Benefits, variants and applications of cyclic delay diversity†

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SUMMARY

Cyclic delay diversity (CDD) is a simple multiple antenna technology which provides additional diversity in Rayleigh fading channels, and therefore, improves the system performance. We recall the principles of CDD and discuss the properties and impact of this transmit (TX) antenna diversity technology. Different applications motivate variations of the CDD principle. This variants are briefly introduced and discussed. We show the application to several types of wireless systems, in particular terrestrial digital video broadcasting, cellular mobile radio communications systems and a wireless communications system using adaptive bit loading (ABL). Simulation results highlight the benefits of CDD for these kind of systems.

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1. INTRODUCTION

Multiple antenna transmission schemes have gained a high attraction since they offer a capacity which rises proportional to the minimum of the number of transmit (TX) and receive (RX) antennas from information theory point of view. In recent years, several approaches have been proposed, which take advantage of multiple TX- respectively RX-antennas. One representative of multiple antenna schemes is cyclic delay diversity (CDD) [1]. CDD is a variant of delay diversity (DD) [2] and adapted to communications systems with cyclic extensions as guard intervals such as orthogonal frequency division multiplexing (OFDM) for instance. Signal delays in DD may cause intersymbol interference (ISI). In contrast, CDD prevents such additional ISI by using cyclic signal shifts. Typically, multi-TX/RX-antenna techniques like space-time coding [3, 4] require signal processing in both the transmitter and the receiver. However, CDD as well as DD can be implemented solely at the transmitter, the receiver or both sides. The fact that the counterpart—e.g., the RX in case of a TX-sided implementation—needs not to be aware of the implementation makes these techniques standard compatible. That is, they can be implemented as an extension for already existing systems without changing the standard.

CDD has extensively been investigated for Rayleigh fading channels. It can be shown that CDD transforms the multiple-input/single-output (MISO) channel into an equivalent SISO channel. This transformation increases the number of propagation paths and the frequency selectivity of the channel, which improves the system performance in multipath Rayleigh fading scenarios. Non-line-of-sight (NLOS) propagation is most likely for cellular wireless communications systems in many environments and scenarios. For line-of-sight (LOS) propagation, CDD transforms the constant parts of the channel into a static multipath channel, which decreases performance. To reduce the LOS loss, we introduce the concept of soft CDD, a generalisation of CDD, which uses different transmission power levels at the TX antenna branches.

Multi-antenna techniques can be applied to a cellular scenario by using the neighboring base stations (BSs) as the multi-antenna setting. Therefore, TX diversity is transformed into macro-diversity. In 2002, Inoue et al. [5] proposed this within the application of space-time block codes (STBCs). CDD offers the exploitation of the increased TX

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diversity at the receiver without any change on the receiver side. Transmitting the same signal from several antennas including cyclic delays will be observed as a channel with higher frequency selectivity at the receiver. This resulting additional frequency diversity can be collected by a channel code for instance. We apply CDD in a cellular scenario (cellular CDD [6, 7]) and highlight the system performance improvements at the cell border region by simulation results.

Water-filling (WF)-based adaptive bit loading (ABL) schemes are well known in the field of transmission over twisted-pair lines [8, 9]. However, practical wireless systems usually operate far from the theoretical capacity. Hence, adaptation policies for such systems should be based on the predetermined coding and modulation schemes rather than accomplishing a WF to maximise the capacity. If we assume that the transmitter has perfect channel state information (CSI), adaptive techniques to improve the average bit error rate (BER) performance in environments with frequency-selective fading are proposed in Reference [10]. In general, this can only be achieved in low mobility scenarios where the channel is changing slowly. For such channels, a typical environment could be a small office or conference room, where the user is moving slowly [11]. However, this scenario may not offer high frequency selectivity and ABL provides only a marginal gain w.r.t. uniform bit loading (UBL). We show that the ABL scheme can be easily combined with CDD in order to increase frequency selectivity, and therefore, improve the ABL gain.

2. PRINCIPLE OF CYCLIC DELAY DIVERSITY

Mobile communications systems benefit from a high number of preferably uncorrelated propagation paths and high channel delay spreads. A simple approach to increase these parameters is to transmit delayed copies of the time domain data signal \( \tilde{s}(k) \) over further TX antennas. Thus, the signal transmitted at TX antenna \( i \) is

\[
s_i(k) = \frac{1}{\sqrt{N_T}} \tilde{s}(k - \delta_i), \quad i = 0, \ldots, N_T - 1
\]

This DD method was proposed in Reference [2]. However, this approach effectively increases the channel delay spread. This results in ISI for cyclic prefixed OFDM systems in case the maximum observed propagation delay exceeds the guard interval length \( N_G \). This constrains the choice of the TX antenna-specific delays \( \delta_i \) to

\[
\max_i \delta_i \leq N_G - N_{\text{max}}
\]

where \( N_{\text{max}} \) is the maximum delay of the radio propagation environment, that is the radio channel.

