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A Multi-Link Extension of Channel Sounding System using Software Defined Radio

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Abstract

This paper proposes a multi-link channel sounding architecture for joint multi-link channel measurement. The implementation with software-defined radios (SDRs) and evaluation results in a back-to-back calibration measurement mode are presented. Real-time measurements of two parallel radio frequency (RF) links are conducted with two transmit units and one receive unit. A frequency-division multiplexing sounding structure is proposed and discussed. Furthermore, system validation and sample results from a reference measurement campaign at 900 MHz in closed-loop cable environment are presented.

1 Introduction

With today's increased use of smartphones and other wireless devices, the demands on the wireless networks have increased dramatically. Research and development of fifth-generation (5G) wireless networks results in the need for higher data rate. One of the key technologies to satisfy this requirement is the multi-link transmission technique which utilizes the cooperative signal processing among spatially distributed multiple users and/or base stations, thus it is considered as more robust in ensuring the degree of freedom in spatial domain over the conventional single-link multiple-input-multiple-output (MIMO) systems [1, 2, 3]. Therefore, the multi-link channel needs to be studied.

Generally, the multi-link measurement techniques can be divided as virtual measurements [4], distributed measurements [5] and real time measurements [6] to measure multiple links [7]. Several channel measurement results investigated the characterization of multi-link propagation channel as summarized in [8]. However in the earlier works, real time multi-link measurement is quite few due to the limitations of channel sounder capabilities. Investigations on multi-link channel sounding are lacking and it has led to concentrate the research effort on channel modeling for multi-link scenarios. A real time multi-link channel sounding system is still missing.

2 System description

In this paper, we consider a multilink system with two transmitters (Tx) and one receiver (Rx). Wireless channel sounding principle and multi-link frame design will be introduced in this section.

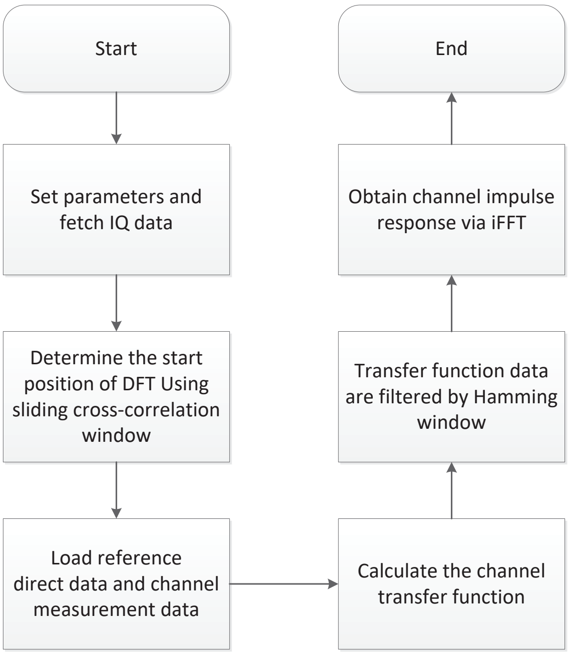

Figure 1. Flow chart of the Rx data process.

2.1 Sounding principle

Multi-tone signal is used for the wideband measurement. It is advantageous over the single carrier pseudo-random binary noise (PN) sequence signal from the viewpoint of the spectrum efficiency although peak-to-average power ratio (PAPR) is higher [9]. Consider the discrete time received signal $y(n)$ and the transmit signal $x(n)$, $y(n)$ can be expressed as a convolution result as

$$y(n) = \sum_{\tau=0}^{L-1} h(n,\tau) * x(n,\tau) + w, \tag{1}$$

where $h(n,\tau)$ is the time variant channel impulse response (CIR) at delay index τ, L is the number of multi-path and w denotes the additive white Gaussian noise (AWGN). According to discrete Fourier transform (DFT), the frequency domain expression of the received signal, the transmit signal and the channel's frequency response can be written as

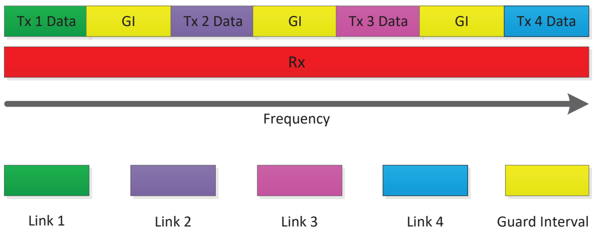

Figure 2. Schematic diagram of FDM multi-link channel sounding structure.

