Parallel Channel Sounder for MIMO Channel Measurements

Yang Yang, Yunsong Gui, Haowen Wang, Wuxiong Zhang, Yang Li, Xuefeng Yin, and Cheng-Xiang Wang

Abstract

In order to address the challenges in MIMO channel measurement and modeling for 5G communication scenarios, a CDM-based parallel channel sounder is developed and evaluated in this article. Compared to traditional TDM-based channel sounders, our parallel channel sounder supports eight-by-eight (8 × 8) MIMO communications, 200 MHz RF bandwidth, 5 ns multipath time resolution, 36 dB dynamic range, and 2 kHz maximum Doppler shift at a speed of 350 km/h. To achieve these performance targets, a series of sophisticated technical solutions are proposed and analyzed to realize 32 ps synchronization accuracy, 51.36 Gb/s parallel data streaming, and high-precision calibration across multiple channels. Key functions and performance metrics are evaluated and verified in a microwave chamber. Real measurement results in a complex campus environment show that our CDM-based parallel channel sounder can capture more detailed channel characteristics, and therefore offer accurate PDPs and RMS delay spreads at both LoS and NLoS positions under MIMO communication scenarios.

Introduction

Multiple-input multiple-output (MIMO) technologies have been adopted for advanced wireless communication networks. Recently, massive MIMO and full-dimension MIMO (FD-MIMO) technologies have made great progress in the ongoing standardization of the fifth-generation (5G) mobile communications [1, 2]. For example, NTT DoCoMo has released a prototype 5G base station using massive MIMO technologies with 256 transmitting (TX) and receiving (RX) antennas [3]. As the numbers of TX and RX antennas increase, it is crucial and challenging to measure channel characteristics in parallel and develop realistic channel models for achieving the spectrum- and energy-efficient design objectives in 5G and future wireless networks [4]. Specifically, key technical challenges for parallel channel measurements include:

- Cross-correlations and interferences in the growing matrix of TX and RX antennas
- Full-dimensional channel sounding and measurement with temporal- and spatial-domain channel consistency
- Millimeter-wave bands with beamforming techniques in 28 GHz and 40 GHz spectra
- Customized service scenarios such as vehicle-to-vehicle (V2V) communications with large Doppler shifts and massive machine type communications (mMTC) with large end-to-end delay spreads

It is therefore very urgent and challenging to develop high-precision channel sounding and measurement instruments for accurately capturing and modeling parallel MIMO channel characteristics in real environments.

There are three methods to extend a traditional one-by-one (1 × 1) channel sounder with only one RF channel on TX and RX sides to a MIMO channel sounder, that is, time-division multiplexing (TDM) [5, 6], code-division multiplexing (CDM) [7, 8], and frequency-division multiplexing (FDM) [9]. TDM-based channel sounders sequentially and periodically switch the only RF channel to every pair of TX and RX antennas for multiple channel measurements. For semi-static channels with long coherent time, this TDM method can capture channel characteristics and obtain the corresponding channel impulse responses (CIRs) as long as it switches the RF channel very quickly among all TX/RX pairs. For example, considering a 2 × 2 MIMO communication system, a TDM-based channel sounder, such as RUSK [5] and the NTT DoCoMo channel sounder [3], needs to execute four measurements between every TX/RX pair in order to obtain an integrated 2 × 2 CIR. Obviously, the total measurement time of the TDM method is proportional to the product of TX and RX antenna numbers. This approach is very much constrained by short coherent time of multiple channels and therefore unsuitable for either complex MIMO systems with large numbers of antennas or dynamic communication environments with high-speed moving terminals. Some channel measurement results based on TDM have been reported in the literature for small MIMO systems at low speed (< 30 km/h) communication scenarios [3, 6, 10], and for large MIMO systems in static scenarios [11, 12]. In [7], considering a high-speed V2V scenario, that is, 100 km/h, a RUSK channel sounder is used to measure the CIRs of a 4 × 4 MIMO channel. Those cannot meet the very challenging 5G performance requirements of a moving speed of 500 km/h with massive TX/RX antenna numbers.