For block modulation schemes which use a cyclic prefix as guard interval, this drawback can be avoided if the TX antenna-specific delays are replaced by cyclic shifts of the modulated data block. Due to cyclic shifts, we refer to this method as CDD. Figure 1 shows the principle of CDD for an OFDM transmitter. For simplicity of notation, we consider the transmission of one OFDM symbol. \( N_{\text{FFT}} \) data symbols \( S(\ell), \quad \ell = 0, \ldots, N_{\text{FFT}} - 1 \) are obtained from a precedent coding, modulation and framing part. These complex valued symbols are transformed into time domain by the OFDM entity using an inverse fast Fourier transform (IFFT) of length \( N_{\text{FFT}} \). Such an OFDM symbol in time domain is represented by the samples \( \tilde{s}(k), \quad k = 0, \ldots, N_{\text{FFT}} - 1 \). Before inserting a cyclic prefix as guard interval, the time domain OFDM symbol is shifted cyclically, which results in an extended version of the OFDM symbol with cyclic prefix. After inserting another cyclic prefix as guard interval, the time domain signal is ready for transmission.

Figure 1. Principle of cyclic delay diversity.

in the antenna-specific TX-signal
\[ s_i(k) = \frac{1}{\sqrt{N_T}} \tilde{s}(k - \delta_i^{\text{cyc}} \mod N_{\text{FFT}}) \quad (3) \]
for \( i = 0, \ldots, N_T - 1 \) and \( k = -N_G, \ldots, N_{\text{FFT}} - 1 \), where the time interval \( k = -N_G, \ldots, -1 \) is the cyclic prefix (guard interval) section. This approach keeps the transmission of the OFDM symbols timely synchronised for the \( N_T \) TX-antenna branches, that is an OFDM-modulated data block starts at the same time at each TX-antenna. The guard interval length for CDD in order to prevent ISI has to fulfil
\[ N_G \geq N_{\text{max}} \quad (4) \]
and does not depend on the cyclic delays \( \delta_i^{\text{cyc}} \). This allows shorter guard intervals compared to DD.

Assuming quasi-static channel fading, we can use the well-known description of OFDM in frequency domain, where each transmitted data symbol is multiplied by a complex valued fading coefficient when observed at the receiver. Therefore, the signal obtained at the receiver in frequency domain—that is after removing the guard interval and subsequent FFT—is
\[ R(\ell) = \frac{1}{\sqrt{N_T}} \sum_{i=0}^{N_T-1} S(\ell) e^{-j \frac{2\pi}{N_{\text{FFT}}} \delta_i^{\text{cyc}} \ell} H_i(\ell) + N(\ell) \]
\[ = \frac{1}{\sqrt{N_T}} S(\ell) \sum_{i=0}^{N_T-1} e^{-j \frac{2\pi}{N_{\text{FFT}}} \delta_i^{\text{cyc}} \ell} H_i(\ell) + N(\ell) \quad (5) \]
where \( N(\ell) \) is complex valued Gaussian noise which is mutually uncorrelated between different subcarriers.
\[ H_i(\ell) = \sum_{k=0}^{N_{\text{FFT}}-1} h_i(k) e^{-j \frac{2\pi}{N_{\text{FFT}}} \ell k} \quad (6) \]
are the frequency domain channel fading coefficients for subcarrier \( \ell \), observed from TX-antenna \( i \) to the receiver, which are calculated from the channel impulse responses \( h_i(k) \). We assume \( h_i(k) \) to be mutually independent complex Gaussian-distributed random variables with zero mean and mean power
\[ E[|h_i(k)|^2] = \sigma_k^2 \quad (7) \]

where \( \sum_{k=0}^{N_{\text{max}}} \sigma_k^2 = 1 \). Note \( \sigma_k^2 = 0 \) if there is no propagation path at delay \( k \).

The first identity of Equation (5) indicates that CDD can be described in frequency domain by multiplication of the frequency domain data symbols with a linearly increasing phase factor \( \phi_i(\ell) \). The second identity, however, shows, that CDD can be described as a single-TX-antenna system using a superposition channel with equivalent channel transfer function \( H(\ell) \).

