mmWave MIMO Channel Sounding for 5G

Technical Challenges and Prototype System

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***Abstract*— Since 5G expects using mmWave frequency band, the mmWave channel sounding system, which are used to characterise the various mmWave wireless channel models, these days, become a very hot topic for 5G.**

In this paper, we mainly focus on how to setup mmWave MIMO channel sounding system with commercial instruments to fulfill the 6 major technical challenges foresee in 5G as well as focusing on the main channel measurement requirements:

- **The use of mmWave frequency band**
- **The use of ultra-broad bandwidth**
- **The use of massive MIMO.**

Then we provide our considerations on how to best address these technical challenges based on the last generation of mmWave/microwave instrumentation, measurement techniques and capabilities.

At last, we propose a reference prototype system design for 5G mmWave MIMO channel sounding system, the functionalities and where performance of the prototype system are discussed.

Keywords-channel sounding; 5G; mmWave;

I. INTRODUCTION

It is often the radio propagation channel along with the antenna array type and geometry that proves to be the major restriction in utilising MIMO technology. The successful deployment of commercial MIMO systems requires a solid understanding of the channel conditions. Thus the experimental characterisation of such propagation channels is vital to the development of MIMO technologies.

In the coming 5G communication, the radio channel is believed to play more important role. The radio channel for 5G, although not been well defined yet, will surely involve 3 key characteristics: mmWave frequency band, ultra-broad bandwidth and massive MIMO, which have not been well studied and understood by the research yet. Thus the channel sounding, which is the measurement technology to study the characteristics of the radio channel, becomes a very hot topic to the 5G researchers and players.

Channel Sounding Concept

Channel sounding technique is vital for studying the properties of wireless radio channel, the instruments to perform channel measurement using channel sounding technique are called channel sounder. The basic principle of channel sounding technique is similar to radar: RF signals are transmitted for the transmitter, pass through the wireless radio channel, and undergo all the influence of radio channel, then received by the receiver. Using channel parameters estimation algorithms the properties of the channel can be extracted from the received sounding signals. The difference between channel sounder and radar is: typically in radar system, the transmitter and receiver locate in the same place and use the same antenna; while in channel sounder system, the transmitter and receiver use two antennas locate in different places respectively.

mmWave Channel Sounding Research

Many research works have been led on the mmWave channel measurement. Since 2005, some research works related to 60GHz channel sounder were presented [1~3]. These proposed mmWave channel sounder were using PN sequence as the sounding stimulus and bandwidth from 100MHz to 3GHz and these systems were SISO (Single Input Single Output) or only 1x2 SIMO system due to system complexity. In addition, all these systems were setup using special designed circuits and components which are not easy for others to duplicate.

In the scope of 5G mmWave channel sounding, the most well-known research is the work from Prof. T.S.Rappaport and his team in New York University[4~6]. In their research, they setup an SISO mmWave channel sounding system based on sliding correlator approach, which can provide propagation loss measurement capability, the angular measurement was performed by rotating the directional horn antenna. Research works done by Samsung [7] also use the similar channel sounding approach.

These above 5G mmWave sounding systems have some limitations: firstly, by using the sliding correlation [8] and rotation approaches, the measurement speed of these sounding systems is very slow, which means they can only measure static channels or channels with very low Doppler frequencies. On the other hand, for channels in mmWave frequency bands, even under pedestrian scenarios, the Doppler frequency will be much

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higher due to the short wavelength of mmWave channels; Secondly, to support MIMO channel sounding, antenna arrays in both transmitter side and receiver side are needed, the interval of the antenna elements should be half of the wavelength, but the directional horn antenna used in these sounding systems are much larger than the wavelength in mmWave frequency band.

So, it is hard to support MIMO mmWave channel sounding measurement for these systems and they cannot satisfy all the requirements of 5G channel.

In this paper we mainly focus on how to use commercial instruments to setup new mmWave MIMO channel sounding system and approach, whose performance will be more accurate and stable and easy to duplicate by others.