$X[m]$, $Y[m]$ and $H[m]$. Thus it can be represented as

$$Y[m] = H[m]X[m] + W. \qquad (2)$$

In a multi-tone transmission system, $X[m]$ yields to N-point inverse fast Fourier transform (iFFT) [10]

$$x(n) = \frac{1}{N}\cdot\sum_{m=0}^{N-1} X[m]\cdot\exp(\frac{j2\pi mn}{N}). \qquad (3)$$

Here we assume that the channel is constant over the duration of one single sub-carrier of the transmit multi-tone signal, i.e., $h(n,\tau) = h(\tau)$. Therefore, equation (2) is derived as

$$Y[m] = (\sum_{\tau=0}^{L-1} h(\tau)\exp(\frac{-j2\pi\tau k}{N}))X[m] + W[m]. \qquad (4)$$

Then, the channel transfer function can be calculated from input-output cross correlation as [10]

$$\tilde{H}[m] = \frac{Y[m]X^*[m]}{|X[m]|^2} + W[m]. \qquad (5)$$

Ultimately, we can obtain the CIRs by

$$\tilde{h}(\tau) = \sum_{n=0}^{N-1} \tilde{H}[m]\cdot\exp(\frac{j2\pi\tau m}{N}). \qquad (6)$$

The whole data process is illustrated as Fig. 1.

2.2 Multi-link frame

In order to implement a parallel real-time multi-link channel sounding system, interference-free coexistence between multiple radio links needs to be designed carefully. Different links may be located in the same frequency band with existing communication link. As shown in Fig. 2, frequency division multiplexing (FDM) multi-link allocation structure is used in this multi-link channel sounding system. Frequency guard interval (GI) are required to avoid interference between different links.

It is noted that the sub-carrier interval of different Tx and Rx should be identical since we are using a multi-tone signal. To achieve this, the sampling rate of different Tx units should be identical as the sampling rate at the Rx side. The subcarrier interval equals the sampling rate divided by the number of sampling points. For example, suppose we want to measure multi-link channels at 900 MHz carrier frequency with a bandwidth of 10 MHz. According to Nyquist theorem [11], the sampling rate at the Rx side must be twice the maximum bandwidth. Thus, the sampling rate at the Tx side should also be set as 20 MHz as the same as the Rx side. In addition, more frequency GIs need to be introduced in the bandwidth under test if we want to establish more communication links, in other words, the real-time parallel multi-link measurements are obtained by the cost of extra frequency resource overhead. Meanwhile, the synchronous stability of different RF chains is getting more challenging. Nevertheless, 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 GI spacing can be designed to be much smaller than the coherent bandwidth. We consider two Tx units and one Rx unit to test the feasibility of FDM multi-link sounding structure.

Table 1. System parameters of the channel sounding system.

Items	Settings
Frequency range	85 MHz to 6.6 GHz
Maximal RF bandwidth	50 MHz
Maximal output power	0 dBm
Maximal dynamic range	140 dB
Data streaming	3.6 GB/s
Channel parameter extraction	CIR, PDP, delay spread

3 Implementation

The National Instrument-PXI based SDR system is used as the hardware system. PXI is a rugged PC-based platform for measurement and automation systems. PXI combines PCI electrical-bus features with the modular, eurocard packaging of compact PCI and then adds specialized synchronization buses and key software features. Tx includes the NI 5673 vector signal generator (VSG), consisting of I/Q generator, I/Q modulator, and the local oscillator (LO) source (left). Rx is a modular RF vector signal analyzer (VSA) consisting of wideband RF downconverter, intermediate frequency digitizer module and the LO source (right). The hardware of our receiver mainly consists of multiple processor subsystem, baseband converters and RF front end. At the Rx side, the receive signal from RF front end in turn pass the mixing, low-pass filter, analog to digital converter (ADC) and turn into digital baseband signal, which will be process subsequently on the host code. Table I summarizes main system parameters of the multi-link channel sounding system. By this structure, we can expand the RF channels by adding more hardware into the chassis, which improves the hardware design efficiency.

