MIMO | Synchronization | Burst Transmission

Technology Reports

Special Articles on Multi-dimensional MIMO Transmission Technology — The Challenge to Create the Future —

Precise Timing Synchronization Algorithm for Burst MIMO-OFDM Transmission

As a result of simulating a new preamble structure and precise timing synchronization algorithm suitable for OFDM burst transmissions, it is confirmed that they achieve better characteristics than existing methods especially in the low SNR region. In verification trials on a testbed, it is also confirmed that similar performance can be achieved in real environments.

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1. Introduction

Wireless packet communication, where signals are transmitted in units of short bursts, is regarded as an effective transmission method for future mobile communications which will have many degrees of freedom and will include many different types of applications and terminals. Key technical requirements for wireless packet communication include the detection of randomly transmitted bursts and precise synchronization to their timing and frequency, both of which are needed to achieve adequate performance in Multiple Input Multiple Output (MIMO)*1-Orthogonal Frequency Division Multiplexing (OFDM)*2 transmission. Receivers generally synchronize themselves by calculating the autocorrelation function*3 of the preamble*4 signal placed at the beginning of each burst. There are basically two kinds of autocorrelation functions. One is delay correlation, which involves providing two identical preamble patterns which are sequentially multiplied by the received signal after a fixed delay [1]-[4]. The other is central symmetry correlation, where two symmetric preamble patterns C and $\tilde{C}$ are set up and are multiplied by the signal in a symmetrical fashion working out from the center [5]-[7] (**Figure 1**).

When using the delay correlation method, it is easy to precisely estimate the frequency offset*5 from the phase shift in the previous and subsequent received signals, but as shown in Fig. 1, the autocorrelation metric*6 has a triangular shape along the time axis making it difficult to estimate the timing accurately. On the other hand, the metric of the central symmetry correlation has a pulse shape along the time axis, which means it is easy to precisely estimate the timing synchronization but difficult to estimate the frequency offset.

K. Kim proposed a method whereby preamble patterns with a central symmetric structure are repeated twice (C, $\tilde{C}$, C, $\tilde{C}$), allowing time and frequency synchronization to be achieved simultaneously by central symmetry correlation and delay correlation [5]. However, this method is liable to run

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*1 **MIMO**: A signal transmission technology that uses multiple antennas at both the transmitter and receiver to perform spatial multiplexing and improve communication quality and spectral efficiency.

*2 **OFDM**: A digital modulation method where the information is divided into multiple orthogonal carrier waves and sent in parallel. It allows transmission at high frequency usage rates.

*3 **Autocorrelation function**: The result of multiplying a signal by time-shifted copies of itself. The peak value is obtained with a time shift of zero (i.e., at the origin), and the values obtained at other points along the time axis are symmetrical about the origin.

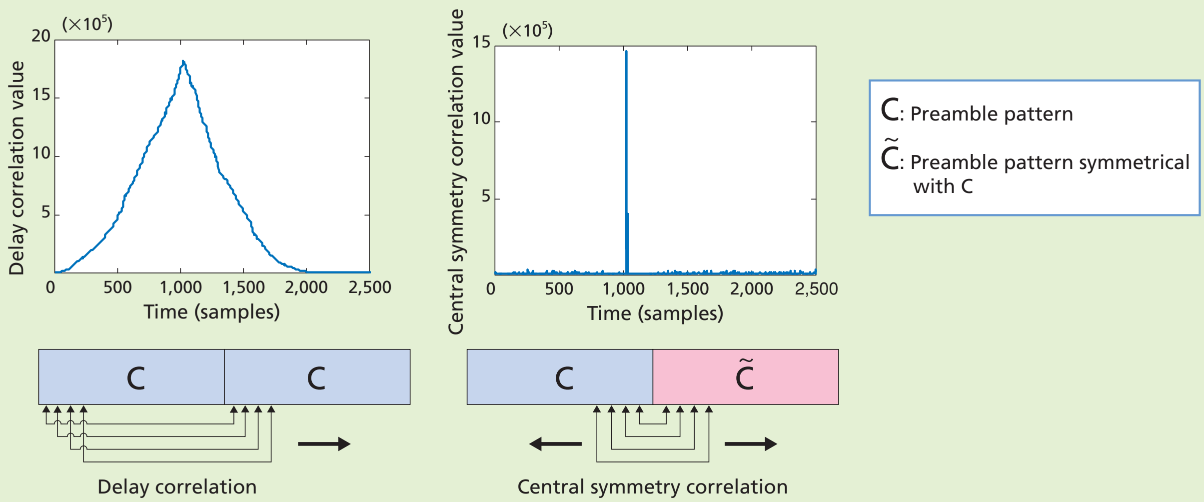

Figure 1 Delay correlation and central symmetry correlation in synchronization preambles

