Experimental evaluation of STBC and CDD for reliable downlink communication

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Abstract: High reliability will be required even in Internet of Things (IoT) communications in the near future for control purposes. To enhance reliability, both uplink (UL) and downlink (DL) communication quality must be considered. In this paper, we focus on the improvement of DL physical layer communication. To enhance the reliability of DL, the use of spatial diversity is a promising technique. We deal with two transmit diversity (TD) techniques, space-time block coding (STBC) and cyclic delay diversity (CDD), which are evaluated by experimentations in real environments. From the results of the experiments, we confirmed that STBC and CDD could improve frame error ratio (FER). CDD can achieve almost the same performance as STBC by setting the amount of cyclic shift (ACS) appropriately. For example, in a non-line-of-sight (NLOS) area where shadowing happens due to hillock, FER could be improved from $5.11 \times 10^{-2}$ to $1.59 \times 10^{-2}$ in STBC and $1.00 \times 10^{-2}$ in CDD.

Keywords: IoT, STBC, CDD

Classification: Wireless Communication Technologies

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1 Introduction

Internet of Things (IoT) will be used in many cases and the number of devices will increase rapidly. To accommodate the huge number of small size data from IoT devices in a base station (BS), we have developed a system named simultaneous transmit access boost low latency (STABLE) [1] that achieves both massive connection and low latency. In STABLE, we must consider both uplink (UL) and downlink (DL) communication quality to assure the reliability of the whole system. In UL, we have already adapted receive diversity (RD) and repetition to improve the reliability [1]. This paper focuses on the DL. To enhance reliability, the use of spatial diversity is a prominent technique. However, regarding RD, the IoT devices may have difficulty in equipping multiple antennas because of limited room. For this reason, we decided to use transmit diversity (TD), which does not impact the number of receive antennas. We prepared two TD techniques using space-time block coding (STBC) [2] and cyclic delay diversity (CDD) [3]. The two techniques were evaluated using STABLE in field experiments as well as in a fading emulator. In the experiments, we measured the frame error ratio (FER) counted by cyclic redundancy check (CRC) errors. From the results of the experiments, we confirmed that TD could improve the performance. In previous work [4], STBC is better than CDD in a bit error ratio criterion. However, we found that CDD could achieve almost the same FER as STBC by appropriately adjusting the amount of cyclic shift (ACS).

2 System description

In STABLE, using single carrier transmission with non-orthogonal multiple access (NOMA) in UL [1], we use orthogonal frequency division multiplexing (OFDM) in DL. The radio parameters in DL are almost the same as those of LTE. STABLE uses time division duplexing (TDD) as shown in Fig. 1(a). The allocation of resource elements (REs) in a sub-frame is shown in Fig. 1(b). 108 out of 1008 REs are used as reference signals (RSs) for estimating channel frequency response (CFR). For STBC, orange and blue REs used as RSs shown in Fig. 1(b) are allocated to the 1st and 2nd transmit antenna, respectively. In the case of CDD or one antenna transmission (which is called No-TD), only orange REs are employed for CFR estimation. Nulls are inserted into blue REs. The green REs are used for conveying payload. In STABLE, the power of RSs is 3 dB higher than that of the payload to accurately estimate CFR.

2.1 Transmitter (BS) and receiver (device)

Fig. 1(c) describes the signal procedure of DL. In BS, the payload is input to a CRC block to attach the CRC bits. The payload with CRC bits is coded by the turbo coder and then interleaved by a block interleaver. The interleaved signals are modulated
and mapped to green REs shown in Fig. 1(b). When STBC and CDD are used, the additional signal procedures of red and blue blocks are inserted, respectively. The detail of the TD procedures is described in the following sub-sections. Then, the signals are combined with RSs and converted into time domain signals by inverse fast Fourier transform (IFFT). The cyclic prefix (CP) is added and then the signals are up-converted to radio frequency signals. Finally, the signals are filtered and amplified by two band-pass filters (BPFs) and a power amplifier (PA).

In the device, the received signals are filtered and amplified by a BPF and low noise amplifier (LNA), respectively. The amplified signals are down-converted into baseband signals and then the CP is removed. The signals are converted into frequency domain signals by fast Fourier transform (FFT). After that, the RSs are extracted to calculate CFR. In STABLE, to obtain the CFR of all REs, the CFR of the RS and its adjacent RS are linearly interpolated in both the frequency and time domain. Then, STBC demodulation explained in the next sub-section is performed. In the case of CDD and No-TD, by setting the CFR of the 2nd antenna to 0. The output from the STBC demodulator is demodulated and de-interleaved. Finally, the de-interleaved signals are decoded by the turbo decoder and checked whether there are errors in the CRC block.

2.2 STBC

The red blocks are the STBC modulator in Fig. 1(c). The Alamouti method [2] is used. In the transmitter of STABLE, the payload (green) REs shown Fig. 1(b) are exchanged in the time direction and converted to REs of the complex conjugate as follows:

\[
RE_{\text{ant}1}(f, 2t - 1) = RE(f, 2t - 1) \\
RE_{\text{ant}1}(f, 2t) = -RE^*(f, 2t) \\
RE_{\text{ant}2}(f, 2t - 1) = RE(f, 2t) \\
RE_{\text{ant}2}(f, 2t) = RE^*(f, 2t - 1)
\]

(1)

where \(RE(f, m)\) is the RE of the \(f\)-th \((f = 1, 2, 3, \ldots, 72)\) subcarrier and \(m\)-th \((m = 2t - 1, m = 1, 2, 3, \ldots, 14)\) symbol before STBC modulation as shown in

![Fig. 1. System description in DL of STABLE.](image-url)
Fig. 1(b). * indicate the complex conjugate. After that, the explanation of \( f \) and \( m \) is omitted. \( R_{\text{ant}1} \) and \( R_{\text{ant}2} \) are the output of the STBC modulator for the 1st and 2nd transmit antennas, respectively.