3.1 Synchronization

The synchronization of carrier frequency offset and timing are critical to the operation of the channel sounding system [12]. The synchronization of local oscillators at the Tx and Rx employing Rubidium clocks is critical in measurement campaigns, especially when both units have to be separated. A small frequency offset can lead to phase rotation (Doppler) and sliding of the delay. Carrier frequency offset (CFO) is caused by the inaccuracy of the receiver and transmitter oscillator clocks, as well as by the Doppler shift [13] caused by relative movement in the system. This causes the received signal to exhibit a low frequency modulation at baseband, even after the full down-conversion process. The multi-link channel sounding system can be synchronized in the following two steps: 1) Local oscillator (LO) clock synchronization, where the relative phase rotation is minimized by tuning the GPS clocks. 2) Snapshot synchronization, where a common absolute time reference is allocated to both units. In our system, there is a 10 MHz reference clock that can be disciplined by Global Position System (GPS) that it brings higher frequency accuracy and closer synchronization. Two PXIe chassis are synchronized via GPS-disciplined rubidium clocks. The GPS device provides 1 pulse per second (PPS) to the rubidium clock for absolute time synchronization, and then the rubidium clock sends a reference signal with 10 MHz frequency for the timing modules. With PXI chassis based SDR system, different hardware can share the same chassis. Therefore, it is easy to synchronize the multiple VSGs and VSAs by share the same reference clock and local oscillator, which is vital to multi-link system.

3.2 Calibration

To achieve reliable channel sounding results, system calibration is required. A calibration measurement before the data acquisition is essential in order to compensate the system and cable losses. Actually, it is measurement of a well-defined channel, usually an attenuator of a certain attenuation which is referred to as back-to-back calibration. A back-to-back calibration measurement is a measurement, in which the output of the TX is connected via a cable, which was used here, or other transmission channel that can be considered as ideal or nearly ideal, to the input of the RX. The purpose of this kind of measurement is to acquire a reference signal to be used as a reference in the acquisition of the frequency response. Using this kind of reference in the correlation instead of the transmitted code has the advantage that when using a measured reference, the effect of the frequency response of the transmitter and receiver units, is compensated. Of course the frequency response of the additional cabling and attenuation used in the back-to-back measurement needs to be measured and compensated. When the use of back-to-back calibrations is combined with the data of wideband antenna calibrations, the effect of measurement hardware can be removed from the measured data and so the acquired channel response will be the response of the channel itself, not a combined response of the channel and the measurement equipment. The received signal can be expressed in the frequency domain as

$$Y(f) = X(f)H_{\mathrm{Tx}}(f)H(f)H_{\mathrm{Rx}}(f), \tag{7}$$

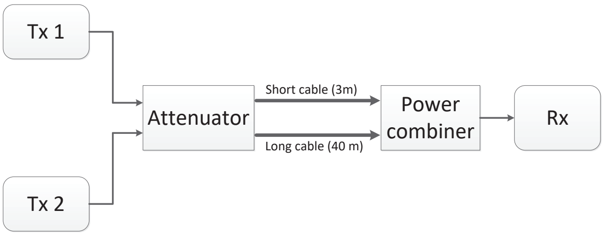

Figure 3. Dual-link back-to-back calibration measurement setup.