into timing synchronization errors because the metric of the central symmetry correlation has code side-lobes[*7] on both sides. Its timing performance is also liable to be degraded by the presence of a frequency offset. B. Park et al. proposed a similar structure where the last two patterns are the complex conjugates of the first two ($C, \tilde{C}, C^*, \tilde{C}^*$) [6]. This system generates no code side-lobes and is also unaffected by frequency offsets, making it capable of highly accurate timing synchronization. But in this case, it is difficult to estimate the frequency offset.

In this study, we have proposed a new synchronization preamble structure to resolve these issues, a corresponding timing synchronization algorithm, and a method for identifying the synchronization point by means of a threshold value [8]. This preamble structure can support both timing synchronization and frequency offset estimation, and at the same time by efficiently suppressing the effects of code side-lobes, it is capable of high timing synchronization performance.

In this article we describe a new preamble structure suitable for MIMO-OFDM, and a precise timing synchronization algorithm. We also demonstrate the superiority of this approach by performing simulations and testbed verification, and we describe how quantization of the received signal can make this scheme easier to implement.

2. Synchronization Preamble Structure and Timing Estimation Algorithm

2.1 Preamble Structure and Timing Metric

The proposed synchronization preamble structure is shown in **Figure 2**. The preamble consists of two identical OFDM symbols, each symbol comprising two parts C and $\tilde{C}^*$. The sequence $\tilde{C}^*$ is the complex conjugate obtained by inverting sequence C, and it is also possible to rotate this pattern through an additional angle ϕ. As this figure shows, the overall sequence is centrally symmetric, while it is possible to obtain the delay correlation at the same time by determining the correlation between the two identical symbols at the beginning and end of the preamble. It is also possible to leave a fixed gap between the symbols as a Cyclic Prefix (CP)[*8].

To estimate the frequency offset, we used the delay correlation of this preamble, which can be obtained by applying the ordinary Moose algorithm. However, the central symmetry correlation has code side-lobes. Thus in this

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*4 **Preamble**: A fixed signal pattern that is placed at the beginning of a packet. On the receiving side, it is used for packet detection, gain control, frame synchronization, and frequency synchronization, etc. to prepare for reception of the data part.

*5 **Frequency offset**: The offset from a standard frequency caused by factors such as clock inconsistencies between different items of communication equipment and Doppler shifts of moving bodies.

*6 **Metric**: A numerical index - in this case, the output value of the autocorrelation function with respect to the temporal shift. This generally has a peak value at the point where the timing is synchronized.

*7 **Code side-lobe**: The autocorrelation metric of a particular code is usually not a perfect impulse, but has non-zero values at other points beside the origin. These are called code side-lobes.

proposal, timing synchronization is performed using a metric obtained by multiplying the central symmetry correlation and delay correlation together. Specifically, the following function is used as a metric:

$$M(d) = \frac{|\Gamma_s(d)| \cdot |\Gamma_d(d)|}{(P(d))^2} \qquad (1)$$

where d is the number of sampling points, $|\Gamma_s(d)|$ is the central symmetry correlation value, $|\Gamma_d(d)|$ is the delay correlation value, and $P(d)$ is the received power. An example of a metric for a multipath channel is shown in **Figure 3**. As this figure shows, the delay correlation has a roughly triangular profile, while the central symmetry correlation consists of a central pulse with code side-lobes on either side. When these are multiplied together, the code side-lobes are suppressed, and the metric value at the timing synchronization position is emphasized. In this way, the effects of code side-lobes can be largely eliminated, and the timing synchronization performance can be further improved.