In the STBC demodulator block of the receiver, the signal is demodulated as follows:

\[
R_{\text{d}}(f, 2t - 1) = H_{\text{ant}1}(f, 2t - 1) \cdot R_{\text{r}}(f, 2t - 1) + H_{\text{ant}2}(f, 2t) \cdot rR_{\text{r}}(f, 2t) \\
R_{\text{d}}(f, 2t) = H_{\text{ant}2}(f, 2t - 1) \cdot R_{\text{r}}(f, 2t - 1) - H_{\text{ant}1}(f, 2t) \cdot rR_{\text{r}}(f, 2t)
\]

(2)

where \( R_{\text{d}} \) and \( R_{\text{r}} \) indicate the decoded RE by the STBC demodulator and received RE, respectively. \( H_{\text{ant}1} \) and \( H_{\text{ant}2} \) are the CFR from the 1st and 2nd transmit antennas, respectively. Here, we assume that the time variation of the CFR between \( t \) and \( t + 1 \) can be ignored.

2.3 CDD

CDD can obtain path diversity gain [3] by forcibly producing the delay waves using the multiple transmit antennas. In STABLE, to generate the delay waves, the output from IFFT in the transmitter shown in Fig. 1(c) is copied and then cyclically shifted as the transmit signal of the 2nd antenna. ACS leads to the delay. Here, the ACS must be appropriately adjusted. The ACS should be basically larger than the delay of the multipath waves to maximize path diversity gain. However, a too large ACS leads to performance deterioration, which is explained in the next section.

3 Experiment

3.1 Environment and configuration

An experiment was conducted in Yokosuka Research Park (YRP). The configuration and radio parameters are shown in Fig. 2(a) and (b) [5], respectively. Regarding the synchronization, STABLE receives 1-pulse-per-second (1PPS) and 10-MHz reference signals from a global positioning system (GPS). In timing synchronization, propagation delay is compensated using the correlation compared with the CP and the tail of the symbols [6] while the 1PPS signal is used for coarse timing synchronization.

In the experiment, although the USRP can perform all signal procedures shown in Fig. 1(c), the baseband signals are stored on a laptop computer. The stored signals are demodulated as shown in Fig. 1(c) by MATLAB [7] to enable us to record several parameters such as CFR. Here, to indicate the reference performance of FER, Fig. 2(c) shows the measured FER using the fading emulator. The common 1PPS and 10-MHz reference signals were shared between the BS and the device for ideal synchronization.

3.2 Result

Fig. 3(a), (b), (c) and (d) show FER calculated by gathering 200 DL sub-frames whose duration is 1 s. This FER is plotted using Google Earth [8] every 1 s following the GPS information. The FER is 0 in the course except in areas A, B, and some of parts in Fig. 3(d). This good performance is attributed to a high signal to noise ratio.
The device is in line-of-sight (LOS) except in areas A and B. However, regarding area A, the air conditioner systems located behind antennas shields the radio waves from reaching it. In area B, there is hillock between the BS and device. In these areas, TD is effective to improve the FER as shown in Fig. 3(e). We can also observe that the dark blue points of areas A and B were
reduced in Fig. 3(a), (b), (c) and (d). As shown in Fig. 3, STBC and CDD with an ACS of 3 have almost the same performance. However, in the case of CDD with an ACS of 5, we confirmed that, except in areas A and B, the FER was deteriorated from 0 to $2.18 \times 10^{-3}$. The reason why a large ACS may deteriorate the FER is that the CFR estimation error becomes large. As the ACS increases, the frequency selectiveness of fading becomes severe. It makes the accuracy of CFR estimation deteriorate since the CFR in STABLE is estimated by linear interpolation of the RSs. Here, FER of Fig. 2(c) in TD is almost the same performance regardless of TD techniques. We consider that the difference between the TD performances in the experiments is attributed to a fading characteristic. Whereas FER of Fig. 2(c) is evaluated in Rayleigh fading, the experimental environment is Rice-Nakagami fading whose measured $K$ factor is from -11 to 17 dB. In a large $K$, almost the same power of strong direct waves from two transmit antennas produces deep notches in frequency selective fading.

4 Conclusion

In this paper, we conducted experiments to examine the effect of STBC and CDD. In the experiments, we confirmed that the use of TD on the basis of both the STBC and CDD with an ACS of 3 for a coded OFDM in DL brings an improvement in FER. Also, it is shown that CDD with an ACS of 5 deteriorates FER, which indicates that the ACS of CDD should be appropriately determined by expected CFR estimation accuracy and presumed fading characteristics since the use of CDD itself generates severe frequency selective fading in principle. As a result, STBC, which does not require the ACS adjustment, brings FER improvement, which is comparable to the improvement derived by CDD with an adjusted ACS.