Development of 4×4 Parallel MIMO Channel Sounder for High-Speed Scenarios

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Abstract. High reliable wireless communication with big data rate in high-speed moving scenarios is currently a hot topic, and channel sounding plays an very important role in the related research as a basic tool to know the channel characteristics. For MIMO channel sounding in high-speed moving scenarios, to meet the requirement of CIR measurement speed is a big challenge so that the fully parallel MIMO structure has to be used, which will induce severe crosstalk at the receiver and usually, the problem can be solved by CDM and FDM methods. But until now, which solution is better, there is no conclusion. So, in this paper we aim at developing a channel sounder that can support 4×4 MIMO sounding at the speed of above 1000 km/h after the performance comparison of FDM and CDM. Based on the autocorrelation and orthogonal properties analysis of common used signal for CDM, including m, ZC and LS sequence, we choose the FDM solution utilizing the multi-carrier technique, because of its higher measurement dynamic range. And finally, we complete the implementation and validation of the hardware.

Keywords: Channel sounding · MIMO · High-speed · CDM · FDM

1 Introduction

Currently, the Internet of Vehicle (IoV), High-Speed Train (HST), and autopilot technologies have become the focus of attention, it drives the wireless communication technology in moving environment to face new challenging requirements. As the basis of wireless communications technologies research, wireless channel research is of great significance to the signal processing algorithm study, network design and system optimization. Wireless channel research relies on an important tool, channel sounder. Unfortunately, commercial channel sounder is monopolized by a few companies like MEDAV and Keysight (after it bought Anite), which led directly to the extremely high cost of channel sounder. Furthermore, limited by the dedicated hardware and software structure, the hardware using efficiency and flexibility are very poor, compared with their price.

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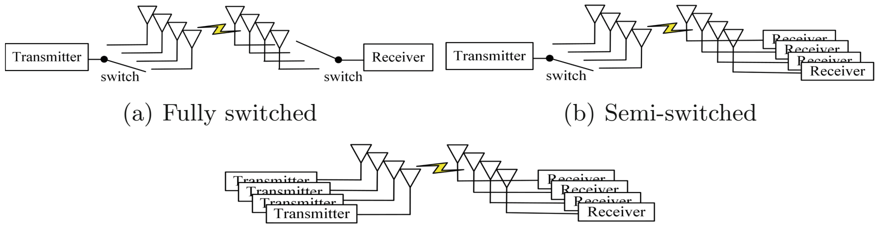
For MIMO channel sounding, especially for high-speed moving scenarios, the impulse response (CIR) measure speed must be fast enough to effectively capture the fast fading characteristics of high-speed mobile channel. And currently, most of the MIMO channel sounders are based on time division multiplexing (TDM) structure which measure the subchannels sequently by electronic switching. According to how the switches are used, the channel sounder can be further divided into fully switched structure [1,2] and semi-switched structure [3,4], as shown in Fig. 1(a) and (b). The TDM structure requires only a single transmitter or receiver, which can effectively reduce the system cost, and effectively eliminate crosstalk between different transmitting antennas. So it is suited to static or lower speed moving scenarios channel sounding, but for high-speed moving scenarios, it will lose much channel information during the switching duration. So, the fully parallel structure has to be used as shown in Fig. 1(c).



(a) Fully switched (b) Semi-switched

(c) Fully parallel

Fig. 1. MIMO channel sounding structures

In fully parallel structure, the crosstalk cancellation between different transmitting antennas is the first thing and usually we can choose to use frequency division multiplexing (FDM) [5,6] or code division multiplexing (CDM) [7,8]. But which solution is better for the 4×4 MIMO channel sounding in high-speed scenarios, there is no final conclusion. So, in this paper, we will compare the performance of CDM and FDM structure and choose the best way to design the sounder by analyzing the autocorrelation and orthogonal property of the common used sounding signal, including m sequence, Zadoff-Chu (ZC), and Loosely Synchronous (LS).

The rest of the paper is organized as follows. Section 2 analyzes the autocorrelation and orthogonal property of common used sounding signal for CDM and chooses the multiplexing structure. Section 3 describes the 4×4 MIMO channel sounder hardware implementation and verification. Section 4 gives the conclusions of the paper.