The rest of this paper is organised as following:

Section.II, the technical requirements and challenges for 5G channel sounding are discussed;

Section.III shows our considerations about how to setup the 5G channel sounding system to address the challenges;

Section.IV shows the proposed mmWave MIMO channel sounding prototype system based on commercial instruments for 5G channel sounding; the current status and next steps for the prototype sounding system will be discussed in Section V.

II. Technical Requirements and Challenges for 5G Channel Sounding

Compared to the previous channel sounding system in 3G and 4G, the channel sounding system for 5G needs to fulfill three fundamental requirements:

- mmWave frequency band (above 6GHz, up to several tens GHz),
- Ultra-broad wideband (500MHz~1GHz, even 2GHz)
- Massive MIMO (several to several hundred antennas).

These requirements make the 5G channel sounding system very challenging. There are 6 major technical challenges for 5G channel sounding system:

1. *Sounding Approach and System Architecture*

The sounding approach and system architecture are first technical challenge. They are the foundation of the channel sounding system, which could determine the basic functionalities, performance of the whole system, and also determine the following considerations of sounding signal processing.

There are different channel sounding approaches and system architectures presented in previous research works [1~7], each of them has its advantages and limitations. Proper sounding approach and architecture are to be determined depends on the measurement requirements for channel sounding. To do this, the following factors need to be considered:

- Dedicated system or integrated system with general purpose instruments?
- SISO channel measurement or MIMO channel measurement?
- Maximum Doppler frequency to be supported, which determine the measurement speed for the sounding system
- System cost and flexibility for system extension
- Sounding signal processing complexity

For 5G channel sounding, channel measurement for massive MIMO is required, which requires a high flexible system architecture that are easily to extend to support multiple antenna elements (from several to several hundreds) at both transmitter and receiver, while the total system should be cost effective.

At the same time, because the sounding system needs to support mmWave frequency band, in which the wave length is quite small compared to current 3G and 4G system. While the Doppler frequency is inversely proportional to the wave length

$$f_d = \frac{v}{\lambda} \tag{1}$$

f_d is the Doppler frequency, v is the velocity of the movement in channel, and λ is the wave length.

(1) Indicates that in 5G channel, even in the low speed scenarios, the Doppler frequency will be relatively higher than the same scenarios in 3G and 4G channel. Thus the measurement speed for 5G channel sounding should be much higher correspondingly.

2. *mmWave Frequency Band*

The second challenge is the RF components with good RF performance under mmWave frequency band.

For 5G channel sounding system, the related RF components include:

- Up-converter and down-converter
- Antenna array
- Power amplifier (for outdoor transmission)
- Low noise amplifier (for outdoor receiver)
- Band-pass filter
- RF switch

3. *Ultra-broad Bandwidth Signal Generation and Acquisition*

Ultra-broad bandwidth signal generation and acquisition is another technical challenge. The key components are the high performance wideband DAC (Digital Analog Converter) and ADC (Analog Digital Converter), with deep bit depth.

4. *Efficient Data Storage and Streaming*

An effective channel sounding for channel modeling requires a long time measurement. The captured data size that are needed for the measurement can be calculated by the following equation:

$$N_{Cap} = T_s F_s N_{Rx} \quad (2)$$

In which T_s is the total sounding measurement time, F_s is the sampling rate, N_{Rx} is the number of channels that simultaneously receive the sounding signal, and N_{Cap} is the total captured data size in samples.

In 5G channel sounding, with the ultra-broad bandwidth (large F_s) and massive MIMO (large N_{Rx}) requirements, the data size for storage and streaming is very large. For example, if 1GHz bandwidth and 8 receiver channel are required, the captured data size for 1 second is $10^9 \times 8 = 8G$ samples, if each sample needs 4 bytes (2 bytes for I data and 2 bytes for Q data), then the data size for 1 second sounding signal is 32GB. This is a big challenge for both storage and streaming.