3. VARIANTS

3.1. Time-variant CDD

CDD increases frequency diversity by increasing the channel frequency selectivity. Similar to that, increasing temporal selectivity of the channel offers further diversity. To increase the fading selectivity in time direction, the TX antenna-specific phase functions \( \phi_i(\ell) = \frac{2\pi}{N_{\text{FFT}}} \delta_i^{\text{cyc}} \ell \) (see Equation (5)) are linearly increased in time, that is
\[ \phi_i(\ell, t) = \phi_i(\ell) + 2\pi F_i t \quad (8) \]
where \( F_i \) is a TX antenna-specific frequency shift. In Reference [12], this approach is introduced as ‘Time-Variant Phase Diversity’. However, it is stated there that this method increases intercarrier interference (ICI) in OFDM due to higher effective channel dynamics. Additional ICI can be prevented if the time variable in Equation (8) is not discretised in sampling time intervals as proposed inherently in Reference [12] but rather in time intervals corresponding to the OFDM symbol duration. This approach can be found in Reference [13]. A further approach, which introduces time variance is presented in Reference [14]. Here, the authors propose to choose the cyclic delays randomly. In Subsection 4.3, some results are presented which use this variant of CDD in a cellular mobile communication system.

3.2. Discontinuous CDD

CDD effectively increases the frequency selectivity of the multipath propagation channel. This can cause additional multiuser interference (MUI) resp. multiple access interference (MAI) in OFDM systems which use an additional spreading component in frequency direction, for example multicarrier code division multiple access (MC-CDMA). Further, channel estimation in frequency direction also suffers from higher frequency selectivity. This drawbacks
can be avoided for a contiguous set of subcarriers, that is a local area of the spectrum, when keeping the phase factors constant for that subcarriers and increase the phase at the transition to the next set of subcarriers only. This prevents additional interferences locally but increases diversity between these sections. Using the frequency description of CDD from Equation (5), the phase functions are

\[
\phi_i(\ell) = \begin{cases} 
\frac{2\pi}{N_{\text{FFT}}} \delta_{i}^{\text{cyc}} \ell, & \text{CDD} \\
\frac{2\pi}{N_{\text{FFT}}} \delta_{i}^{\text{cyc}} L(\ell \div L), & \text{Discontinuous CDD}
\end{cases}
\]

\(\div\) is an integer division (division with remainder) and \(L\) denotes the number of contiguous subcarriers for which the phase factor is kept constant. This is proposed in Reference [15] under the term discontinuous CDD.

### 3.3. Soft cyclic delay diversity

LOS propagation is a severe problem for CDD since the constant (LOS) paths of the channel are transformed into a static frequency selective one. Using 2-TX-antenna CDD, for instance, transforms an AWGN channel with CTF \(H_{i}(\ell) = 1\) into an equivalent channel with an absolute square CTF \(|H(\ell)|^{2} = 1 + \cos(2\pi \delta_{i}^{\text{cyc}} f / N_{\text{FFT}})\) according to Equation (5). This is depicted in Figure 2 for \(\delta_{1}^{\text{cyc}} = 1.09 \mu s\). We can clearly observe deep fades (see graph for \(\Delta P = 0\) dB), which degrade the system performance compared to the 1-TX-antenna case. The reason for these deep fades is the equal power distribution among the TX-antennas.

A solution to overcome this problem is to weight the signal at each TX-antenna branch by different factors \(\alpha_{i}\). The implementation principle is shown in Figure 3. To keep the transmitted power independent of the number of TX-antennas yields to the normalisation

\[
\sum_{i=0}^{N_{T}-1} E(|\alpha_{i}|^{2}) = 1
\]

First of all, the implementation shown in Figure 3 allows a flexible allocation of power to the different TX-antenna branches with several degrees of freedom. In order to describe the power distribution by one parameter, we define

\[
\Delta P = 10 \log \frac{|\alpha_{0}|^{2}(N_{T} - 1)}{1 - |\alpha_{0}|^{2}} \text{ (dB)}
\]

as the TX power ratio between the first TX antenna and the average power of the CDD extension, that is TX-antennas \(1 \ldots N_{T} - 1\). The parameter \(\Delta P\) allows to switch on/off CDD softly. Therefore, we call this principle soft CDD.

