Development of Coherent Base Station Scanner with Real-Time Demodulation

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\textbf{Abstract:} A base station scanner that can evaluate MIMO antennas for LTE downlink signaling has been proposed. In this system, all signal processing is done offline, so analysis is significantly delayed. Further, only FDD-LTE is supported. This report details a coherent base station scanner that offers real-time demodulation of not only FDD but also TDD. Experiments on LTE signals using both duplex modes confirm that the developed scanner offers excellent performance and reduced post analysis times.

\textbf{Keywords:} vehicular MIMO (Multiple Input and Multiple Output), LTE (Long Term Evolution), fading analysis

\textbf{Classification:} Antennas and propagation

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1 Introduction

In order to support safe and automated driving, research is underway on connected cars that use cellular V2X (Vehicle to Everything) and other wireless communication technologies to connect the vehicle to everything [1]. This communication requires high capacity and high reliability, and vehicular MIMO (Multiple Input and Multiple Output) antenna technologies are a key element. Since the electrical characteristics of vehicular MIMO antennas are greatly affected by the vehicle body and its components, it is necessary to evaluate the characteristics as the antenna is mounted on an actual vehicle [2]. In [3][4], a simple and small-scale method is proposed for evaluating vehicular MIMO antennas; a coherent base station scanner measures downlink signals from base stations in actual driving tests. In this method, SINR (Signal to Interference plus Noise Ratio), antenna correlation, and channel capacitance of a vehicular MIMO antenna can be determined by receive-only measurements using the aforementioned system. However, that system was too slow because all required signal functions, such as LTE (Long Term Evolution) demodulation, channel estimation, and fading analysis, were carried out offline after LTE signal recording. In addition, the system supported only FDD (Frequency Division Duplex)-LTE; the current LTE offers not only FDD but also TDD (Time Division Duplex) communication [5], and it is desirable for practical purposes to evaluate MIMO systems for vehicles regardless of the duplex mode used.

This report deals with the development of a real-time coherent base station scanner that implements FDD/TDD-LTE demodulation functions in FPGA (Field Programmable Gate Array). Measurements in an anechoic chamber show that antenna correlation and channel capacity can be evaluated for TDD-LTE and FDD-LTE base stations. It is also shown that this scanner offers significant reductions in post analysis time.

2 Measurement system design

Fig. 1(a) shows the diagram of the proposed scanner. It runs the demodulation and channel estimation functions performed in offline mode by conventional systems on FPGAs. Therefore, the RS (Reference Signal) measurements are performed in real-time. In addition, the scanner supports not only FDD but also TDD measurements. Fading analysis, which is necessary to obtain parameters for evaluating vehicular MIMO antennas (SINR, antenna correlation and channel capacity), is realized as a post analysis step. RS measurement and fading analysis are explained below.

2.1 RS measurement

Fig.1(b) shows the RS placement in LTE and a conceptual diagram of channel matrix assembly. Fig.1(c) shows the frame structure of FDD-LTE downlink and Fig. 1(d) shows the frame structure of TDD-LTE. The real-time coherent base station scanner in Fig. 1(a) implements coherent LTE reception and offers real-time demodulation and channel estimation for the received data. Using the obtained demodulated RS symbols for each frequency and time, channel matrix \( H(f, t) \) is constructed as shown in Fig.1(b).
Let $M_R$ be the number of receiving antennas, $M_T$ is the number of transmitting antennas, $f$ is the frequency, and $t$ is time. Channel matrix $H(f, t)$ is stored in the HDD of the control PC. As shown in Fig.1(c) and (d), the frame structure differs between FDD and TDD. Therefore, the measurement targets of this system are the RSs present in the 0th and 5th subframes allocated to the downlink for both FDD and TDD. Since antenna evaluations in mobile communication environments are often done statistically to account for fading variations, this scanner acquires RS in a 450 ms window as one measurement point. This time was determined by taking into account the ability to acquire data for approximately 30 wavelengths necessary for fading analysis when driving at 10 m/s [6] and the memory capacity of the coherent receiver. These measurements are repeated, and fading analysis is performed as a post analysis step after all measurements have been completed.
2.2 Fading analysis (post analysis)

Channel matrix $H(f, t)$ obtained in Sec. 2.1 is normalized to obtain $H_{\text{norm}}(f, t)$.

$$H_{\text{norm}}(f, t) = H(f, t) \frac{M_R M_T}{\sqrt{\|H(f, t)\|_F^2}} \quad (2)$$

Let $\|\cdot\|_F$ be the Frobenius norm. From the obtained $H_{\text{norm}}(f, t)$, the received channel correlation matrix can be obtained by referring to [7] as follows

$$R_k^R(f, t) = H_{\text{norm}}(f, t) H_{\text{norm}}^H(f, t). \quad (3)$$

The SINR per received-transmitted antenna, $\gamma_{pq}$, is calculated by the following equation.