5. *Channel Parameter Estimation Processing*

Various channel parameter estimation algorithms have been presented for MIMO channel sounding [9]. For 5G channel sounding, with the higher path delay resolution (due to ultra-broad bandwidth) and increased inter-channel phase difference (due to much shorter wavelength in mmWave frequency), parameter estimation algorithms need to have much higher estimation accuracy. To our knowledge, there is no related research discussed about how the existing estimation algorithms work in 5G channel sounding. Thus, this is also an uncertain factor and technical challenge.

6. *Synchronisation and Calibration*

In 5G channel sounding system, the system synchronisation and calibration to achieve precision measurement becomes more challenging, due to the following reasons:

- Higher path delay resolution
- Decreased system flatness in broad bandwidth
- More sensitive to inter-channel delay
- mmWave antenna non-ideal amplitude/phase pattern

III. Considerations for 5G Channel Sounding

As we are working on prototype system setup for 5G channel sounding system, the technical challenges in Section II are what we need to address. We have the following considerations on how to setup the 5G sounding system:

Sounding Approach and System Architecture

We can categorise various channel sounding approaches as follow:

From the sounding technique perspective, there are 3 approaches:

1) *Wideband signal correlation,*
2) *Sliding correlator*
3) *Frequency swept.*

Compared to the other two approaches, the processing speed of wideband signal correlation approach is much faster because it measures the CIR (Channel Impulse Response) of the whole bandwidth simultaneously, while the other two only measures a narrow band channel or produce one piece of CIR bit by bit. The approach 2) and 3) can only provide amplitude CIR without phase information, which is needed for angular measurement. Thus we prefer to use wideband signal correlation approach in our system

From the method of how to support MIMO sounding measurement perspective, there are also 3 approaches: 1) switch at both transmitter and receiver, 2) parallel transmitting and receiving without switch, 3) switch at transmitter and parallel acquisition at receiver side.

The measurement speed of the above 3 approach is 1) <3) < 2). The approach 2), although much faster than the others, will introduce the cross-interference from different transmitting channels which can degrade the sounding measurement performance. By using a set of orthogonal codes and interference cancellation techniques can reduce the cross-interference, but additional signal processing are needed and the interference cannot be completely removed. Approach 1) and 3) don't have the problem of cross-interference in 2), and 3) is much faster than 1), so we prefer approach 3) in our system.

Based on above discussion, in our sounding system, we use the approach of wideband signal correlation, switching at transmitter and parallel acquisition at receiver. The system architecture is shown in Figure 1

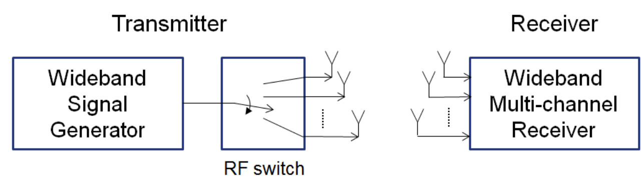

Figure 1. 5G channel sounding system architecture

2. *mmWave Frequency Band*

To support mmWave frequency band, instead of designing dedicated RF up-converter and down-converter, high performance commercial RF instruments are considered.

In our channel sounding system, the VSG (Vector Signal Generator) Keysight E8267D is selected to be the up-converter which can support from 250kHz up to 44GHz

The 4-channel PXI down-converter Keysight M9362A is used as down-converter which can support from 10MHz up to 50GHz, a Keysight N5173B is needed to provide 9kHz~40GHz LO signal to M9362A, thus the down-converter in the system can support 10MHz~40GHz.

Additional mmWave modules are needed in both transmitter and receiver to support frequency above 40GHz.

3. *Ultra-broad Bandwidth Signal Generation and Acquisition*

To support ultra-broad bandwidth signal generation and acquisition, the wideband AWG (Arbitrary Waveform Generator) and high speed digitiser are considered

In our sounding system, Keysight 12G Sa/s AWG M8190A is used to generate wideband sounding signal, which can support up to 6GHz bandwidth signal generation.