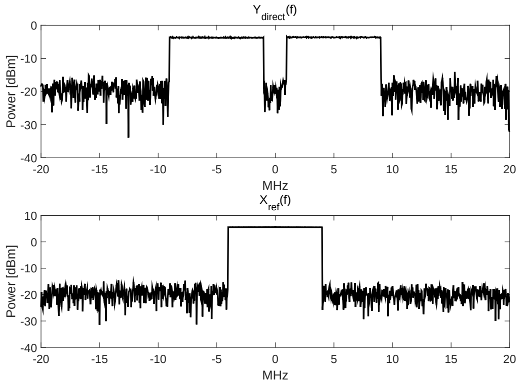

Figure 4. Power spectrum of reference multi-link signals.

where $X(f)$ and $Y(f)$ are the transmitted and received signals, $H(f)$ is the transfer function of the radio channel, and $H_{\mathrm{Tx}}(f)$ and $H_{\mathrm{Rx}}(f)$ are the transfer functions of the Tx and Rx equipment including antennas and cables. To remove the impact of the equipment, reference measurement have been conducted in an anechoic chamber. The received reference signal can be expressed as

$$Y(f) = X(f)H_{\mathrm{Tx}}(f)H_{\mathrm{ref}}(f)H_{\mathrm{Rx}}(f), \tag{8}$$

Then, the transfer function of the channel can be computed by

$$H(f) = \frac{Y(f)}{Y_{\mathrm{ref}}(f)}H_{\mathrm{ref}}(f), \tag{9}$$

where $H_{\mathrm{ref}}(f)$ is the free-space reference transfer function. A separate back-to-back calibration measurement is needed for both TX-RX pairs.

Table 2. Multi-link test parameters.

Items	Settings
Center frequency	900 MHz
Bandwidth	20 MHz
Sampling rate	40 MHz
Frequency GI	2 MHz
TX power at antenna output	0 dBm
RF attenuator	30 dB
Cable loss difference	3 dB

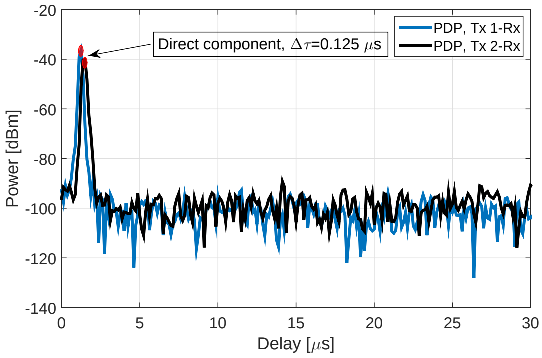

Figure 5. Power delay profile results of two links.

4 Results

To verify the measurement accuracy of the multi-link channel sounding system, we build a closed-loop test system with two Tx units and one Rx unit as shown in Fig. 3. A back-to-back measurement is performed by making a cable connection between Tx 1, Tx 2 and Rx. RF attenuators are also used in-between in order to ensure the safety of the Rx input port. Each of the measurement unit has one single antenna. To distinguish two links, we used a short cable (3m) and a long cable (40m), thus we can have two links with different delay and power levels. As shown in Fig. 3, signals from two Tx units are sent to the same Rx by using power combiner and cables. Fig. 4 presents the power spectrum of Y_{direct}, consists of signals of link 1, link 2. The free-space reference measurement X_{ref} is also performed to calculate the CIRs. The data process at Rx side is as introduced in Fig. 1. Table II provides multi-link test parameters. Fig. 5 compares the measured power delay profiles (PDPs) of two-link channels. Although further adjustment is necessary, the resultant responses are in good agreement. The direct component is the transmit signals via cables. We can see the delay difference $\Delta\tau$ is 1.25 μs, which is agree with the distance difference of cables. Also, there is 3 dB difference of direct component power levels for Tx 1-Rx PDP and Tx 2-Rx PDP. This is mainly caused by the cable loss difference since we are using cables of different length. As a result, it verifies the measurement ability of this system.

5 Conclusion

A real time multi-link channel sounding system based on a SDR platform for evaluating the wireless multi-link channel characterization has been proposed and implemented. Based on the implementation, a way of performing multi-link tests in FDM mode has been presented. Tests with two cables and power combiner have been performed and difference between two parallel channels has been characterized. Based on the measurement results, the system is calibrated and verified. Because of the PXI module based hardware structure, it is easy to expand to multi-link channel sounding system at the cost of frequency resource overhead.

6 Acknowledgements

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