2.2 A Two-step Threshold Value Detection Method

When performing timing synchronization on randomly transmitted packets, it is first necessary to identify the temporal range in which to search for the peak value of the metric by detecting whether or not a signal is present. Also, in multipath environments, the peak value of the metric may be detected in some other path besides the first path, and the maximum value may not necessarily occur in the first path, so it is possible that fluctuations may occur in the timing synchronization if we simply search for the peak value. To address these issues, we propose the following two-step threshold value detection algorithm.

- Step 1:

  Extract an effective search area as the temporal region where the delay correlation metric exceeds a

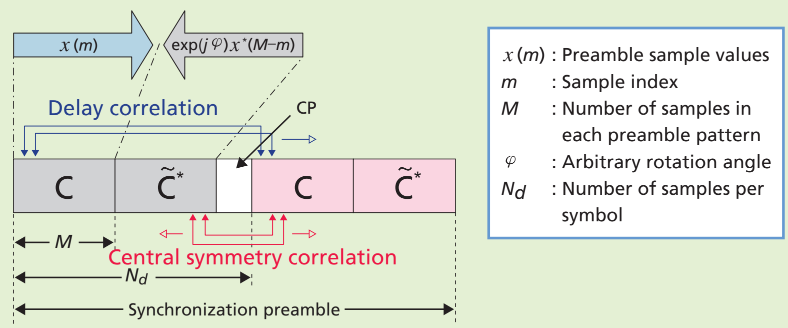

Figure 2 Synchronization preamble structure

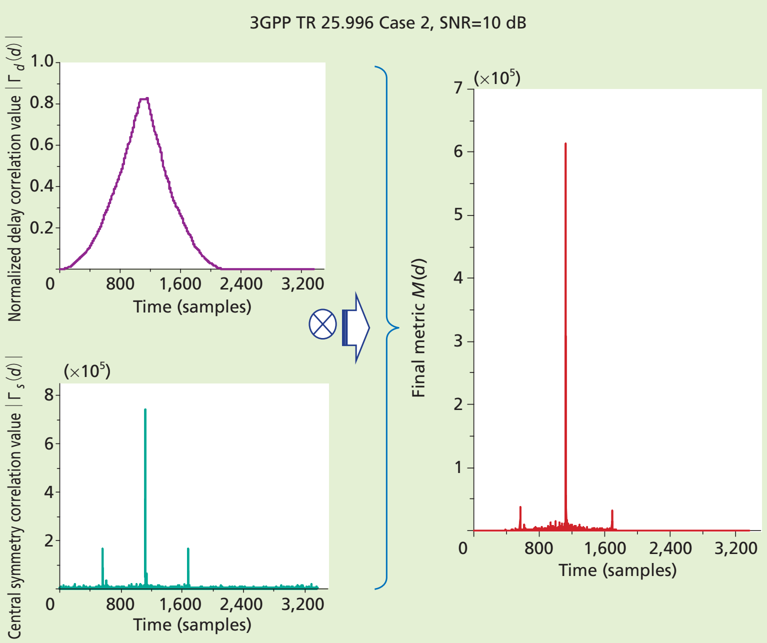

Figure 3 Example of a multipath channel metric

*8 **CP**: A guard time provided between symbols in an OFDM signal to suppress interference with the neighboring symbols resulting from multipath propagation or the like. Normally, this part of the signal consists of a partial copy of the latter part of the symbol. Also called a guard interval.

preset threshold value 1.

- Step 2:

  Search for the point where the metric has the highest value in the effective search area extracted at step 1, set a separate threshold 2 based on this value (threshold 2 ≤ peak value), and extract the points where the metric exceeds threshold 2. The final timing synchronization point is taken to be whichever of these points occurs first.

In the delay correlation of step 1, efficient signal detection is possible because the metric is added including the multipath components. With the processing of step 2, it is also possible to perform identification accurately at the reception timing of the first path.