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For 2-TX-antenna CDD definition, Equation (11) provides a unique description of the power distribution among the antennas. In this case the equivalent CTF for pure LOS (AWGN) is

$$|H(\ell)|^2 = 1 + \frac{2\sqrt{\Delta P_{\text{lin}}}}{1 + \Delta P_{\text{lin}}} \cos \left( \frac{2\pi \delta_{\text{cyc}}}{N_{\text{FFT}}} f \right)$$  \hspace{1cm} (12)

which is shown in Figure 2 for $\delta_{\text{cyc}} = 1.09$ μs and different TX antenna power ratios. $\Delta P_{\text{lin}} = 10^{(\Delta P/10)}$ is the linear representation of $\Delta P$. For more than 2-TX antennas, the power distribution within the CDD extension is a further degree of freedom. Its optimisation is not in the scope of this paper. Here, we use a uniform distribution, that is $E[|\alpha_1|^2] = E[|\alpha_2|^2] = \cdots = E[|\alpha_{N-1}|^2]$ for the first approach. In this case, $\Delta P = 0$ yields to the original definition of CDD, where the transmission power is equally distributed among the TX antennas. Note that $\Delta P \to +\infty$ completely switches off the CDD extension.

4. APPLICATIONS

4.1. Digital video broadcasting

As a first example for the application of CDD, we consider the terrestrial digital video broadcasting system (DVB-T) [16]. Figure 4 shows the block diagram of the so-called inner coding and modulation part of the physical layer. The DVB-T transmission parameters used for simulations are 8k FFT, 16-QAM Modulation, Coderate 2/3, guard interval length 1/4. This combination provides a data rate of 13.27 Mbit/s in 8 MHz channels and is typically used in Germany to provide four TV services [17].

Figure 5 shows the BER versus $E_s/N_0$ for both an indoor and an outdoor environment. The channel models used for simulations are the ‘Indoor Commercial—Channel B’ (7 paths, max. delay 750 ns) and the ‘Outdoor Residential—High Antenna—Channel B’ (10 paths, max. delay 15 μs) [18]. The BER performance of a single-antenna system is shown as a reference. Applying 2-TX-antenna CDD at the transmitter with a cyclic delay of $\delta_{\text{cyc}} = 10$ samples (≈1.1 μs), 2-TX-antenna CDD, DVB-T, 8k FFT, 16-QAM, Coderate 2/3, Guard Interval 1/4.

The additional diversity, provided by the transmitter, is exploited by the channel code at the receiver. Figure 6 shows the SNR gain versus cyclic delay $\delta_{\text{cyc}}$ of 2-TX-antenna CDD at $\text{BER} = 2 \times 10^{-4}$, DVB-T, 8k FFT, 16-QAM, Coderate 2/3, Guard Interval 1/4.
shows the SNR gain for CDD with different cyclic delay at the 2nd TX-antenna. It can be observed that there is a saturation effect, that is a cyclic delay of $\delta_1^{\text{cyc}} > 1.5$ $\mu$s results in no further improvement. Different from the indoor results, the outdoor DD gain shows local minima for $\delta_1^{\text{cyc}} \approx 0.55$ $\mu$s. In that case, powerful propagation paths of the outdoor channel model overlap. In particular, these are tap 4 (1050 ns, $-1.5$ dB) and tap 3 (500 ns, 0 dB), which—together with the cyclic delay of $\delta_1^{\text{cyc}} \approx 0.55$ $\mu$s—also results in an effective delay of 1050 ns.

### 4.2. Line-of-sight propagation in DVB-T

In this section, we provide simulation results for CDD with antenna power weighting applied to the inner DVB-T system. We use the 2k mode with a subcarrier spacing of $\Delta f = 4464$ Hz, 16-QAM modulation and an inner code rate of $R = 3/4$. The guard interval length is $N_G = 1/32 \times N_{\text{FFT}} = 64$ samples, which equals 7 $\mu$s for 8 MHz channels. This parameter set results in a net bit rate after the outer Reed–Solomon decoder of 18.1 Mbit/s for 8 MHz channels. We consider 2-TX- and 4-TX-antenna CDD with linear delay increment $\delta_i^{\text{cyc}} = i \times 1.09$ $\mu$s. Results in Reference [19] have shown that no further gain is achievable for the considered channel model if we further increase the cyclic delays $\delta_i^{\text{cyc}}$. The Doppler spectrum of the Rayleigh (non-LOS) components is uniform with a bandwidth of $f_{\text{Dmax}} = 4.464$ Hz, which is 0.1 per cent of the subcarrier spacing and thus negligible in terms of ICI. At the receiver, we assume exact knowledge of the channel states, that is channel estimation is perfect.