In order to meet the MIMO channel measurement requirements in high-speed moving scenarios, CDM- and FDM-based parallel channel sounders

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Digital Object Identifier: 10.1109/MWC.2018.1800042

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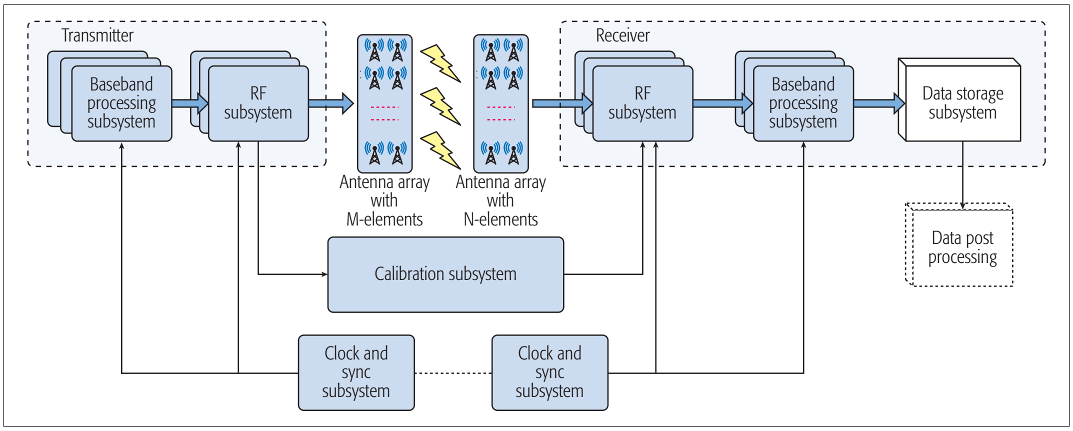

FIGURE 1. System architecture of the MIMO parallel channel sounder.

In order to achieve high spatial and temporal resolutions in channel parameters estimation, 70-ps synchronization accuracy across MIMO channels must be guaranteed in all time. Two high-precision reference clocks at TX and RX sides should be accurately synchronized with a constant coherent phase.

have been proposed in the literature. In particular, a CDM-based 2 × 2 prototype is developed in [8] for V2V channel measurements at a peak speed of 240 km/h, at the expense of low spatial resolution. In [13], another CDM-based instrument is proposed, which is assembled by using off-the-shelf commercial equipment. It is cost effective, but does not support continuous data streaming function. In [10], an FDM-based parallel channel sounder is made to use equally spaced subcarriers for multiple frequency channels. These subcarriers are not continuous and hence reduce the effective range for delay estimation. In addition, due to limited data streaming capability, previous parallel channel sounders cannot record large-volume raw measurement data in real time, but only provide multiple CIR results. This common drawback significantly decreases the analytical and modeling accuracy of Doppler shifts, and temporal- and spatial-domain channel consistency.

This research addresses the aforementioned challenges and develops a series of technical solutions for high-accuracy synchronization across MIMO channels, high-speed data streaming for real-time storage of large-volume raw measurement data, high-precision calibration of parallel RF channels, and so on. Specifically, our CDM-based parallel channel sounder can support 8 × 8 MIMO communications, 200 MHz RF bandwidth, 5 ns multipath time resolution, 36 dB dynamic range, and 2 kHz maximum Doppler shift at a speed of 350 km/h.

The remainder of this article is organized as follows. The following section introduces the system architecture of the proposed MIMO parallel channel sounder. Major technical challenges for developing, testing, and evaluating this sophisticated high-precision measurement instrument are then analyzed and discussed. Our solutions and main contributions for achieving those design targets are then provided. After system implementation, we verify key functions and performance metrics in a microwave chamber, followed by a real measurement campaign in a complex campus environment for comprehensive system evaluation. Finally, we conclude this article.