2.3 Application to MIMO

The above algorithm can easily be extended to MIMO. The simplest way is to use a method where the numbers of transmitting and receiving antennas are both fixed at one. When there are multiple receiving antennas, it is possible to consider a method where the antenna with the largest received Signal to Noise Ratio (SNR) is dynamically selected. However, although this scheme has good synchronization performance, it is impractical due to the difficulty of actually producing hardware that can switch antennas while receiving a synchronization preamble while still guaranteeing that the metric is accurately output. Therefore in these tests we adopted a method where the effective search area and metric function obtained from each receiving antenna are used by combining them together. Specifically, a logical OR operation is applied to the effective search areas, and the sum of the values from each receiving antenna is obtained for the metric function $M(d)$.

3. Overview of Testbed

Figure 4 shows a logic diagram of

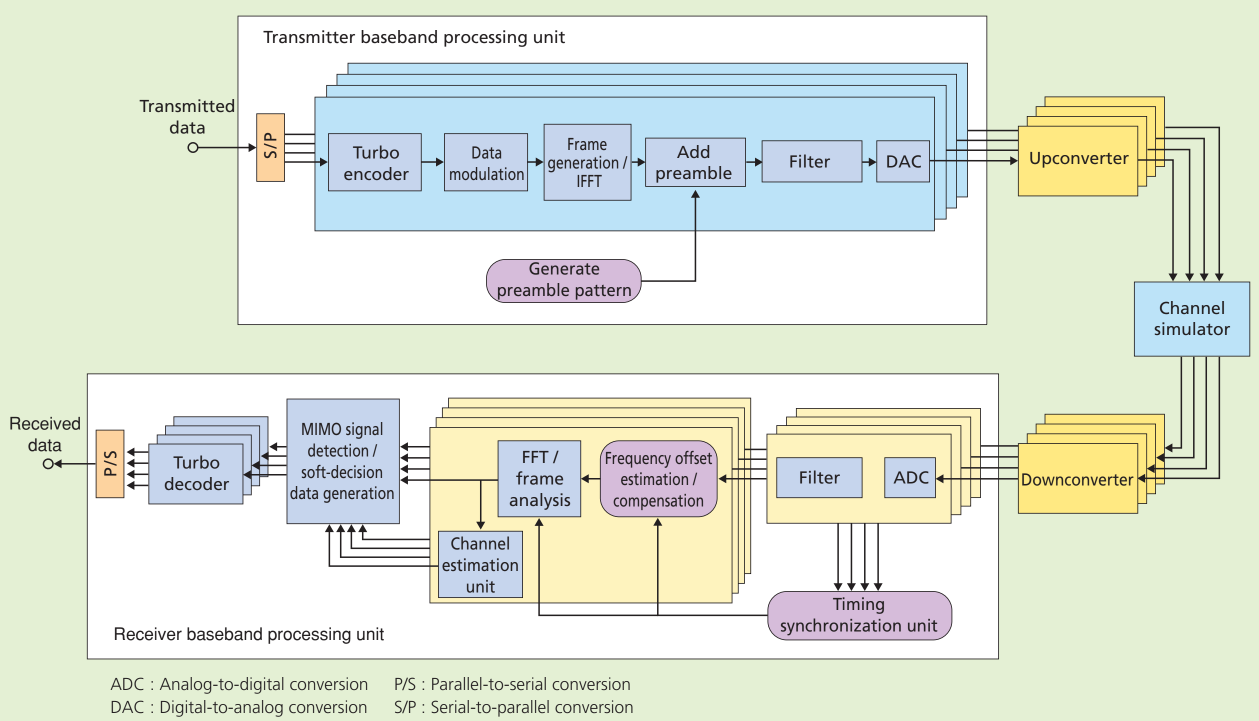

Figure 4 Logic configuration of MIMO-OFDM testbed

the MIMO-OFDM testbed made using Field Programmable Gate Arrays (FPGAs)[*9] for the purpose of experimental verification trials. At the transmitting side, the data is first converted into a four-channel parallel data stream. Each data stream is modulated by Turbo encoding[*10], mapped to 896 subcarriers[*11], and then transformed into time-domain signals by a 1,024-point Inverse Fast Fourier Transform (IFFT)[*12]. A CP and preamble are then added, and the signal is transmitted after filtering, D/A conversion and upconversion[*13].

At the receiver, the baseband signal is extracted by performing downconversion[*14], A/D conversion and filtering. At this point, the proposed method is used to perform timing and frequency synchronization, after which the signals are transformed into the frequency domain by a Fast Fourier Transform (FFT)[*15], and channel estimation is performed. The MIMO signals are then detected, and finally the transmitted data are recovered by performing Turbo decoding and parallel-to-serial conversion.

