio signal processing framework.

Efforts have already been made to realize a complete channel sounding system in GNU Radio. For instance, a spread spectrum based channel sounding system is presented in [11]. Later, an OFDM-based channel sounder has been realized in GNU Radio [12]. However, the implementation lacked the ability of sounding multiple frequency bands and it is very hardware specific. To overcome these limitations, we develop a complete channel sounding system, which can be used for various types of applications and standards. Additionally, it can utilize different variants of Ettus USRP series as front-ends. Moreover, our channel sounding system can sound multiple frequency bands – sweeping the complete spectrum in a fully automated manner.

III. Channel Sounder Design

In a typical channel sounding system, a known signal is transmitted over the air through a front-end design that normally supports limited frequency spectrum. The received sounding signal is then used to characterize the channel between the transmitter-to-receiver (Tx–Rx) setup. A high level description of the channel sounding system considered in this work is depicted in Figure 1. The design comprises three parts: (1) A GNU Radio-based software implementation for both multi-tone sounding signal and channel characterization based on the received signal, (2) a simple handshake mechanism for spectrum sweeping and Tx–Rx gain management, remotely adjustable at the receiver-end for dynamic channel characterization, and (3) a USRP-based flexible front-end selection.

A. Sounding Signal and Channel Characterization

Our transmitted baseband sounding signal is a multi-tone signal that is based on OFDM sub-carriers structure for wide-band channel characterization. The equivalent time domain samples of the employed sounding signal are obtained as

$$x[n] = \sum_{k=-N/2}^{N/2-1} X[k] e^{j2\pi kn/N} \ , \tag{1}$$

where k represents the tone index, X is the amplitude of each tone, and N is the total number of tones in the sounding signal. Each tone in the signal is BPSK modulated for easy per sub-carrier phase and amplitude estimation at the receiver side. The inter-tone spacing depends on the used sampling rate as

$$\Delta f = F_s / N \ , \tag{2}$$

where Δf is the inter-tone spacing and F_s the sampling frequency.

At the receiver, the channel characterization is done through the received baseband samples of the sounding signal. Our channel sounder design characterizes the channel in both time and frequency domain. For the time domain characterization, the technique of least square time domain estimation is employed, where the Channel Impulse Response (CIR) is acquired as

$$\hat{\bar{h}} = \mathbf{X}^{\dagger}\bar{y} \ , \qquad (3)$$

where $\hat{\bar{h}}$ is the CIR, $\bar{y}$ are the received samples, and $\mathbf{X}^{\dagger}$ is the Moore-Penrose (pseudo) inverse of the Toeplitz matrix $\mathbf{X}$, cf. [19]. Likewise, for the frequency domain channel characterization, we use the least square frequency domain approach to compute the Channel Frequency Response (CFR) as

$$\hat{\bar{H}} = \bar{Y} \cdot / \bar{X} \ , \qquad (4)$$

where $\hat{\bar{H}}$ is the CFR for each sent tone, $\bar{Y}$ are the received sounding tones, and $\bar{X}$ are the sent tones.

B. Software-based Signal Processing

In our channel sounder design, the baseband signal processing is done in the GNU Radio framework. The software implementation of the channel sounding transmitter is rather straightforward. First, we modulate a known BPSK sequence onto the multi-tone sounding signal in frequency domain, then perform the Inverse Fast Fourier Transform (IFFT) operation to obtain time domain samples, and finally, we send them to the USRP device acting as the front-end.

The channel sounding receiver design involves significantly more signal processing. It starts with the coarse synchronization and Carrier Frequency Offset (CFO) correction step [15], then fine synchronization is achieved through the received wideband sounding signal samples. Afterwards, channel estimation is performed based on the chosen approach, i.e., either time or frequency domain, for the characterization of the channel. Finally, the key channel parameters including CIR, CFR, Power Delay Profile (PDP), Channel Phase Response (CPR), and Received Signal Strength (RSS) are extracted from the computed estimate. A high level channel sounding process along with a screenshot of the channel sounder block and real-time channel information as provided in the GNU Radio companion is shown in Figure 1.