System Architecture

As shown in Fig. 1, our proposed CDM-based parallel channel sounder consists of five subsystems. This is a time-domain MIMO channel sounder that sends and receives signals in all TX and RX channels simultaneously. A set of orthogonal sequences has been carefully chosen to distinguish multiple TX channels. Besides transmission and reception parts, the key functions and subsystems of this sounder, such as synchronization, calibration, and data streaming, are described in detail as follows.

Baseband Processing Subsystem

At the transmitter side, orthogonal pseudo-noise (PN) codes and quadrature phase shift keying (QPSK) modulated sequences are generated as baseband signals for different transmission channels. Up-sampling and shaping filters are used to improve frequency-domain shapes of these orthogonal signals before sending them to corresponding RF channels.

At the receiver side, baseband measurement signals with complex MIMO channel information are obtained from down-converters and high-speed A/D converters at parallel RF channels. These signals contain complete MIMO channel characteristics of measurement environment and frequency band. It is therefore very crucial but challenging to store all valuable raw data into disk arrays in real time.

RF Subsystem and Antenna Arrays

At the transmitter side, each channel uses a single-stage direct-conversion (I/Q) up-converter to transfer baseband signals into RF signals at a specific local oscillator (LO) frequency. By adopting wideband quadrature correction techniques, this approach can minimize residual sideband images and LO power for wide instantaneous RF bandwidths. Finally, multiple RF signals are simultaneously transmitted through an antenna array with M elements; for example, $M = 8$ in this work.

At the receiver side, RF signals from multiple paths are captured by an N-element antenna array ($N = 8$) and then down-converted from the specific LO frequency to baseband for digitization, storage, and analysis.

Clock and Synchronization Subsystem

In order to achieve high spatial and temporal resolutions in channel parameters estimation, 70 ps synchronization accuracy across MIMO channels must be guaranteed at all times. Two high-precision reference clocks at TX and RX sides should be accurately synchronized with a constant coher-

Performance parameters	TDM-based	FDM-based [10]	CDM-based parallel channel sounder
Carrier frequency	0.1 ~ 6 GHz	2.4425 GHz	0.1 ~ 6 GHz
TX/RX RF channel number	1	4	8
RF bandwidth	125 MHz	80 MHz	200 MHz
TX power (per antenna)	27 ~ 40 dBm	N/A	15 ~ 40 dBm
Dynamic range	40 dB	N/A	36 dB
Multipath time resolution	8.33 ns	12.5 ns	5 ns
Maximum Doppler shift	60 Hz	500 Hz	2 kHz
Maximum moving speed	30 km/h	80 km/h	350 km/h
Data storage type	CIR	CIR	Raw data and CIR

TABLE 1. Key performance parameters of different MIMO channel sounders.

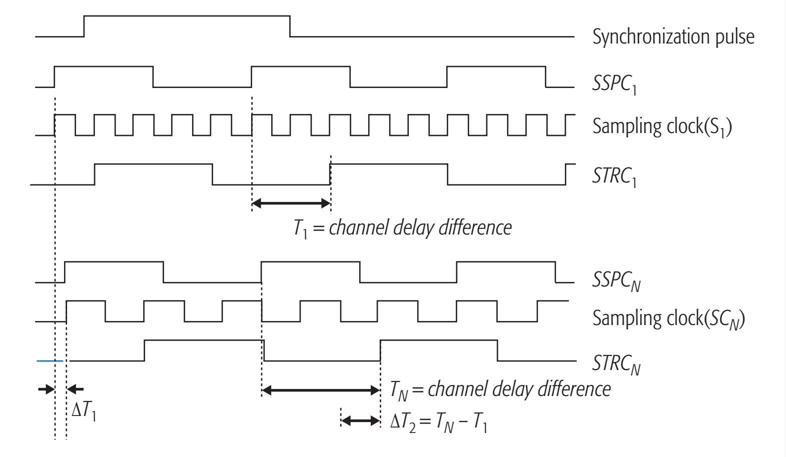

FIGURE 2. Clock phase alignment and synchronization mechanism.

ent phase. In addition, all TX/RX channels rely on the same LO and triggering mechanism to generate/sample baseband signals and to transmit/receive phase-coherent RF signals. The Global Positioning System (GPS) provides a stable 1 pps pulse sequence, which is an excellent trigger signal for the arbitrary waveforms generator (AWG) to produce necessary periodic signals for initial coarse synchronization between transmitter and receiver.