2 CDM or FDM

The performance of channel sounding mainly depends on two features of the sounding signal, the power continuity and measurement dynamic range, the former determines the measurement validity which means not losing channel information of time and frequency domain, and the latter determines the measurement range of distance and delay. Compared to FDM, the CDM signal has consecutive power in both time and frequency domain, but FDM signal only consecutive in time domain. So, from the aspect of power continuity, CDM is better. Then, we will focus on the performance of measurement dynamic range for CDM and FDM.

For CDM, the measurement dynamic range mainly depends on the autocorrelation and orthogonal property of the sounding signal for which the m sequence, ZC, and LS are common used.

2.1 Autocorrelation Property

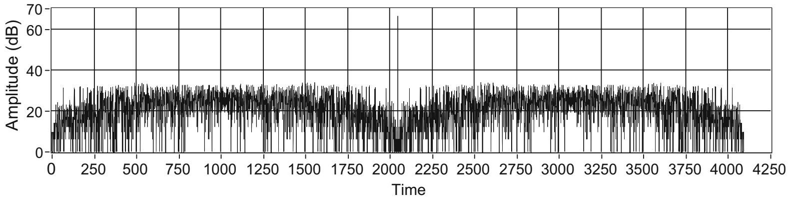
Figure 2 shows the autocorrelation property of the sequences with the maximal amplitude of 1 and the length of 2048 samples. The Y axis is the logarithmic amplitude, and the X axis is the relative time. As we can see, each sequence has a good autocorrelation peak more than 40 dB. So, the dynamic range is big enough for channel sounding. Especially, compared to m sequence, the ZC sequence has a much weaker sideband, which means it has better autocorrelation property.

For the LS sequence, there are strong autocorrelation values in some parts of the sideband, slightly higher than the first two sequences, but in the other parts, the autocorrelation values are extremely weak, close to −300 dB, as shown in the sequence Fig. 1(c). The part marked by red line is called Interference Free Window (IFW). Therefore, according to the principle of channel sounding, if the length of IFW is greater than the maximal channel delay, it can be used for effective channel sounding and the perfect autocorrelation property will greatly increase the measurement dynamic range. But we can also find that, the length of IFW is only one-fourth the whole signal length, which will reduce the CIR measurement speed.

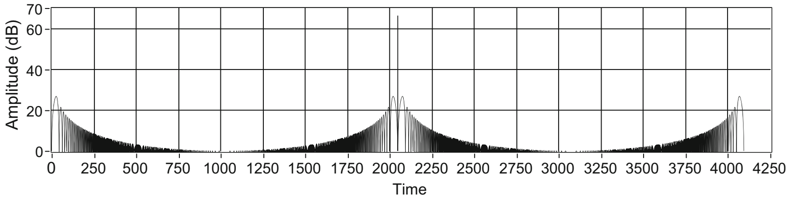
2.2 Orthogonal Property

Figures 3 shows the orthogonal property of the sequence pairs. And we can see that the orthogonality of the m and ZC sequence are relatively poor, the cross-correlation value approaching 40 dB, which will introduce large crosstalk in parallel MIMO structure, especially with the increasing of the antenna number. So, it will reduce the measurement dynamic range significantly. Compared to m and ZC sequence, LS sequence shows a perfect orthogonal property, because it doesn't introduce additional crosstalk compared with the autocorrelation, the cross-correlation value approaching −300 dB. So, it seems like the LS sequence is an ideal candidate sounding signal for CDM structure.

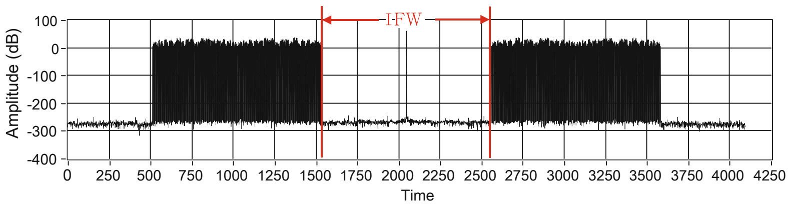
In our system, we want to build a 4 × 4 MIMO sounding system, so we need 4 LS sequences with each sequence orthogonal to the others. It's worth noting that, in the 6 (C_4^2) LS sequences pairs, there are only two mate pairs [7], for example Nos. 1 and 2, 3 and 4 in our situation, and the others are not mate pairs. Figure 3(c) and (d) show respectively the orthogonal property of