Figure 5 shows the MIMO-OFDM frame structure used in these tests. As this figure shows, the synchronization preamble is only transmitted from antenna 1. This is so that the synchronization performance is only related to the SNR of the received signal, and if the overall energy of the preamble remains constant, then its characteristics will not change even if the transmission is split between multiple transmitting antennas.

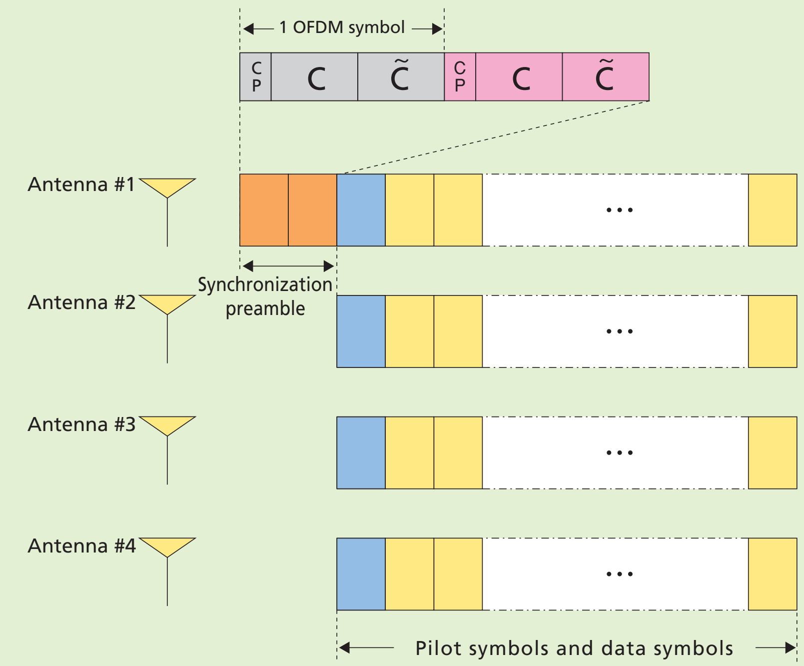

Figure 5 MIMO-OFDM frame structure

4. Implementation in Hardware

The hardware configuration of the timing synchronization unit is shown in **Figure 6**. Here, the signals received by four antennas are each processed to calculate the central symmetry correlation $|\Gamma_s(d)|$, the delay correlation $|\Gamma_d(d)|$, and the received power $P(d)$ which is used for normalization. To simplify the calculation of $|\Gamma_s(d)|$, it is quantized into three states {-1, 0, 1} with respect to the received signal. The system's effective search area is obtained by taking the logical OR of the results derived from step 1 processing of each receiving antenna, and for the metric $M(d)$, the results from all the receiving antennas are added together as a system metric. From the effective search area and system metric obtained in this way, the timing synchronization point is identified by performing the processing of step 2.

5. Test Results

Figure 7 compares the characteristics of the proposed scheme with those of Park's scheme for a slow-moving

*9 **FPGA**: An LSI whose logic can be freely designed.

*10 **Turbo encoding**: A type of error-correcting code proposed in 1993 by Berrou et al. in France. Together with Low-Density Parity Check (LDPC) codes, it is known to produce the codes that are closest to the Shannon limit, and has already been implemented in systems including Third-Generation mobile communications.

*11 **Subcarrier**: One of the individual carrier waves used to transmit a signal in multi-carrier transmission schemes such as OFDM.

*12 **IFFT**: A fast algorithm for converting discrete frequency domain data into discrete time domain data.

*13 **Upconversion**: In this article, upconversion refers to the conversion of an intermediate-frequency signal to a radio carrier frequency.

*14 **Downconversion**: In this article, downconversion refers to the conversion of a radio carrier frequency to an intermediate frequency signal.