Calibration Subsystem

The proposed MIMO parallel channel sounder can be considered as a multi-channel time-varying complex system. In order to guarantee channel estimation accuracy, a parallel calibration subsystem is designed to carefully compensate different non-ideal channel responses at every TX/RX pair, which are rooted in multipath clock phase-locked loop (PLL) circuits and RF devices at both transmitter and receiver. Calibrated transmitting signals are stored and will be used in the data post-processing stage.

Data Storage Subsystem

At the receiver, raw measurement data from parallel channels is huge in volume and must be stored simultaneously into disk arrays. It is very important and necessary to ensure continuous data streaming capacity in the parallel channel sounder for measuring channel consistency in the time and space domains. In order to capture more detailed time-varying channel characteristics, a real-time high-throughput data streaming scheme is developed to store large-volume raw measurement data, together with the corresponding GPS and calibration information encapsulated as valuable records. This approach effectively guarantees time alignment and accuracy of measurement data across parallel channels, thus enabling synchronous multi-channel data processing and analysis afterward.

Design Challenges and Key Technologies

As shown in Table 1, compared to TDM- and FDM-based approaches, our CDM-based parallel channel sounder achieves significant performance improvements, which are due to the following key technical solutions for high-accuracy synchronization, high-speed data streaming, and high-precision calibration.

32 ps Synchronization Accuracy across MIMO Channels

For a carrier frequency of 3.5 GHz, antenna elements are placed with a distance of a half wave length, that is, 4.3 centimeters. So the time difference for electromagnetic waves traveling across two adjacent elements is about 140 ps. In order to accurately estimate angle of arrival/angle of departure (AoA/AoD) parameters, the synchronization accuracy across all TX/RX channels needs to be improved to a level of 70 ps.

In practice, different sampling frequencies may be used in multiple channels; these sampling clocks need to be aligned with a common reference clock. In addition, due to the differences between clock PLL circuits across multiple RF channels, it is crucial to design a robust triggering mechanism for achieving very accurate synchronization of the clock's phases. As detailed in the following, our proposed solution can solve this challenging problem with an average synchronization accuracy of 32 ps.

First, both TX and RX channels share the same 10 MHz reference clock.

Second, according to various channel sampling frequencies, a common reference clock, named share trigger reference clock (STRC), is set with its period equal to the least common multiple of the periods of different sampling clocks. The sampling clock for each channel and STRC is phase locked, but not phase aligned, to the 10 MHz reference clock.

Third, a common synchronization signal, named share sync pulse clock (SSPC), is generated by an arbitrary channel, say Channel 1 in Fig. 2. SSPC is distributed through finely calibrated paths to different channels so as to ensure accurate phase alignment among these SSPC signals.

Fourth, by using an external trigger signal, Channel 1 generates a sync pulse and distributes it to all channels. After detecting this sync pulse, every channel measures the delay gap between the first rising edges of SSPC and STRC signals. As shown in Fig. 2, the delay gap between Channel 1 and Channel N is measured as ΔT_2. Every channel adjusts its digital-to-analog/analog-to-digital conversion (DAC/ADC) output phases according to its own delay gap against Channel 1. In doing so, the STRC and different sampling clocks of all channels are accurately synchronized and phase aligned.

51.36 Gb/s Parallel Data Streaming for Real-Time Storage of Raw Data

Different from most traditional channel sounders only providing calculated CIRs, we would like to capture and store the complete raw measurement data in all MIMO channels in order to conduct comprehensive post-processing and analysis with sophisticated parallel SAGE algorithms. Roughly speaking, with a sampling rate of 180M/s and a quantization accuracy of 14 bits at each of eight RX channels, the total required speed for real-time data streaming of sampled IQ raw data is about 40 Gb/s, that is, 180M × 14 × 2 × 8 b/s.