At the receiver side, the Keysight 12-bit high speed digitiser M9703A is used for sounding signal acquisition, which can provide 1 channels 1.6G Sa/s (625MHz bandwidth), or 4 channels 3.2G Sa/s interleaving acquisition (1GHz bandwidth). If greater than 1GHz acquisition bandwidth is needed, wideband oscilloscope is used instead. While the typical bit depth of oscilloscope is 8 bit, which is low for channel sounding, the latest 10 bit ADC oscilloscope, Keysight MSO-S series high-definition oscilloscope is considered.

Efficient Data Storage and Streaming

Due to the huge data size of the captured channel sounding signal, it's very difficult for the acquisition sub-system (either using M9703A or the oscilloscope) to store the data in embedded memory or transfer the data stream out to disk.

To solve this challenge, we present a new approach that can efficiently reduce the data size of sounding signal: we utilise the embedded FPGA in M9703A to perform real-time correlation processing to the captured sounding signal with the transmitting sounding waveform, after the correlation we will get the CIR (Channel Impulse Response) signal, the effective CIR signal (corresponding to the maximum delay spread of the channel) will be much shorter that the raw sounding data. The reduced CIR data could be stored in embedded memory for longer time, or could be streamed out to disk in real-time.

For example, a 4x4 MIMO channel sounding system with 1GHz bandwidth, as calculated in the last section, the data size for 1 second measurement is 32GBytes per channel which provides 128GB for 4 channels. Using the approach we presented, suppose the sounding signal transmitting period is 500us (which supports up to 1/500us/2/4=250Hz Doppler frequency), and the effective CIR length is 1us (corresponding to 1us/c=333.3m path delay, c is the velocity of light), the effective CIR data size for 1 second is 128GB/500=256MB for 4 channels, which is 500 times smaller than the raw sounding data. Using the embedded 16GB memory of M9703A, we could perform 64 second continuous sounding measurement; it is also possible to transfer the CIR data out to disk with 256MB/s data rate.

Channel Parameter Estimation Processing

Among different channel parameter estimation algorithms, SAGE (Space-Alternative Generalized Expectation-maximization) [10~12] is well accepted and widely used due to its high estimation precision and its capability of joint parameter estimator for multiple channel parameters, what's more, the maximum estimating path number is not limited by the number of antenna array elements.

We also consider SAGE algorithm in our system, while further investigation is needed to verify the performance and capability of SAGE algorithm under 5G channel scenarios.

Synchronisation and Calibration

High performance rubidium clocks are used in our system for synchronisation between transmitter and receiver, which can provide high precision reference 10MHz signal with ≤1e-12 accuracy and ≤1e-12 stability.

High performance instruments used in the system provide high RF channel stability (both amplitude and phase), so the issue left for channel sounding calibration is to measure the amplitude and phase impairment of the system and compensate them in the sounding measurement, including:

- Inter-channel phase error
- Antenna amplitude/phase error
- I/Q mismatch error
- Spectral flatness error

IV. A Proposed mmWave MIMO Channel Sounding Prototype System for 5G

Based on the above discussion, we proposed an mmWave MIMO channel sounding system, the system diagram is shown in Figure 2.

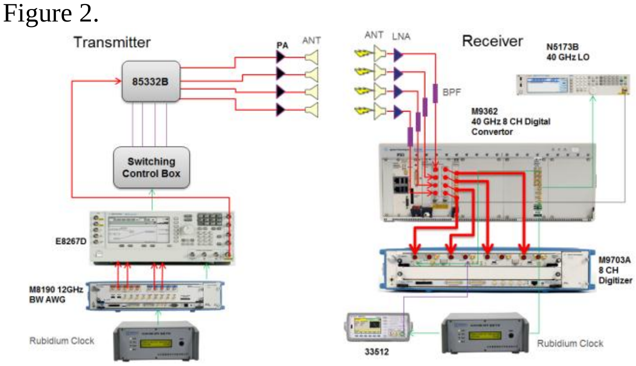

Figure 2. 5G channel sounding prototype system diagram

All the components (except the customized antenna arrays) used the proposed channel sounding system are general purpose commercial products, which means others can duplicate this sounding system very easily. The main components in the proposed sounding system are listed in Table 1.