(a) m sequence



(b) ZC



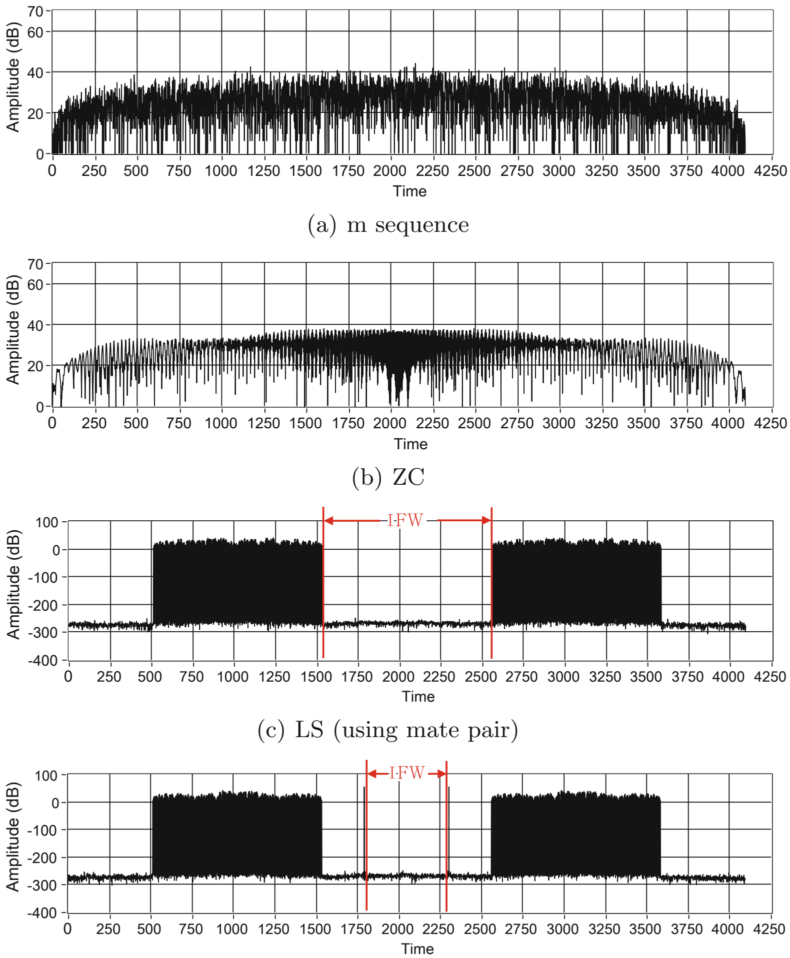
(c) LS

Fig. 2. Autocorrelation property of the sounding signals

LS mate pairs and not mate pairs. And we can see that, for the LS sequences which are not mate pairs, the achievable IFW length is the half of the case of mate pairs. That's to say, when we want to use LS sequence for 4×4 MIMO channel sounding, only one-eighth of the total sequence length is effective, thus decreasing the CIR measurement speed greatly. And this problem will be further exacerbated if we want to expand the system channels. So, in this paper, we will choose FDM structure for the system to increase the measurement dynamic range because there is little crosstalk among the Tx antennas when the signals are frequency divided.

2.3 FDM Solution

There are two solutions usually used for channel sounding, as shown in Fig. 4. In solution 1, all the Tx antennas are enabled concurrently to transmit specific sub-band of signals. So, when the total measurement bandwidth is B and the number of Tx antennas is N, the bandwidth of each sub-band is B/N. In the time domain, each Tx antenna change the transmitting signal to other sub-band in the next symbol duration to traverse all the sub-bands. This solution can be used for channel sounding in static scenario, but not for high-speed moving scenarios



(a) m sequence

(b) ZC

(c) LS (using mate pair)

(d) LS

Fig. 3. Orthogonal property of the sounding signals

because at the definite time or place, the antennas are transmitting signals very different from each other in frequency domain, which will cause measurement error for MIMO system.