To reach this target, direct memory access-first-in first-out (DMA-FIFO) is adopted to take advantage of a huge transmission data rate of 64 Gb/s at the backplane bus, by which an SSD disk array can be connected to the field programmable gate arrays (FPGAs) of every vector signal transceiver (VST). In addition, the zero-copy technology [14] is extended to effectively reduce the latency at operating system kernel by avoiding extra copies and state transitions.

Specifically, as shown in Fig. 3, zero-copy technology only needs two direct memory access (DMA) copying processes from hard drive to kernel buffer and from socket buffer to protocol engine to complete a file transmission. Compared to normal file I/O operations, two file copying processes from kernel buffer to user buffer and from user buffer to socket buffer are saved under the zero-copy technology, thus greatly reducing the latency and CPU's burden at extensive parallel data streaming and real-time storage. Finally, thanks to this ultra-high-speed and low-latency solution, our parallel channel sounder can achieve a data rate of 51.36 Gb/s for real-time storage of raw measurement data from all channels.

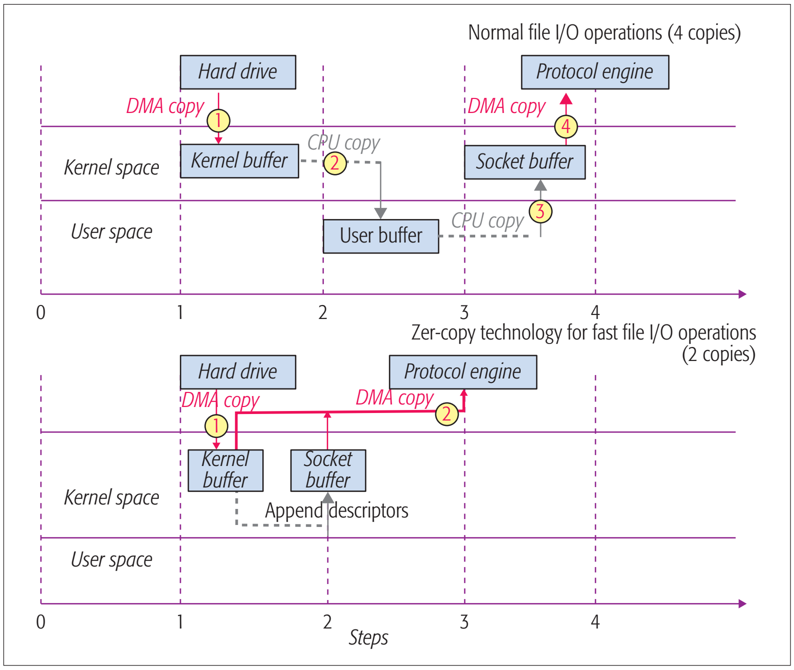

FIGURE 3. Zero-copy technology for high-speed data storage

High-Precision Calibration of Parallel RF Channels

The hardware and RF devices in multiple TX and RX channels are identical but not ideal, so the exact channel responses at parallel RF chan nels are different and would greatly reduce the accuracy in channel characteristics analysis and cross-channel parameters modeling. It is a must to develop a sophisticated, high-precision RF channel calibration scheme for our parallel channel sounder. Therefore, the negative effects of different non-ideal channel responses in time and space domains across multiple channels can be minimized before the analytical processes of channel characterization and modeling.

In order to capture the calibration data at parallel RF channels in real measurement scenarios, an 8 × 8 RF coupler is used to connect TX and RX sides in back-to-back testing. The physical responses between every input and output port pair of this RF coupler are measured in advance using a vector network analyzer. Just like a standard channel sounding process, orthogonal PN sequences are simultaneously transmitted from eight TX channels, and the comprehensive raw measurement data is recorded at the RX side. An 8 × 8 matrix of channel responses, for every pair of TX and RX channels, can be derived by calculating the correlations between transmitted PN sequences and received signals at parallel channels, and removing the RF coupler responses at every corresponding pair of input and output ports. With these 64 channel responses at all TX/RX pairs, the calibrated transmitting signals can be obtained by a series of convolution operations with the orthogonal PN sequences. At the data post-processing stage, these calibrated transmitting signals are used to derive the ultimate, pure channel responses and modeling parameters across parallel wireless channels in real measurement environments.

