Frequency Correlation Investigation of Massive MIMO Channels in a Stadium at 4.45 GHz

Yanping Lu*, Cheng Tao*[†], Liu Liu*[†], Wenjuan Li *, Jingcheng XIAO*, Pengyu LIU*

* Institute of Broadband Wireless Mobile Communications, Beijing Jiaotong University, Beijing 100044, P. R. China

[†] National Mobile Communications Research Laboratory, Southeast University, Nanjing 210096, P. R. China

{**yanping_Lu, chtao, liuliu, 13120105, 13120147, 13125028**}@bjtu.edu.cn

Abstract—**Massive multiple-input multiple-output (MIMO) is a potential key technology for the 5th generation (5G) of wireless communication systems. A reliable and realistic channel model serves as the enabling foundation for practical design and testing of the massive MIMO communication systems. In this paper, based on the realistic measurement conducted in open stadium environments, the frequency correlation properties are investigated. By using the direct method of calculating from the channel transfer function and the traditional method of derivation via a Fourier transform of the channel's average power delay profile, the frequency correlations are compared. These results reveal the correlation characteristics of massive MIMO channels and provide the basis for the practical deployment of massive MIMO systems.**

Keywords— **Massive MIMO, wireless channel, channel measurement, correlation bandwidth, frequency correlation.**

I. INTRODUCTION

Massive multiple input and multiple output (Massive MIMO), as a potential technique for the emerging 5th generation (5G) wireless communications systems, presents a highly promising solution to meet the demanding requirements of spectrum efficiency and the energy efficiency [1], [2], [3]. The research works of propagation characteristics and channel modeling in theory are mostly under an assumption that the channels are wide sense stationary (WSS) and uncorrelated scattering (US). In practice, however, the benign environment condition will never be exactly satisfied, even in a dense scattering environment or a line of sight (LOS) propagation scenario. Such environments (e.g., stadium, dense urban information society, and shopping mall) have been proposed in The Mobile and wireless communications Enablers for the Twenty-twenty Information Society (METIS) which aims to lay foundations for future mobile and wireless system [4].

To date, there are few published research results on fading correlation properties of massive MIMO propagation channels. In [5], performance of antenna selection on transmitter side in realistic environment was investigated. In [6], the Rice factor, received power level and antenna correlation were extracted from the measurement data at 2.6 GHz. In [7], the time delay spread properties in line-of-sight (LOS) and non line-of-sight (NLOS) scenarios were studied. In [8], linear pre-coding performance was investigated using the realistic massive MIMO measurement data. In [9], a cluster-based parameterization method was used for channel characterization. The channel parameters included the total number of clusters, their visibility regions and visibility gains.

The fading correlation in frequency domain is an indicator of the coherence bandwidth. In this paper, based on the realistic measurement data, we estimate the frequency correlation of massive MIMO channels. The frequency correlation estimate (FCE) is derived from the channel transfer function, which shows a significantly difference while using the traditional method of derivation via a Fourier transform of the channel's average power delay profile. The difference is mainly caused by the reason that frequency correlation characteristics are a function of frequency, rather than just frequency deviation, and multipath components are correlated to some degree. Measured data are presented to verify the conclusions.

The paper is organized as follows: in Section II, the measurement campaign and data processing method is described. Section III details the frequency correlation estimate, and presents test results derived from 2 different methods. The conclusion is drawn in Section IV.
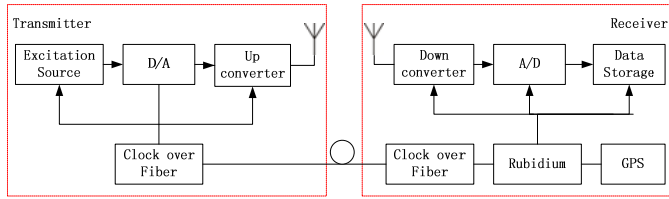
II. MEASUREMENT SETUP

A. Channel measurement

A vector signal generator (R&S SMBV100A) is used as the excitation source. A 128-element virtual linear structure antenna works at the transmitter side, on which a single bi-conical antenna moving along the linear rail track. The special advantage of the bi-conical antenna is that it has an almost equal gain in the H-plane, therefore different directional signals can reach the receiver with the same antenna gain. The data collector is composed of a RF down-converter, a high-speed digitizer card and a data storage unit. The time synchronism is maintained by using the rubidium clock trained by the GPS. Then the clock system is connected with a fiber for the perfect time synchronization. TABLE I lists the measurement parameters, and Fig. 1 shows the measurement system topological diagram.