TABLE I. Channel Sounding System Components List

Component	Description
Keysight M8190A	Ultra-broadband arbitrary waveform generator, playing wideband sounding signal
Keysight E8267D	mmWave vector signal generator, as up-converter
Keysight 85332B&85330	mmWave RF switch and switching controller
Keysight M9703A	Wideband 8-channel digitiser for sounding signal acquisition
Keysight M9362A&M9352A	mmWave down-converter and intermediate frequency amplifier
Keysight N5173B	mmWave analog signal generator, as LO for down-converter
Keysight 33512	Arbitrary waveform generator, for acquisition triggering signal generation
TaiFuTe HJ5418B	Rubidium clock, for synchronisation between transmitter and receiver

Currently the system is 4x4 MIMO sounding system, but it's easily to expend for more channels by adding RF switch ports at transmitter, and by adding M9362A+M9703A at receiver.

The frequency range the system supports is up to 40GHz, by adding additional mmWave components, the system can support higher frequency bands.

The sounding bandwidth is up to 1GHz (by using interleave mode of M9703A).

By implementing real-time correlation processing in M9703A embedded FPGA, the system can compress the captured sounding signal, the storage length using onboard memory is about 64 seconds (in scenario in section III.D) and the CIR signal can be transferred in real-time through PCIe bus.

The system can support all the technical requirements for 5G channel sounding measurement.

V. Prototype mmWave Channel Sounding System

Prototype mmWave Channel Sounding System

Based on the proposed 5G channel sounding system prototype, we are now working on setup the prototype system. Currently a SISO sounding system with cable conducted between transmitter and receiver has been built and some preliminary validation tests have been done. The picture of the prototype system is in Figure 3.

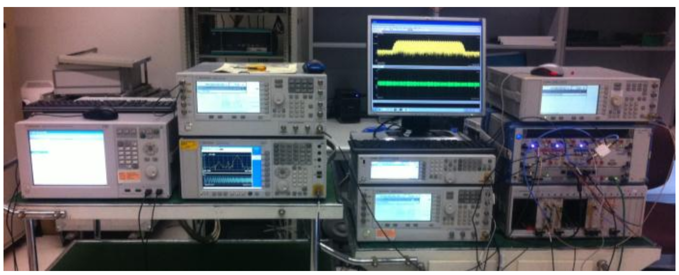

Figure 3. Picture of 5G channel sounding prototype system

The sounding system is on the right side in the picture, the left side is a channel emulator system that can provide controllable fading channels for the validation tests of the prototype system.

Preliminary Channel Sounding Validation Test Results

Three validation tests have been performed based on the above prototype system.

The frequency band in the test is 15GHz, and the bandwidth is 40MHz (due to the bandwidth limitation of the channel emulator).

1) Path delay and path loss test

The purpose of this experiment is to test the following 3 measurement matrices of the channel sounding system:

- Path delay resolution
- Path delay accuracy
- Path loss accuracy

In this test, a 3 paths channel scenario is used in the channel emulator, the path configuration is shown is Table 2.

TABLE II. Path Configuration for Test 1

Path No.	Path Delay (ns)	Path Loss (dB)
1	0	0
2	25~50	0
3	1000	-20

The first two paths can be distinguished when the path delay of the 2nd path is 36ns, as shown in Figure 4, which means the path delay resolution of the system is 36ns. The measured PDP (Power Delay Profile) of the test is shown in Figure 4.

