Scalable Wideband MIMO Channel Sounding Technique using Hybrid Scheme of Frequency and Time Division Multiplexing

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Abstract

In this paper, a novel architecture of MIMO channel sounding is presented, which uses hybrid multiplexing scheme in time and frequency division. It offers high scalability and flexibility for both directional MIMO channel and multi-link MIMO channel measurements. Through the computer simulations the validity of the proposed technique and the robustness to the IQ imbalance of RF front-ends will be illustrated.

Keywords: Channel sounder, MIMO, Wideband channel, FDM, Multiplexing, Multitone

1 Introduction

Knowledge of radio channel property is usually necessary to develop wireless transmission systems. In order to characterize radio channel property, various channel sounding techniques have been developed so far including pulse sounding, frequency sweep, and cross-correlation using a known sounding signal. In cases of MIMO channels, multiplexing techniques are utilized to separate all transmitted signals from multiple antennas at receiver side. Basically TDM (time division multiplexing), FDM (frequency division multiplexing) [1] and CDM (code division multiplexing) schemes can be appropriately chosen or hybrid methods among them are applied depending on the system architecture. The advantages and drawbacks are already well discussed, for example in [2]. In future MIMO cellular systems, it should be necessary to operate in the microcellular environment to increase the capacity much more where the channels are more specific to individual environments. In particular, the analysis and design of multi-link technologies such as multiuser MIMO and base station cooperation require more sophisticated models of correlation among the links and the ranks of channels. In addition, it is necessary to investigate the detail of the directional properties of the environment to predict the possible channel ranks and to design the MIMO array antennas.

This paper presents a scalable channel sounding technique using FDM-TDM hybrid scheme on fully parallel architecture. With high scalability of the proposed scheme, it is suitable both for the directional MIMO channel and multi-link MIMO channel measurements. Through computer simulations, the operation of the proposed technique is verified and a robust technique to the IQ imbalance of RF transceivers is also presented.

2 Scalable Architecture

In MIMO channel characterization, fully switching architecture which has single radio front-end respectively both at transmitter and receiver have been commonly used, such as MEDAV RUSK channel sounder [3]. The advantages include low complexity signal processing, simple RF calibration, easy cabling to the antenna and relatively low cost per channel. On the other hand, the well-known drawback of fully switching system is the fact that the number of antennas to be switched usually limits the channel acquisition rates, thus the measurement in some environments with high Doppler frequency is difficult to be managed, and the measurement time span for delay spread is also limited.

In order to reduce measurement time, transmit switching architecture which has single radio front-end at transmitter but has complete set at receiver, and fully parallel architecture which has complete sets of radio front-ends both at transmitter and receiver have been considered. These architectures can reduce the measurement duration for single snapshot by $1/N_{\mathrm{R}}$ where N_{R} denotes the number of receive antennas. Although fully parallel architecture is also transmit switching free, but unfortunately it cannot save measurement time anymore because simultaneous transmission needs longer time for signal separation at receiver side.

In this paper, a novel highly scalable architecture which is based on the modular concept of transmitter and receiver unit is proposed. It offers an easy extension with new units, combination with multiple units for directional MIMO channel measurement and separation into multiple units for multi-link MIMO measurement. The FDM-TDM hybrid scheme on fully parallel architecture allows simultaneous transmission at all transmit antennas. Thanks to this, the total transmission power per channel can be relatively small. Moreover, the same hardware can be utilized for both transmission test and channel sounding at the same time.

3 Channel Sounding Technique

Figure 1 shows the concept of $N_{\mathrm{T}} \times N_{\mathrm{R}}$ MIMO channel sounding system with FDM-TDM hybrid multiplexing scheme with N_{Utx} transmitter units where each has N_{A} transmit antennas where $N_{\mathrm{T}} = N_{\mathrm{Utx}} N_{\mathrm{A}}$, and similarly with N_{Utx} receiver units where $N_{\mathrm{R}} = N_{\mathrm{Urx}} N_{\mathrm{A}}$. Both of FDM and TDM are used for multiplexiqng the transmitting signals from N_{T} antennas. As shown in Fig.2, single measurement duration of fully parallel MIMO channel sounder becomes $N_{\mathrm{T}} T_{\mathrm{sym}}$ where T_{sym} denotes the sounding symbol duration which is corresponding to the delay spread to be measured. The sounding symbol for the k-th FDM channel is represented by

$$s^{(k)}(t) = s(t) \exp\left(j 2\pi (k-1) \Delta_f t\right), \tag{1}$$

where the symbol duration is lengthened by N_A times of that of the unmodulated multitone signal of $s(t) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} \exp\left(j 2\pi n \Delta_F t + j\phi(n)\right)$ with the Newman phases $\phi(n) = \frac{n^2 \pi}{N}$ for peak-to-average power ratio reduction [4]. N denotes the number of carriers to be allocated over the given frequency band and Δ_F $(= 1/T_{\mathrm{sym}})$ is the carrier spacing and the FDM frequency shift $\Delta_f = \Delta_F / N_{\mathrm{A}}$ [1]. In Fig.2, the signal for each FDM channel at n-th TDM slot which is generated by (1) and then added by cyclic prefix as GI (guard interval), is simultaneously transmitted by the transmitting beamforming. By aggregating all signals for k-th FDM channel, the signal vector for k-th FDM channel can be represented by