Central frequency	4.45GHz
Bandwidth	100MHz
Antenna number	128×1
Synchronization	Rubidium + GPS.
Excitation signal	Zad-off Chu sequence
Code Length	2047
Tx antenna height	8m (grandstand is include)
Rx antenna height	2.5m

Figure 1. Measurement system topological diagram

We conducted the measurement in a stadium at Beijing Jiaotong University. The propagation scenario is open and clear. A grandstand lies at the west side, and two tall buildings stand behind the grandstand. We placed the transmitter antenna array on the grandstand, with a height of 5 m from the ground, and located the receiver equipments in the ground field, the transmitter is fixed and a total of six measurements were performed at six different receiver positions. Fig. 2 shows the measurement scenario.
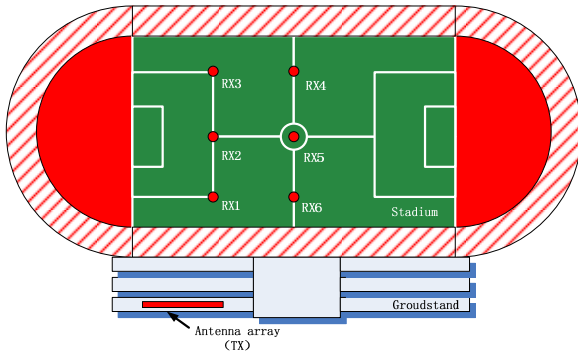
Figure 2. Measurement scenario

B. Data processing

The complex-valued Zad-Off Chu sequence with the length of 2,047 is employed as the excitation signal due to its orthogonality and constant amplitude. Here, let $r(m;k)$ be the raw baseband signal with k time index at antenna m, and then the channel impulse response (CIR) can be calculated by the serial correlation operation as

$$h_1(m,k) = \frac{1}{N} \sum_{n=0}^{N-1} r(m, k+n) \cdot c^*(n) , \qquad (1)$$

where N is the size of the correlation window, n represents the

time index, $c(n)$ is the local transmitting copy signal, and $*$ denotes the conjunction operation.

Then the channel's power delay profile (PDP) can be denote as below

$$P_{PDP}(m;n) = \frac{1}{L} \sum_{i=1}^{L-1} |h(m;n+iL)|^2 , \qquad (2)$$

where L represents the number of record samples.

III. FREQUENCY CORRELATION ESTIMATE

Correlation analysis is an effective way to study the characteristics of a signal. For the purpose of capacity prediction, system design, and channel allocation, it is necessary to estimate the frequency correlation and figure out the correlative bandwidth for wireless communication system. Here two different ways to estimate the frequency correlation are employed.

A. Method 1: derived from the channel PDP

According to the definition, the frequency correlation function can be expressed as

$$R_H(f_1, f_2; t_1, t_2) = E[H^*(f_1; t_1) \cdot H(f_2; t_2)] , \qquad (3)$$

in (3), $H(f;t)$ represent the low-pass channel transfer function, and can be expressed as

$$H(f;t) = \int_{-\infty}^{\infty} h(\tau;t) \cdot e^{-j2\pi f \tau} d\tau , \qquad (4)$$

where τ represents the time delay. So we have

$$R_H(f_1, f_2; \Delta t)$$
$$= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} E[h^*(\tau_1; t) \cdot h(\tau_2; t+\Delta t)] e^{j2\pi f_1 \tau_1} e^{-j2\pi f_2 \tau_2} d\tau_1 d\tau_2 .$$
$$(5)$$

Since the channel satisfied the wide sense stationary uncorrelated scattering (WSSUS) condition, when the multipath signals arrive the receiver side respectively at time delay τ_1 and τ_2, they must come from different scatterers, which means they are uncorrelated, so the formula can be rewritten as

$$R_H(f_1, f_2; \Delta t) = \int_{-\infty}^{\infty} R_h(\tau, \Delta t) e^{-j2\pi(f_2-f_1)\tau} d\tau . \qquad (6)$$

By defining $\Delta f = f_2 - f_1$, which means the frequency deviation, and setting $\Delta t = 0$ then, we derived the frequency correlation function

$$R_H(\Delta f) = \int_{-\infty}^{\infty} R_h(\tau) e^{-j2\pi\Delta f \tau} d\tau = F[R_h(\tau)] , \qquad (7)$$

where $F[\cdot]$ denotes the Fourier transform. $R_h(\tau)$ equals to the PDP of the channel P_{PDP}.