So, in our system, we choose the solution 2, in which, each Tx antenna utilizing multiple carriers by allocating sub-carriers that are orthogonal among them with comb type as shown in Fig. 4. This methods has a big advantage that it can measure all Tx signals simultaneously and there is no big difference among the Tx signals because the sub-carrier spacing can be designed bo be much smaller than the coherent bandwidth.

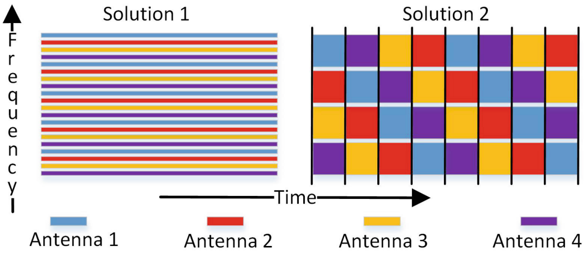


Fig. 4. FDM solutions

3 Hardware Implementation and Verification

In our system, we will use the PXI based SDR system as the hardware system as shown in Fig. 5. It mainly consists of host controller, PXI/PXIe chassis, vector signal generator (VSG), vector signal analyzer (VSA) and FPGA models. In this system different hardware can share the same chassis, so it is easy to synchronize the multiple VSGs and VSAs by share the same reference clock and local oscillator, which is very important for MIMO system. In addition, by this structure, we can easily expand the RF channels, e.g. from 4×4 to 8×8 or 16×16 just by adding more hardware to the chassis. Especially we can also connect multiple PXI chassis by PXI cable, and that is why we can realize both channel sounding and emulation functions on the same system to improve the hardware efficiency.

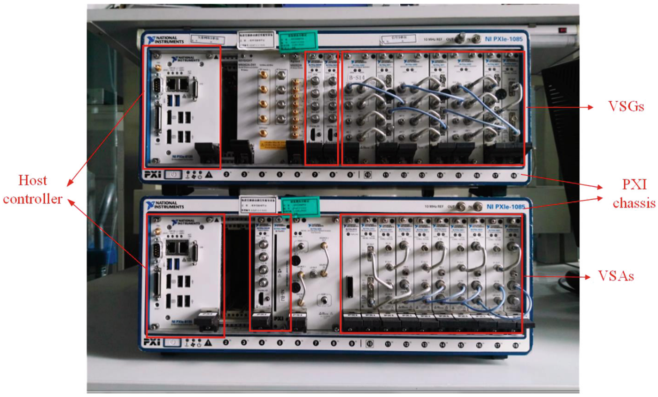


Fig. 5. The hardware equipment

The principle block diagram is shown as Fig. 6. The VSGs are used as transmitter and the VSAs are used as receiver. At the transmitter, all the VSGs share the same local oscillator (LO) and reference clock which is disciplined to GPS

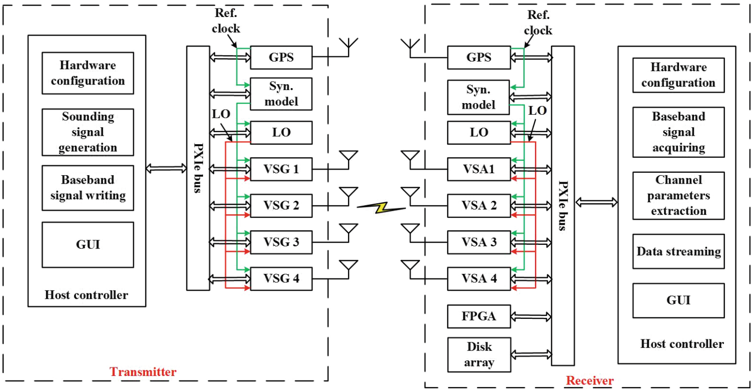


Fig. 6. The hardware block diagram

PPS clock, as well as the VSAs at the receiver. So the synchronization performance can be guaranteed and it is a basic requirement for MIMO measurement system. The system parameters are shown in Table 1.