$$\boldsymbol{x}_n^{(k)}(t) = \left[\begin{array}{cccc} x_{k,n}(t) & x_{N_{\mathrm{A}}+k,n}(t) & \cdots & x_{N_{\mathrm{A}}(N_{\mathrm{Utx}}-1)+k,n}(t) \end{array} \right]^T = \boldsymbol{w}_n s^{(k)}(t), \tag{2}$$

where $\boldsymbol{w}_n \in \mathbb{C}^{N_{\mathrm{Utx}} \times 1}$ is the transmit othonormal beamforming weight vector for n-th TDM slot. On the other hand, the received signal can be represented in frequency domain as

$$\boldsymbol{Y}^{(k)}(f) = \tilde{\boldsymbol{H}}^{(k)}(f) S^{(k)}(f) + \boldsymbol{N}(f), \tag{3}$$

where,

$$\begin{aligned}
\boldsymbol{Y}^{(k)}(f) &= \left[\begin{array}{ccc} \boldsymbol{Y}_1^{(k)}(f) & \cdots & \boldsymbol{Y}_{N_{\mathrm{Utx}}}^{(k)}(f) \end{array} \right] \in \mathbb{C}^{N_{\mathrm{A}} N_{\mathrm{Urx}} \times N_{\mathrm{Utx}}}, && (4)\\
\tilde{\boldsymbol{H}}^{(k)}(f) &= \boldsymbol{H}^{(k)}(f) \boldsymbol{W} \in \mathbb{C}^{N_{\mathrm{A}} N_{\mathrm{Urx}} \times N_{\mathrm{Utx}}}, && (5)\\
\boldsymbol{H}^{(k)}(f) &= \left[\begin{array}{ccc} \boldsymbol{H}_k(f) & \cdots & \boldsymbol{H}_{N_{\mathrm{A}}(N_{\mathrm{Utx}}-1)+k}(f) \end{array} \right] \in \mathbb{C}^{N_{\mathrm{A}} N_{\mathrm{Urx}} \times N_{\mathrm{Utx}}}, && (6)\\
\boldsymbol{W} &= \left[\begin{array}{ccc} \boldsymbol{w}_1 & \cdots & \boldsymbol{w}_{\mathrm{N}_{\mathrm{Utx}}} \end{array} \right] \in \mathbb{C}^{N_{\mathrm{Utx}} \times N_{\mathrm{Utx}}}, && (7)
\end{aligned}$$

and $S^{(k)}(f)$ and $\boldsymbol{N}(f)$ denote the Fourier transforms of the signal $s^{(k)}(t)$ and white Gaussian noise process $\boldsymbol{n}(t)$. By dividing (5) by (7) the channel matrix for k-th FDM channel is finally obtained by

$$\boldsymbol{H}^{(k)}(f) = \tilde{\boldsymbol{H}}^{(k)}(f) \boldsymbol{W}^{-1}. \tag{8}$$

By using proposed technique, we have initially developed the basic configuration with 4×4 MIMO system [5], namely $N_{\mathrm{A}} = 4$ and $N_{\mathrm{Utx}} = N_{\mathrm{Urx}} = 1$ and it will be extended by 24×24 MIMO configuration where $N_{\mathrm{Utx}} = 6$ and $N_{\mathrm{Urx}} = 6$. It aims at wideband channel characterization with the bandwidth of 400 MHz at 11 GHz for fundamental study of the next generation wireless mobile communication systems. The number of carriers $N = 2048$ and the carrier spacing $\Delta_F = 195.3\mathrm{kHz}$. Thus the sounding symbol duration and the measurement duration are $T_{\mathrm{sym}} = 5.12\ \mu\mathrm{s}$ and $T_{\mathrm{mea}} = T_{\mathrm{sym}} N_{\mathrm{A}} + \mathrm{GI} = 24.48\ \mu\mathrm{s}$ where GI is 4 μs, respectively.

As a hybrid multiplexing scheme is illustrated in Fig.2, CDM-TDM as well as FDM-TDM can be implemented in the same architecture with same parameters. For example, Zadoff-Chu sequence that is a well known CAZAC (constant amplitude and zero autocorrelation) sequence [6] is considered where N_{A} Zadoff-Chu sequences with the length of $N_{\mathrm{A}} N_{\mathrm{sym}}$ cyclically shifted by N_{sym} are generated for N_{A} antennas within a unit, and similarly to FDM-TDM, they are transmitted by beamforming with another Zadoff-Chu sequence with the length of N_{Utx}.

4 Performance Evaluations

In this simulation, MIMO channel was generated by Rayleigh fading model with exponentially decaying power delay profile of $\beta^{-d/(N_{\mathrm{path}}-1)}$ where $d = 0, ..., N_{\mathrm{path}} - 1$ and β dentes the power ratio of the first and last path. Herein, $N_{\mathrm{path}} = 20$ and the delay spacing was 20 samples. For each path, Rayleigh fading is generated by adding 5 ray components with equal power but random phases. It is also assumed that the channel responses are constant during the measurement, namely, Doppler frequency is zero.