C. Features Supporting Dynamic Channel Characterization

Our channel sounding system provides a set of features which ease the sounding process and improves its practical use in real-world experiments. The main features are listed in Table I. For brevity, we only discuss the automatic frequency spectrum-sweeping feature through which multiple bands can be sounded within the desired spectrum. To enable automatic spectrum-sweeping, we implemented a wrapper around the GNU Radio-based channel sounder which takes a set

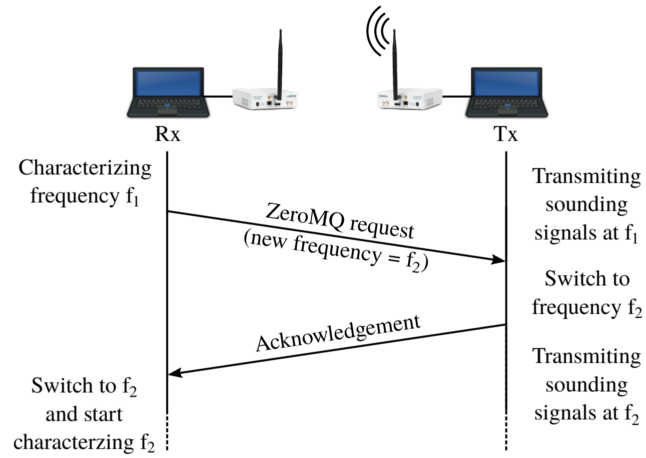


Figure 2. Handshake mechanism between transmitter and receiver to synchronize frequency switching during automatic spectrum sweeping.

of parameters, e.g., total-bandwidth $\mathrm{BW}_{\mathrm{total}}$, starting carrier frequency f_1, sampling frequency F_s (sounding signal bandwidth), and live-view refresh rate as input. Certain parameters like transmitter gain can also be modified in run-time from the GNU Radio's user interface at the receiving end.

While sweeping through the given bandwidth, both transmitter and receiver need to be synchronized with each other. This synchronization is done via a ZeroMQ-based[1] handshake mechanism as shown in Figure 2. To execute the handshake mechanism, both transmitter and receiver are connected - via ad-hoc WLAN (cf. Figure 1). The receiver initiates the handshake procedure by sending a ZeroMQ request message containing the starting frequency for sounding. Once the message is received, the transmitter switches to that frequency, starts transmitting the sounding signal, and acknowledges the change of frequency to the receiver. Upon receiving the acknowledgment, the receiver tunes to the starting frequency and starts sounding the channel. This process is repeated for each incremental frequency change within the desired spectrum, where the total number of frequency carriers required to sweep the whole spectrum N_{CF} and the incremental carrier frequency f_n are calculated as

$$N_{\mathrm{CF}} = \mathrm{BW}_{\mathrm{total}} / F_s \qquad (5)$$

and

$$f_n = f_1 + (n-1) \times F_s \ , \ n = 2, 3, 4, \ldots, N_{\mathrm{CF}} \ . \qquad (6)$$

[1]Distributed messaging framework, http://www.zeromq.org

Table I
FEATURES SUPPORTING DYNAMIC CHANNEL CHARACTERIZATION.

Automatic Spectrum-Sweeping	✓
Transmitter Gain Management	✓
Sounding Signal Bandwidth Selection	✓
Refresh Rate Selection	✓
Data Recording (for post-processing)	✓
Online Visualization	✓

With the automatic spectrum sweeping in our channel sounder, we improve its usability and reduce the user involvement, therefore, minimizing chances of human error during experiments. Additionally, live visualization provided by the GNU Radio user interface enables immediate feedback and allows prompt reaction in case of possible issues. It is important to mention that when an ad-hoc network is not possible between the transmitter and the receiver for dynamic channel characterization, then the spectrum-sweeping can be done manually. In this case, user involvement is only required for multi-band sounding.

D. Front-end Extensions

We use Ettus USRPs variants as front-end for our channel sounder implementation. They incorporate an FPGA with digitizing chains and a software configurable RF daughterboard. For accurate channel characterization, fine multipath resolution is the key requirement, which is essentially dependent on the supported sampling rates of the used USRP. The available sampling rate goes to as high as 200 MS/s for USRP X series, which translates to a temporal resolution of 5 ns.