$$\gamma_{pq} = \frac{1}{T} \sum_{t=1}^{T} p_{pq}^D \frac{p_{pq}^D}{p_{pq}^\text{total}} , \quad (4)$$

where $p_{pq}^D$ is received power from the desired base station per OFDM symbol from the desired base station, $p_{pq}^\text{total}$ is total received power per OFDM symbol, $p$ is the original number of receiving antennas, $q$ is the original number of transmitting antennas and $T$ is the number of time samples. Since the average SINR of all receiving antennas is used to obtain the channel capacity, the average SINR, $\bar{\gamma}$, is given by

$$\bar{\gamma} = \frac{1}{M_R M_T} \sum_{p=1}^{M_R} \sum_{q=1}^{M_T} \gamma_{pq} . \quad (5)$$

Using the received channel correlation matrix $R_k^R(f, t)$ and $\bar{\gamma}$, the channel capacity $\bar{C}$ is given by eq. (6)

$$\bar{C} = \frac{1}{F} \sum_{f=1}^{F} \left( \frac{1}{T} \sum_{t=1}^{T} \log_2 \left( \frac{1}{M_T} \frac{\bar{\gamma} R_k^R(f, t)}{I + \frac{\bar{\gamma}}{M_T} R_k^R(f, t)} \right) \right) , \quad (6)$$
where $I$ is the identity matrix, and $F$ is the number of frequency samples. To obtain the correlation characteristics in the fading variation, it is necessary to obtain the fading correlation matrix, $R_R(f)$, for each frequency, which is given by the following equation

$$R_R(f) = \frac{1}{T} \sum_{t=1}^{T} R_R^t(f, t). \quad (7)$$

For obtaining the antenna correlation coefficient $\rho_{Rab}(f)$ for each frequency, the components in the fading correlation matrix $R_R(f)$ is substituted into the following equation

$$\rho_{Rab}(f) = \left( \frac{R_{Rab}(f)}{\sqrt{R_{Raa}(f)R_{Rbb}(f)}} \right)^2, \quad (8)$$

where $R_{Rab}(f)$ represents the $a$-th row and $b$-th column of the $R_R(f)$ shown in eq. (7). The antenna correlation coefficient $\overline{\rho_{Rab}}$ can be obtained by averaging the antenna correlation coefficients for each frequency from eq. (9)

$$\overline{\rho_{Rab}} = \frac{1}{F} \sum_{f=1}^{F} \rho_{Rab}(f). \quad (9)$$

### 3 Anechoic chamber measurements

Tests on LTE signals (FDD and TDD) and the developed scanner are shown to yield the parameters needed to evaluate a MIMO antenna for a vehicle. Fig. 2(a) shows the layout of the wave sources in the anechoic chamber experiment conducted. To obtain antenna correlation $\overline{\rho_{Rab}}$ and channel capacity $\overline{C}$ at the antenna spacing of the receiving antennas, the experiments in an anechoic chamber used 2×2 MIMO with two Rayleigh faded arriving waves. The two fading LTE signal streams $E_{1\text{Tx1}}$ and $E_{2\text{Tx1}}$, specifically generated by the fading simulator to be uncorrelated, are combined in a 90-degree hybrid and transmitted from Tx1. In addition, LTE signals $E_{1\text{Tx2}}$ and $E_{2\text{Tx2}}$ with different fading variations from $E_{1\text{Tx1}}$ and $E_{2\text{Tx1}}$ are generated and transmitted from Tx2. The SINR is set to 15 dB, the angle difference between the two waves ($\sigma$) is 8 degrees, and the various characteristics are measured at the receiving antenna interval.
Fig. 2 (a) Wave source layout in the anechoic chamber.  
(b) Measurement parameters.

| Parameter       | Value |
|-----------------|-------|
| Frequency [MHz] | 2000  |
| Transmitted signal | FDD-LTE (downlink) TDD-LTE |
| Bandwidth [MHz] | 10    |
| Number of streams | 2     |
| Number of Rx    | 2     |
| $f_0$ [Hz]      | 66.7  |
| $\sigma$ [deg.] | 8     |

Fig. 3(a) plots antenna correlation vs. antenna spacing, and Fig.3(b) plots channel capacity vs. antenna spacing. Fig. 3(a) shows that the antenna correlation decreases as the antenna spacing increases, for both FDD and TDD. In addition, Fig. 3(b) shows that the channel capacity increases as the antenna spacing increases, for both FDD and TDD. The results show that it is possible to evaluate MIMO antennas for vehicles in both duplex modes. Fig.3(c) compares the post analysis times of the conventional system and the developed scanner for the same number of measurement points. The developed scanner cuts the number of computations needed in post analysis as it performs demodulation and channel estimation in real-time; its post analysis time just one one-sixth that of the conventional system. Therefore, the proposal is both practical and effective.
Fig. 3 (a) Antenna correlation vs. antenna spacing. (b) Channel capacity vs. antenna spacing. (c) Post analysis processing time.

4 Conclusion
To speed up post analysis processing and support TDD as well as FDD in LTE, this report introduced a real-time coherent base station scanner with FDD/TDD-LTE demodulation functions implemented on FPGAs. The developed system was evaluated by measurements in an anechoic chamber using faded LTE signals. The results confirmed that the proposed scanner can be used to evaluate vehicular MIMO antennas for FDD/TDD-LTE signaling. The proposed scanner cut the processing time for post analysis by approximately 83%. We intend to evaluate the developed scanner using LTE signals from actual outdoor base stations.