Table 1. System parameters of the 4 × 4 MIMO sounder

Parameters	Value
Frequency range	85 MHz to 6.6 GHz
Maximal RF bandwidth	50 MHz
Maximal output power	40 dBm
Input dynamic range	−120 to 20 dBm
Data streaming	3.6 GB/s, capacity: 3.5 TB
Channel parameter extraction	CIR, PDP, AoA, AoD, DS, AS
Support moving speed	>1000 km/h

To verify the measurement capability of the sounding system, we build a closed-loop test system with commercial channel emulator as shown in Fig. 7. The channel emulator supports up to 16 sub-channels emulation with the maximal bandwidth of 75 MHz and the frequency range from 85 MHz to 3 GHZ. In the test system, a 4 × 4 MIMO channel model with customized multi-path is used. The simulated and measured CIR of sub-channels at receive antenna 1 is shown in Fig. 8, and we can see that they have good consistency, including the amplitude and delay. So, it verifies the measurement ability of this system because many other channel parameters can be derived by CIR.

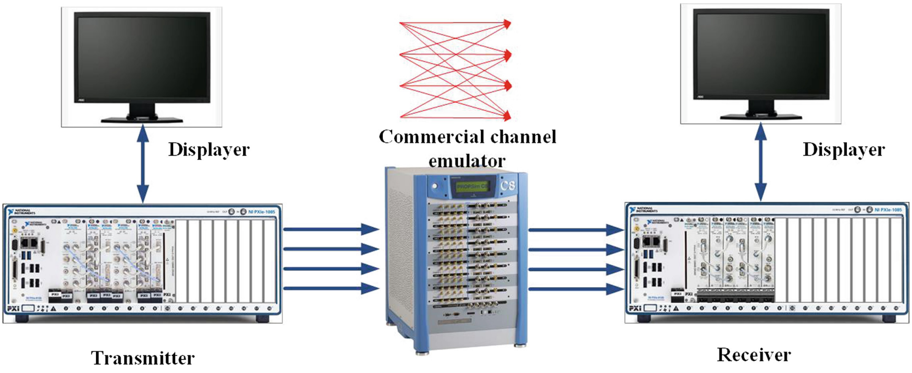


Fig. 7. The verification system

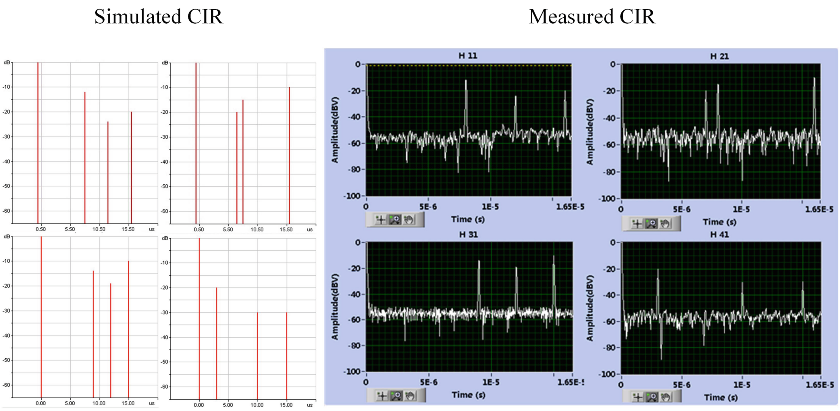


Fig. 8. The simulated and measurement result

4 Conclusion

In this paper, we compared the CDM and FDM methods for the sounding structure based on the analysis of autocorrelation and orthogonal properties for the common used sounding signals, including m sequence, ZC and LS sequence. Based on the results, we chose the FDM for the system design because of its high measurement dynamic range. And finally, we build a broadband wireless channel sounder that can support 4×4 MIMO wireless channel sounding in high-speed moving scenarios based on PXI software defined radio system with many special features, including fully parallel MIMO channel sounding structure with high-speed data streaming up to 3.6 GB/s and supporting high-speed moving scenarios above 1000 km/h. And because of the PXI module based hardware structure, it is easy to expand to 8×8, 16×16, and even 32×32 MIMO system. Especially, it also supports MIMO prototype system development since the SDR structure, which is on-going in our future works and in the next few months, we will use the system for the channel sounding in Datong to Xian high-speed railway.

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