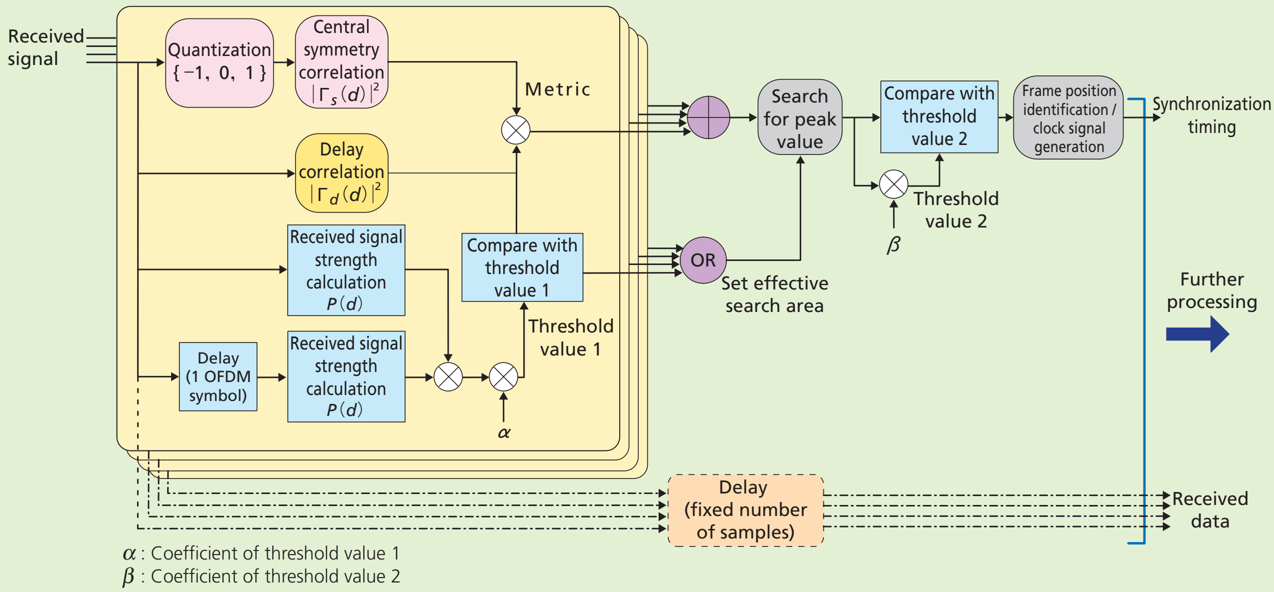

Figure 6 Hardware configuration of the timing synchronization unit

speed (3 km/h). Here, synchronization is performed using just one receiving antenna. The vertical axis shows the probability that the offset between the resulting synchronization timing and the actual timing of the first path is within a range of ten samples. By way of comparison, this figure also shows the characteristics obtained by performing a peak value search within an effective search area that had been fixed in advance under the assumption that the packet is definitely known to have arrived. As this figure shows, in each detection method, the proposed preamble structure and metric calculation method allowed better characteristics compared with the existing schemes. In particular, when the SNR is greater than 5 dB, it can be seen that the proposed scheme is compatible with burst transmission and has roughly the same performance as ideal peak value detection when using the two-step threshold value detection method. It can also be seen that the quantization in the calculation of $|\Gamma_s(d)|$ has almost no effect on the threshold value detection method, although a slight performance loss is observed at low SNR values in the ideal peak value detection method. The char-

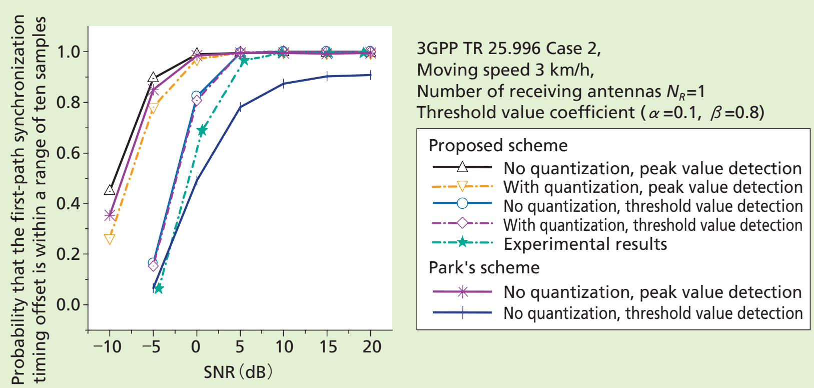

Figure 7 Comparison of timing synchronization performance

*15 **FFT**: A fast algorithm for converting discrete time domain data into discrete frequency domain data.

acteristics obtained when implemented in an actual testbed were almost identical to the results obtained by computer simulation, allowing us to confirm the effectiveness of the proposed scheme in real environments.