Figure 3 illustrates the performances of the proposed technique with mean square error (MSE) of the channel estimation by Monte Carlo simulation where $N_{\mathrm{A}} = 4$, $N_{\mathrm{Utx}} = N_{\mathrm{Urx}} = 1$ and 6. As can be seen, the performances become ideally improved in proportion to the SNR irrespective of the number of antennas. However in fact they are usually degraded in the presence of hardware imperfection such as phase noise and IQ imbalance in RF front-ends. Due to phase noise and IQ imbalance effect, we can see that the performances are significantly degraded, thus we see that the system should be precisely calibrated, although it is quite time consuming task with large number of MIMO transmitters and receivers. To avoid the IQ imbalance effect especially, the reduced-tone FDM-TDM scheme where only a tone is allocated every $M (= 4$, herein) tone locations with some offset which generates the image components only at the empty tone locations, was evaluated where the model parameters of hardware imperfection is given in Table 1. Although the delay spread to be measured becomes smaller by $1/M$, we can see that the performance does not depend on the IQ imbalance effect any longer.

5 Summary

This paper presented a scalable architecture of MIMO channel sounding with hybrid multiplexing scheme in time and frequency division for both directional MIMO channel and multi-link MIMO channel measurements. Computer simulations of the channel impulse response estimation showed the validity of the proposed technique and the robustness to the IQ imbalance of RF front-ends.

Acknowledgment

This work was partly supported by “The research and development project for expansion of radio spectrum resources” of The Ministry of Internal Affairs and Communications, Japan.

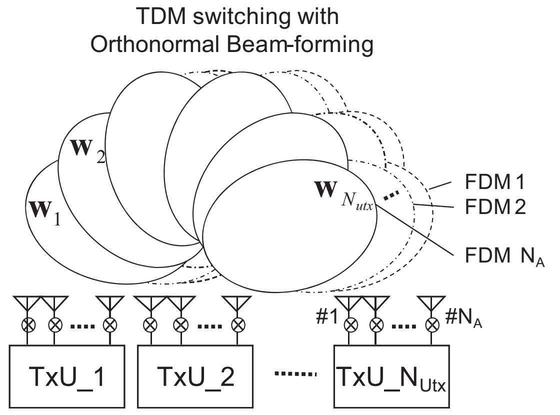

Figure 1: FDM-TDM Hybrid Multiplexing Scheme.

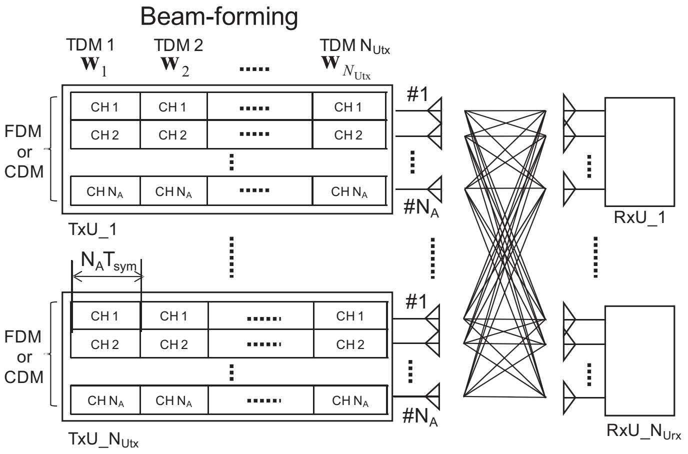

Figure 2: Scalable Hybrid Multiplexing Scheme.

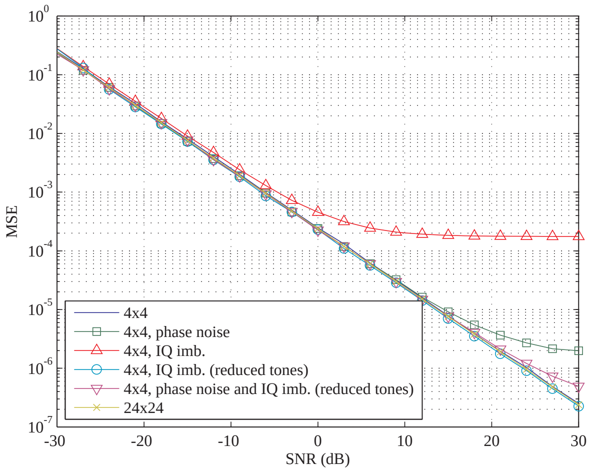

Figure 3: MSE of channel impulse response in FDM-TDM hybrid scheme.

Table 1: Hardware imperfection model

IQ imbalance model

	IQ phase offset	IQ gain difference	DC offset (I)	DC offset (Q)
value	3°	0.1	20 mV	10 mV

Phase noise model

[dB]	1 kHz	10 kHz	100 kHz	1 MHz
level	-48	-72	-101	-124

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