System Implementation and Measurement Results

In this section, the issues and details about system implementation of the parallel channel sounder (Fig. 4) is first described, which is divided into hardware and software parts. Then the performance of key functions and subsystems, including synchronization, calibration, and data streaming, is evaluated and verified in a microwave chamber. Finally, real MIMO channel measurement results at both line of sight (LoS) and non-LoS (NLoS) positions are presented for a complex campus environment. More detailed channel characteristics and more accurate delay spread models can be captured and analyzed.

System Implementation

Hardware: A sophisticated 18-slot chassis with high-speed PXI data bus is chosen to support the aforementioned technical solutions. Both TX and RX sides are equipped with two chassis sharing the same PXI data bus via an extension card, thus integrating eight VSTs with high-performance controllers for enabling 8 × 8 channel measurement campaigns in real communication scenarios. A GPS signal receiver and a rubidium atomic clock are used at both TX and RX sides for channel synchronization.

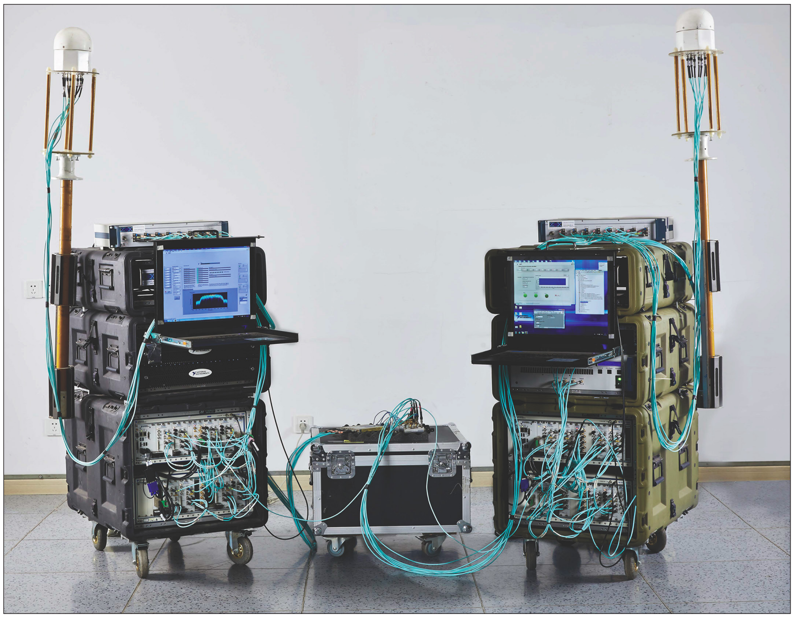

FIGURE 4. Implementation of the MIMO parallel channel sounder.

Software: A resource management software platform is developed in LabView, which is running at high-performance controllers to monitor and manage all hardware resources in real time. The complete baseband signal path, including signal generation, processing, and acquisition functions, is realized by a series of signal processing programs written in VHDL for onboard FPGA modules. In addition, a parallel SAGE algorithm is developed in MATLAB to estimate and model cross-channel parameters and characteristics in complex MIMO communications at the post-processing stage of raw measurement data.

Performance Verifications

Experimental Settings: A 4 m × 6 m professional microwave chamber is used to verify the key functions and performance indices of our parallel MIMO channel sounder. At the carrier frequency of 3.5 GHz, two uniform circular antenna arrays are installed at both TX and RX sides, which are separated by 5 m. Meanwhile, some metal reflectors are placed in the chamber to construct a realistic multipath fading environment. Every snapshot in channel sounding and measurement consists of 100 PN sequences with 4096 symbols, and the duration of each symbol is 10 ns at a sampling rate of 100 MHz.