Eq. (7) indicates under some conditions a channel's FCF can be calculated through a Fourier transform to its average power delay profile (PDP). Fig. 3 is the FCE result according to Eq. (7).
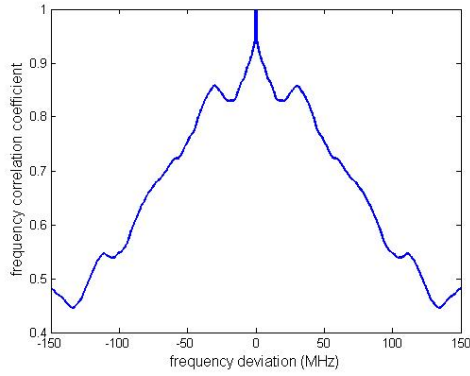
Figure 3. FCE result from the PDP

The curve in Fig. 3 shows the relative variation of the frequency correlation coefficient over the frequency deviation. It is obvious that the correlation coefficient rapidly decreases along with the increase of the frequency deviation. Coherence bandwidth is about 100MHz according to the correlation coefficient being of 0.75, while 10MHz when the correlation coefficient being equal to 0.9. Especially when the correlation coefficient is larger than 0.75, the curve indicates that the coherence bandwidth is continuously increasing to exceed the measurement bandwidth. Besides these, when the frequency derivation is about 15MHz, there exist an jumping change of the correlation bandwidth. This curve seems unreasonable.

B. Method 2: derived from the channel transfer function

To overthrow the validity of the FCE results from method 1, an alternate method, free from the US conditions, is proposed.

Let $\{a_i \mid a_{i,j} = H(f_i; t_j)\}$ be a frequency related power at a determined frequency of f_i, which equals to the complex amplitudes of the channel transfer function at different spectral lines, setting f_{ref} to be the reference frequency, and $\Delta f = f_i - f_{ref}$, then the estimation of frequency correlation can be derived as below [10]

$$R_H(\Delta f) = \frac{\gamma_H\left(a_{ref}, a_i\right)}{\sqrt{\gamma_H\left(a_{ref}, a_{ref}\right)\gamma_H\left(a_i, a_i\right)}}, \qquad (8)$$

where $\gamma_H\left(a_{ref}, a_i\right)$ represents the cross-correlation between the time related power sequence set $\{a_i \mid a_{i,j} = H(f_i; t_j)\}$ relative to the sequence set at the reference frequency $\{a_{ref} \mid a_{ref,j} = H(f_{ref}; t_j)\}$, and can be expressed as

$$\gamma_H\left(a_{ref}, a_i\right) = \frac{1}{N}\sum_{j=1}^{N} a_{ref,j} a_{i,j}^{*} \quad . \qquad (9)$$

Similarly, $\gamma_H\left(a_{ref}, a_{ref}\right)$ and $\gamma_H\left(a_i, a_i\right)$ respectively represent the auto-correlation of set $\{a_i\}$ and $\{a_{ref}\}$, N represents the number of the recorded samples.

The FCE results calculated using Eq. (8) are illustrated in Fig. 4 and Fig. 5. In Fig. 4, the horizontal axis shows the frequency deviation relative to the reference frequency. The vertical axis indicates the relative variation of the frequency correlation coefficient. According the curve, the coherence bandwidth keeps stable, and does not vary significantly with the correlation coefficient. The Fig. 5 shows the fluctuation of the frequency correlation coefficient over the antenna array. It is clear that the FCEs over the antenna array are relatively coherent. From the first antenna moving to the last antenna, the curves are very approximate on both side of the midband. Fluctuation turns up at about 50MHz from the midband. That is to say, in every antenna position, the interesting coherence bandwidth of 100MHz can be promised. The slight fluctuations might result in measurement noise or system performance limitation. It is obvious that these results are considerably different from Fig. 3.
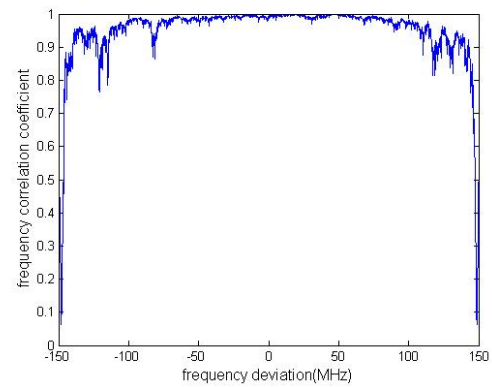