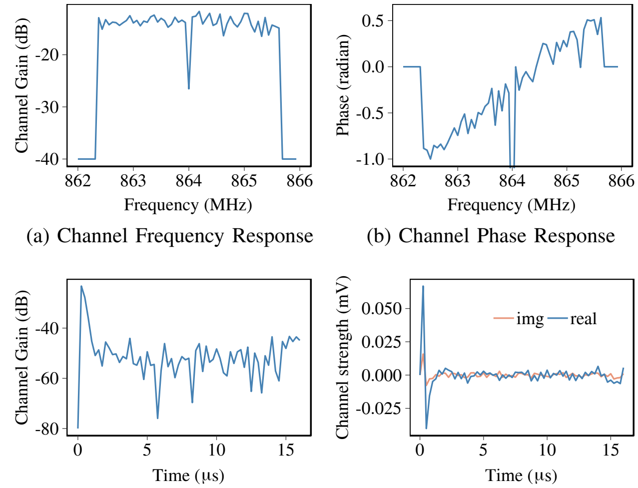
Nevertheless, the software signal processing is GPP-based, which means that the real-time processing capability highly depends on the available CPU cores at the time of processing. For extremely high sampling rates (of over 25 MS/s), a dedicated CPU with high compute power is often required for real-time processing and channel response visualization. If such higher sampling rates are to be used with average CPU, then received samples can be recorded online, and the channel is characterized via post-processing of the recorded data.

IV. Practical Performance

Validation and performance evaluation of our channel sounding systems are done in two steps. The first step involved simulative validation, in which we sent the multi-tone sounding signal through a known 6 tap multipath channel. Afterwards, we compared the actual CIR with the estimated CIR, and the difference between them was only due to the complementary Additive White Gaussian Noise (AWGN) component in the received sounding signal. These results validated the fine CIR computation by the channel sounder block (we omit the results due to space limitations).

Table II
KEY PARAMETERS FOR PRACTICAL PERFORMANCE EVALUATION.

Tones in Sounding Signal	52
IFFT Size (N)	64 bins
Sampling Frequency (F_s)	4 MHz
Inter-tone Spacing (Δf)	62.5 kHz
Transmit Power	0 dBm
USRPs	B-210
Carrier Frequency (Single-band)	864 MHz
Total Bandwidth (BW_{total}) (Single-band)	4 MHz
Carrier Frequency (f_1) (Multi-band)	872 MHz
Total Bandwidth (BW_{total}) (Multi-band)	16 MHz
Carries Required (N_{CF}) (Multi-band)	4



(a) Channel Frequency Response (b) Channel Phase Response

(c) Power Delay Profile (d) Channel Impulse Response

Figure 3. Sample measurement of single-band channel sounding experiment.

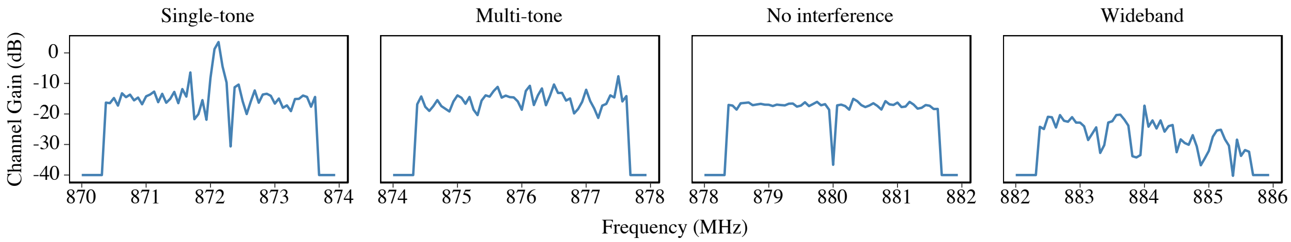
In the second step, the practical performance of the channel sounder is tested with Ettus B-210 USRPs in an indoor environment. We performed two sets of sounding experiments: single-band sounding and multi-band sounding. The key parameters of the experiments are listed in Table II. For the real-time (live) visualization of the channel parameters, a low sounding bandwidth of 4 MHz with 250 ns multipath resolution is selected in both types of experiments, because of the limited processing power in the used laptops. Nevertheless, with a high-processing power PC, the real-time sounding bandwidth can go as high as 15 MHz, which is the maximum streaming bandwidth of B-210 USRPs.

Figure 3 shows a sample measurement of the single-band sounding experiment. The key channel parameters, i.e., CFR, CPR, PDP, and CIR, are obtained for Non-Line-of-Sight (NLOS) link between transmitter and receiver. The PDP plot in the figure clearly shows the richness of multipath in the beginning of the plot, i.e., below 800 ns, which is expected because the delay spreads are often quite smaller in indoor channels as compared to outdoor channels.