Figure 8 shows how the synchronization performance varies with changes in the number of receiving antennas used for synchronization when the SNR is –5 dB. Here, we compared a method where the antenna is dynamically selected according to the received SNR with the method we actually implemented where the received signals are combined with each other. As this figure shows, when using the two-step threshold value detection method, the antenna selection and signal combination methods have more or less the same performance, while in each method the synchronization performance was improved at smaller SNR values by using signals from multiple antennas. This trend was also backed up by the results obtained with the testbed.

Figure 9 shows the timing synchronization performance for changes in moving speed. Overall, the timing synchronization performance decreases as moving speed increases, but as long as its speed remains below 500 km/h, the probability that the timing deviation is within ten samples is at least 99%, so it can be said to fully satisfy the requirements of real systems.

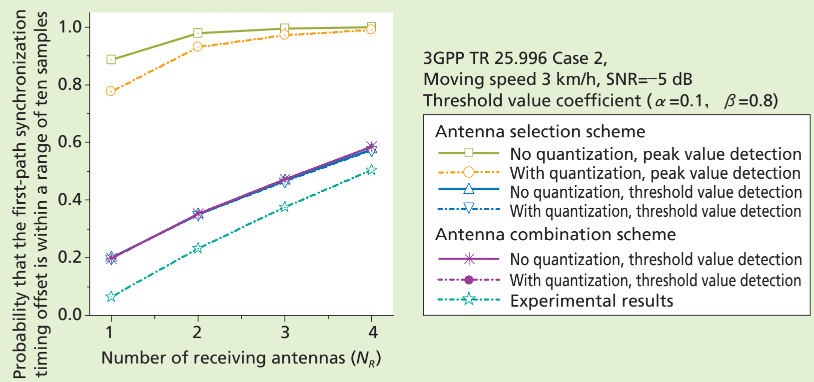

Figure 8 Variation of timing synchronization performance with the number of receiving antennas

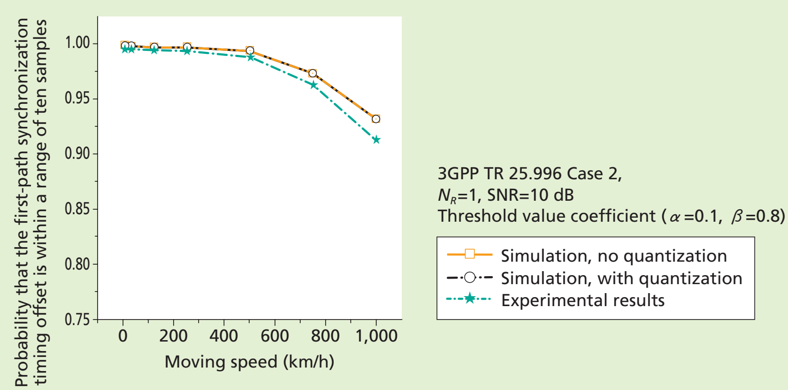

Figure 9 Variation of timing synchronization performance with moving speed

6. Conclusion

In this article, we have proposed a new synchronization preamble structure and timing synchronization algorithm for use in burst MIMO-OFDM transmission. We have shown that this scheme is simultaneously equipped with delay correlation and central symmetry correlation characteristics, and that it is capable of frequency offset estimation and precise timing synchronization. We have also presented a two-step threshold value detection algorithm compatible with wireless packet communication, and we have shown that it is possible to obtain more or less the same synchronization performance as the peak value detection method under ideal conditions, except at low SNR values. Furthermore, we have constructed a MIMO-OFDM testbed using FPGAs, and we have confirmed that it is capable of more or less the same characteristics as the computer simulation. In the future we plan to conduct a more detailed design and evaluation aimed at applying this technique to future systems.

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