Synchronization: A high-end dual trace oscilloscope is used to measure the synchronization discrepancies between all RF paths. Through extensive experiments, the minimum, maximum, and average time discrepancies are obtained as 30.8 ps, 34.2 ps, and 32.1ps, respectively, which meet our system design requirement on synchronization.

Data Streaming: On average, 10 TB raw data from eight parallel channels is stored in real time at each channel measurement campaign over 1557.64 s, which is equivalent to a speed of 51.36 Gb/s (i.e., 10,000 × 81 ÷ 557.64 Gb/s) for data streaming.

Calibration: As shown in Fig. 5, the raw measurement data (left) and pre-calculated calibration data (middle) have similar patterns of power delay profiles (PDPs) over the same order of 64 TX/RX channel pairs. This observation indicates that the spread of PDPs is not due to wireless environments, but is the result of different channel responses at parallel RF channels with identical hardware devices. After 64 convolution operations, the PDPs of calibrated transmitting signals (right) are finally aligned, that is, non-ideal channel responses at parallel RF channels are perfectly compensated by using high-precision calibration data. Specifically, the standard deviation of PDPs across 64 TX/RX channel pairs is greatly reduced from 3027.7 ps to 48 ps, a very impressive improvement of 98.4 percent.

Measurement Results

With our newly developed parallel channel sounder, a three-month campaign of MIMO channel measurements and modeling in different frequency bands and various communication scenarios has been conducted at indoor and outdoor environments, for example, canteen, gym, office, campus, park, beach, rural, and city areas. Following the open source philosophy, key experiment parameters and raw measurement data are published at a free-access website (www.wise.sh) for data sharing and further discussion with the global 5G R&D communities.

Specifically, for a typical university campus environment, eight TX antennas are put on top of a nine-floor building (30 m in height), and eight RX antennas are set at 2.1 m from the ground. The total transmission power is 30 W over a bandwidth of 200 MHz at the 3.5 GHz carrier frequency. Without loss of generality, four LoS positions (i.e.,

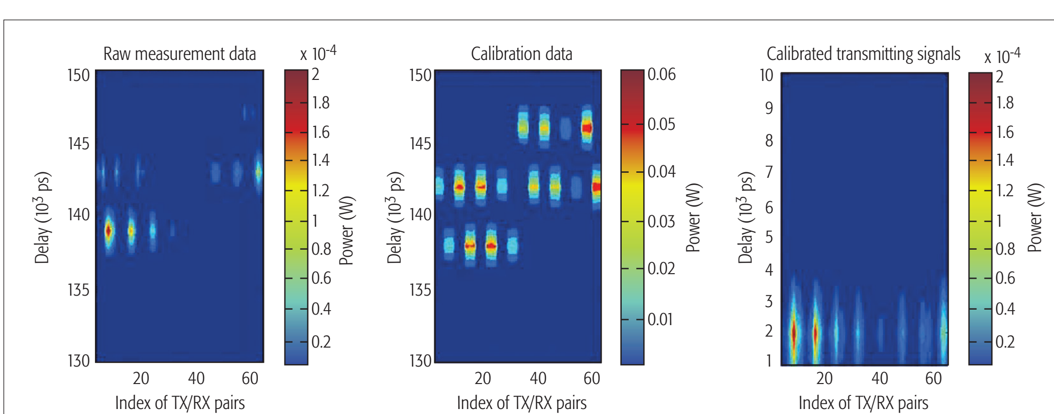

FIGURE 5. Power delay profiles at 64 TX/RX pairs before and after calibration.

300 m, 380 m, 310 m, and 200 m) and five NLoS positions (i.e., 320 m, 230 m, 275 m, 200 m, and 150 m) are chosen at different directions and distances from the TX antennas for a series of parallel channel measurements and analyses.