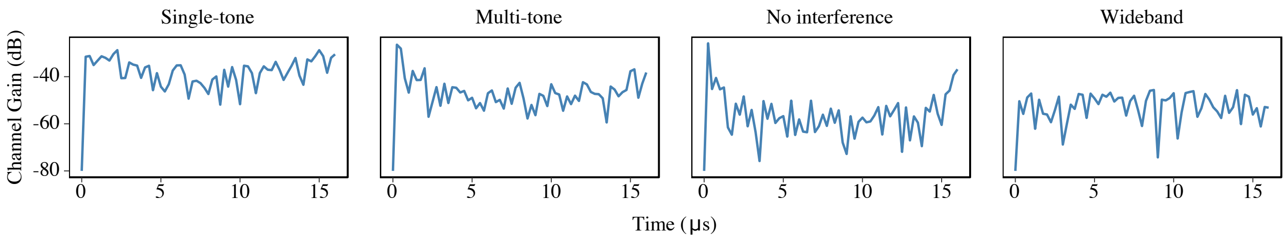
The sample measurement of the multi-band channel sounding experiment are presented in Figure 4. The figure shows the CFR and PDP plots in the multiple bands, sweeping a total bandwidth of 16 MHz. The CFR plot of the first band is obtained under a single-tone interference. Similarly, the second band is measured under multi-tone interference, the third band is with no interference, and, finally, the fourth band with wideband interference. It is worth noticing here that the delay spread in the 880 MHz band is larger as compared to the 864 MHz band (cf. Figure 3) within the same indoor environment. The sample measurement shown here demonstrates the working of our channel sounder in both single-band and multi-band sounding modes.

V. Application Scenario

Knowledge about the characteristics of the wireless channel can be especially useful if reliability is an important objective



(a) Channel Frequency Response



(b) Power Delay Profile

Figure 4. Sample measurement of multi-band channel sounding, showing the channel behavior in multiple frequency bands under different channel conditions.

for a wireless communication system. As an example, we present results of a study that we conducted in an automated multi-storey car park. The car park includes multiple independent units which are coordinated via a wireless communication link to move cars from and to their parking positions. The research question is, to what degree wireless communication can be used in this application assuming certain reliability constraints. We made use of our automated channel sounder to not only get live visualization of the channel as shown before, but also to fully automate rather complex measurements conducted in repeatable experiments.

Multiple transport vehicles can move back and forth (horizontally) within the car park lanes. Each transport vehicle is equipped with two shifters that can slide under a car and move it from the transport vehicle and place it at the parking spot (cf. Figure 5). The commands for moving the shifters are sent from the transport vehicle over a wireless radio connection. If the wireless communication fails, the shifters stop moving and the system has to be controlled manually.

We conducted extensive measurements to study this wireless channel, and to determine possible causes of such communication outages. For the measurements, we installed a transmitter on the transport vehicle and a receiver at the shifters, and then moved the shifters via manual control from the transport vehicle to the end of the parking space. While moving the shifters, we continuously measured the channel behavior at the receiver as well as the position of the shifter with a laser distance meter so that we can compare the individual runs. In order to investigate the different environmental influences that can change the channel, we conducted experiments at different positions, i.e., close to a concrete wall and in a more open space, and with/without a car parked in the parking space. In the following, we report only selected results.

In order to get a first impression of the channel, we conducted a simplified experiment where we sent the sounding

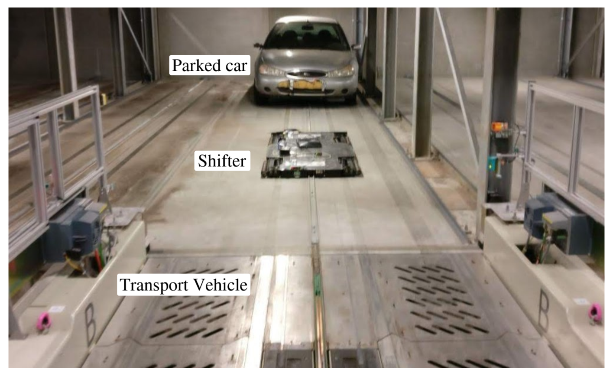


Figure 5. Experimentation environment: The shifter is equipped with the receiver to sound the channel. During the experiments, it moves from the transport vehicle to the wall at the end of the parking space, while sliding through the parked car.