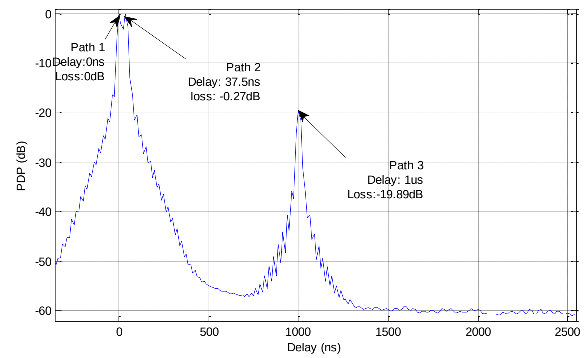

Figure 4. Measurement results for test 1

2) Receiver sensitivity test

The purpose of this experiment is to test the minimum received path power of the receiver, which represents the sensitivity of the sounding system.

In this test, we use a one path scenario, tuning the input level of the receiver, observing whether the path can be detected from the received signal. The test results show that even the input level is -100dBm the path can still be detected, as shown in Figure 5. This means the sensitivity of the sounding system is below -100dBm.

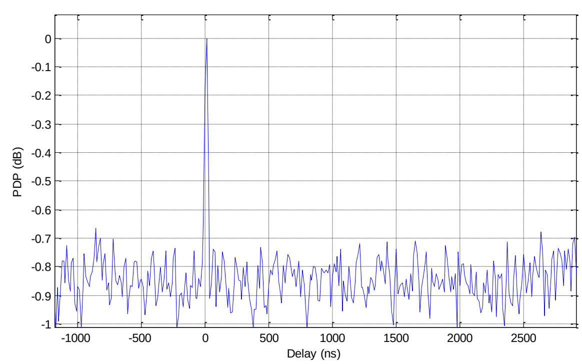

Figure 5. Measurement results for test 2 (-100dBm input level)

3) Multi-path dynamic range test

The purpose of this experiment is to test the dynamic range of the maximum and minimum path that the sounding system can measure simultaneously.

In this test, we use a two paths channel scenario as shown in Table 3.

TABLE III. PATH CONFIGURATION FOR TEST 3

Path No.	**Path Delay (ns)**	**Path Loss (dB)**
1	0	0
2	2000	-20~-80

By tuning the path loss of the 2nd path, observing whether the 2nd path can be detected, we can determine the multi-path dynamic range of the sounding system. The test results show that the 2nd path can still be detected when its path loss is set to be -64dB, as shown in Figure 6.

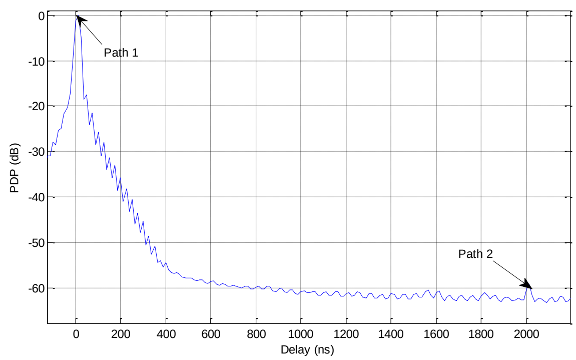

Figure 6. Measurement results for test 3 (path loss of 2nd path: -64dB)

VI. CONCLUSION

In this paper, the requirements and technical challenges of the 5G mmWave channel sounding system have been discussed; the considerations about how to address these challenges have been discussed too. Based on these considerations, architecture of the 5G mmWave channel sounding prototype system has been proposed. Some preliminary works of the prototype system setup and validations have been shown, too.

In the next step, we are planning to complete the 5G mmWave channel sounding prototype system as designed in Section IV. Keysight Technologies is also open and happy to discuss and tailor this system for individuals, to integrate additional capabilities and dedicated requirements, to discuss and investigate on 5G channel measurement and modeling with the proposed 5G sounding system.

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