At each measurement position, the CIRs of 64 TX/RX pairs can be derived from large-volume raw data collected through multiple sounding and measuring snapshots (e.g., 100 snapshots for this example). By considering the complex cross-correlations between multiple TX/RX channels, a parallel SAGE algorithm is developed to estimate and model key channel parameters and characteristics at different communication scenarios. As seen in Fig. 6, after power normalization over all transmission paths, the corresponding PDPs at LoS positions have much fewer multipath delay components, but with much more concentrated powers than those at NLoS positions. Therefore, the root mean square (RMS) delay spreads for LoS and NLoS positions in this case are calculated as 62 ns and 91 ns, respectively, by using the approach specified in the 3GPP spatial channel model [15]. Compared to the International Telecommunication Union — Radiocommunication Standardization Sector (ITU-R) M2135 Urban Micro scenario (Umi) containing only the LoS result with an RMS delay spread of 64 ns [11], our measurement data verifies this LoS result and, more importantly, provides an additional NLoS result in this real communication scenario.

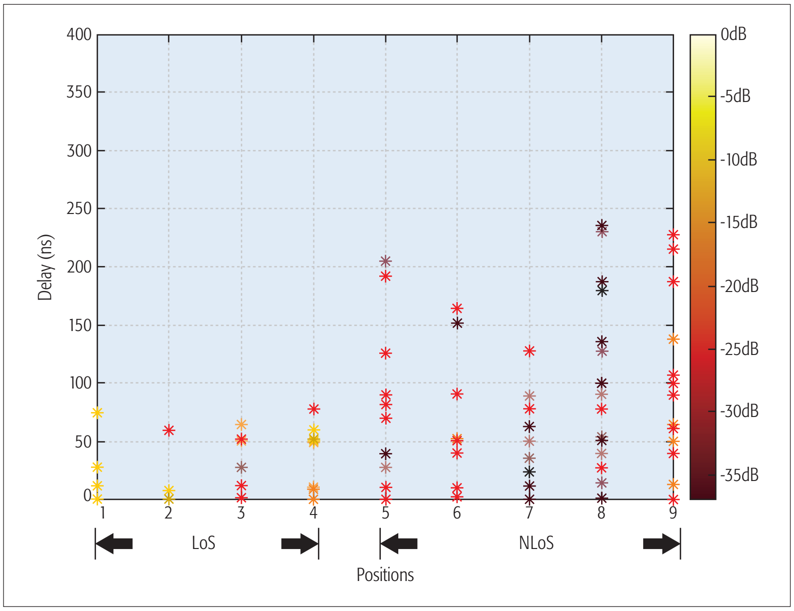

FIGURE 6. Normalized power delay profiles at LoS and NLoS positions.

Conclusions

In this article, a CDM-based parallel channel sounder has been proposed and implemented for MIMO channel measurement. Its system architecture, design challenges, and key technologies, such as multi-channel synchronization, real-time parallel data streaming, and high-precision calibration, have been described and analyzed in detail. After function and performance verifications in a microwave chamber, real measurement results have been obtained by using our parallel channel sounder in a complex campus environment with both LoS and NLoS positions. Accurate RMS delay spread values have successfully been derived for those LoS and NLoS positions by using data post-processing software.

Our future work is to extend the capabilities of this parallel channel sounder, for example, from 8 × 8 to 256 × 256 TX/RX channels, so as to meet the requirements of massive MIMO communication scenarios. Obviously, it will be very expensive and complex to greatly increase the number of TX/RX channels. Super precise synchronization and calibration need to be achieved and maintained across all these channels, which will be very challenging but crucial for reliable system performance. Specifically, a pure TDM-based approach will experience a much longer switching cycle, which is not acceptable for mobile channels with short coherent time. However, a pure CDM-based approach will require much larger bandwidth for real-time parallel data streaming, which is not affordable. A much more economic approach could be using a hybrid TDM and CDM architecture for the implementation of a massive MIMO channel sounder, through which the huge pressure on massive channel synchronization and calibration can be effectively relieved, but at the expense of slightly reduced Doppler range of dynamic channels. More measurement data in different communication scenarios [15] will be continuously added to our free data sharing platform: www.wise.sh.

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