signal and measured the Received Signal Strength (RSS) at the receiver. Figure 6 shows the RSS over distance for 5 independent runs. In the considered scenario, a car was parked close to a concrete wall at the distance of 1026 cm (shown as a vertical line in the plot) and the shifter move towards, and later beneath this car. For each run, similar sharp drops in signal strength can be observed even at closer distance, which further drops down to −80 dBm as soon as the shifter slides down under the car. These performance drops are first due to the multipath environment, and later because of the additional shadowing effect caused by the parked car. Additionally, the similar RSS behavior (e.g., the deep drops in signal strength) over the different runs is quite interesting; it shows the time invariance of the channel.

In the second experiment, we switched from a simple sounding signal to a packet-based communication, where we continuously sent out complete packets with a known payload and computed the Packet Delivery Ratio (PDR) at the receiver. Figure 7 shows the PDR over distance for the same scenario.

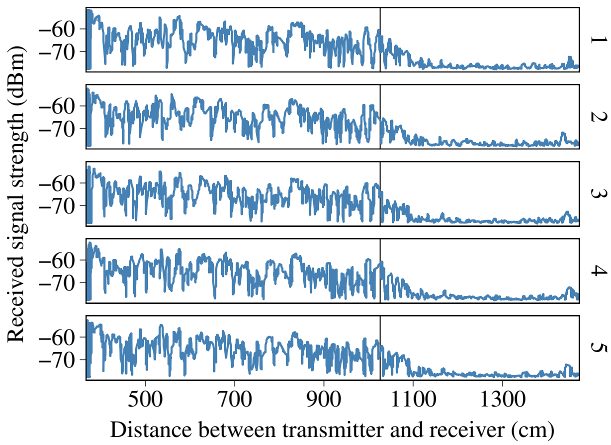


Figure 6. Results of 5 consecutive runs of the initial experiment. The drop in RSS is due to multipath and shadowing by the parked car.

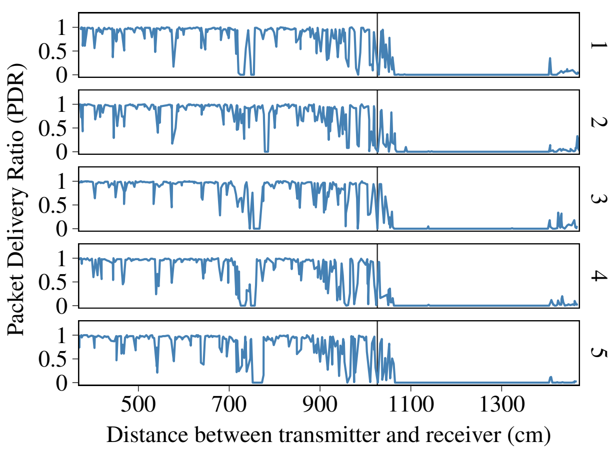


Figure 7. Results of 5 consecutive runs of the packet-based experiment. The PDR is significantly affected by interference and shadowing.

Even without the shadowing due to the car, at some positions (i.e., around 750 cm) the PDR can drop to zero due to the destructive interference caused by the multipath environment. Additionally, when the shifter slides under the car, RSS drops to the noise level, resulting in complete packet loss.

VI. Conclusion

We presented a novel GNU Radio-based flexible real-time multi-band channel sounder, which can be used for live visualization of the channel characteristics as well as for fully automated experiments in complex wireless communication environments. We use bandwidth-limited USRP SDRs to measure larger bandwidth channels or wide-spectrum in general by automatic spectrum-sweeping. The presented system with limited hardware requirements has a big advantage over expensive commercially available channel sounders, with typical limitations of operational frequency, sounding bandwidth, and ease of use. We explored the feasibility of our sounding system in a measurement campaign, first, looking at a very controlled environment and, secondly, making use of the automation capabilities in a very complex indoor communication environment in a car park system. Our results show that with the presented channel sounder such experiments can easily be conducted and automated to gain an insightful knowledge about the characteristics of a wireless channel. This information is quite useful when designing a new system or when debugging communication problems in an existing one.

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