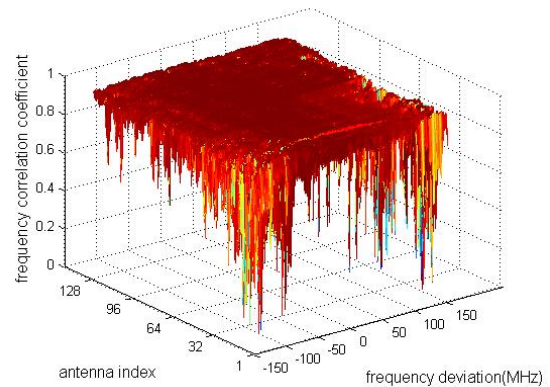**Figure 4.** FCE result from the transfer function

Figure 5. FCE result from the transfer function over the antenna array

By assumption of channel to be uncorrelated scattering (US) and to be wide sense stationary (WSS), Eq. (5) can be rewrite to Eq. (6). With the condition of the channel's transfer function independent of frequency, which means that the channel's transfer function is constant over the interesting bandwidth, and if the measured records are ergodicity, the FCF in Eq. (7) can be replaced by time averages from measurement snapshot. That is to say, under the above conditions, we have method 1 come into existence. While in

method 2, directly cross-correlation of time varying $H(f;t)$ in the frequency domain makes it independent of the conditions. The different results are clear evidence for that wide sense stationary uncorrelated scattering (WSSUS) channel condition and constant means of the channel frequency response condition that are required for method 1, are not hold.

IV. CONCLUSIONS

This work summarized the theory of estimation of frequency correlation based on channel measurement. Then the frequency correlation characteristics separately using the method of Fourier transform to the channel PDP, and of directly cross-correlation to the transfer function are compared. From the presented results, it can be determined that the US condition and constant means of transfer function are not hold.

These results may be helpful to parameters design in wireless communication systems..

ACKNOWLEDGMENT

REFERENCES

[1] T. Marzetta, "Noncooperative CellularWireless with Unlimited Numbers of Base Station Antennas," *IEEE Transactions on Wireless Communications*, vol. 9, no. 11, pp. 3590–3600, November 2010.

[2] E. Larsson, O. Edfors, F. Tufvesson, and T. Marzetta, "Massive MIMO for next generation wireless systems," *Communications Magazine, IEEE*, vol. 52, no. 2, pp. 186–195, February 2014.

[3] H. Q. Ngo, E. Larsson, and T. Marzetta, "Energy and Spectral Efficiency of Very Large Multiuser MIMO Systems," *Communications, IEEE Transactions on*, vol. 61, no. 4, pp. 1436–1449, April 2013.

[4] "Deliverable D1.1 Scenarios, requirements and KPIs for 5G mobile and wireless system," Mobile and wireless communications Enablers for the Twenty-twenty Information Society, Tech. Rep., 2013.

[5] X. Gao, O. Edfors, J. Liu, and F. Tufvesson, "Antenna selection in measured massive MIMO channels using convex optimization," in *2013 IEEE Globecom Workshops (GC Wkshps)*, Atlanta, GA, Dec 2013, pp. 129–134.

[6] S. Payami and F. Tufvesson, "Channel measurements and analysis for very large array systems at 2.6 GHz," in *2012 6th European Conference on Antennas and Propagation (EUCAP)*, Prague, March 2012, pp. 433–437.

[7] Sohail Payami, Fredrik Tufvesson, "Delay spread properties in a measured massive MIMO system at 2.6 GHz," in *2013 IEEE 24th International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC)*, London, United Kingdom, Sept 2013, pp. 53–57.

[8] X. Gao, O. Edfors, F. Rusek, and F. Tufvesson, "Linear Pre-Coding Performance in Measured Very-Large MIMO Channels," in *2011 IEEE* Vehicular Technology Conference (VTC Fall), San Francisco, CA, Sept 2011, pp. 1–5.

[9] X. Gao, F. Tufvesson, and O. Edfors, "Massive MIMO channels - Measurements and models," in 2013 Asilomar Conference on Signals, *Systems and Computers*, Pacific Grove, CA, Nov 2013, pp. 280–284.

[10] R. J. C. Bultitude, "Estimating frequency correlation functions from propagation measurements on fading channels: A critical review," IEEE J. Sel. Areas Commun., vol. 20, no. 6, pp. 1133–1143, Aug. 2002

Yanping Lu, received the B.E. degree from Wuhan University, Wuhan, China, in 2002. received the M.S. degree from Beijing Jiaotong University, Beijing, China, in 2005. And is now a Ph.D. candiadate in the School of Electronic and Information Engineering of Beijing Jiaotong University. Her research interests include channel measurement and modeling, signal processing of wireless communication.

.