In Rayleigh fading channels, CDD provides additional propagation paths, which increases the available diversity. In pure LOS (AWGN), however, these additional propagation paths are static, and thus, transform the AWGN channel into a static frequency selective one, which degrades the system performance. So, the SNR gain turns into a loss if we increase the LOS component in a Ricean channel. This can clearly be seen in Figure 7.

For the indoor Rayleigh fading environment, we get an SNR gain of 3.5 dB at BER $= 2 \times 10^{-4}$ for 2-TX-antenna CDD compared to the 1-TX-antenna case (Figure 7(a)). For the AWGN channel (Figure 7(b)), however, we observe an SNR loss of 6 dB. As CDD is softly switched off, that is $\Delta P$ is increased, the SNR loss decreases significantly and almost vanishes for $\Delta P = 20$ dB. For the Rayleigh fading channel, the SNR gain decreases. For $\Delta P = 10$ dB, the SNR loss reduces by 5.3 to 0.7 dB, whereas the SNR gain for the Rayleigh channel is still 2.3 dB. For $\Delta P \to +\infty$, no signal power is transmitted over the 2nd TX antenna, which yields finally to the single-TX-antenna case.

With soft CDD, we have got the ability to find a compromise between SNR gains and losses in non-LOS respectively LOS scenarios. We define the Ricean factor

$$K = 10 \log \frac{|h|^2}{1 - |h|^2} \text{ (dB)}$$

where $|h|^2$ is the power of the constant part of the channel. We normalise the channel impulse response such that $|h|^2 + \sum_{p=0}^{N_p-1} E(|h_p|^2) = 1$. $|h_p|^2$ are the powers of the Rayleigh fading channel paths. Figure 7 shows the extremal cases ($K = \pm \infty$) of the Ricean channel.

Our interest now is in on the SNR gain/loss in Ricean channels for different Ricean factors $K$. Numerical results for the SNR gain at BER $= 2 \times 10^{-4}$ versus the Ricean factor $K$ are shown in Figure 8 for 2-TX-antenna CDD.

As the power of the LOS propagation path increases (the Ricean factor $K$ increases), the SNR gain vanishes.
and turns over into an SNR loss. This turnover point is at about $K = 6.5\,\text{dB}$ for $\Delta P = 0\,\text{dB}$ and shifts to higher Ricean factors with increasing $\Delta P$. Results in Figure 7 have already indicated the ability of soft CDD to reduce LOS losses significantly. However, the price to pay is a reduction of the SNR gain in non-LOS scenarios, which is relatively small compared to the reduction of the LOS loss.

The diversity power weighting factor $\Delta P$ is an additional parameter for network planning and tuning. In practice, it can be set by network operators in order to trade-off coverage areas for LOS and NLOS reception. Note that this parameter is standard conformable and, therefore, does not require a definition in the standard or even any signalling.

### 4.3. Cellular mobile communications

A method is presented to take advantage of the constellation of neighboring BSs serving the same area, namely their cell borders by applying CDD within these broadcasted regions. This results in a further source of diversity in addition to the existing macro-diversity in such broadcasted areas. Therefore, macro-diversity and TX diversity techniques are combined which transform to cellular diversity.

For the defined broadcast region for users with similar demands or users within soft/softer handover procedures, the CDD principle can be applied within this cellular setup by using adjacent BSs. This leads to the cellular CDD (C-CDD) scheme [7]. The main goal is to increase performance by avoiding interference, using the same sub-carrier resources, and increasing diversity at the most critical areas.

Figure 8. SNR gain of 2-TX CDD compared to 1-TX at BER $= 2 \times 10^{-4}$ versus the Ricean factor $K$, DVB-T 2k-mode, 16-QAM, $R = 3/4$, perfect channel estimation.

Figure 9. Block diagram of the C-CDD principle.

For C-CDD, the neighboring BSs also transmit a copy of the users’ signal as the desired BS to the designated mobile station (MS) located in the broadcast area. Additionally, a cyclic shift is inserted to these signals. A block diagram describes the principle of C-CDD in Figure 9. Therefore, the overall delay of the signal from BS $m$ in the cellular system can be expressed by

$$\delta_m = \delta(d_m) + \delta_m^{\text{cyc}}$$

where $\delta(d_m)$ represents the natural delay of the signal depending on distance $d_m$ of the MS to BS $m$. For C-CDD, no additional configurations at the MS for exploiting the increased TX diversity are necessary and an arbitrary number of involved BSs can be chosen without a rate loss. Transmitting the same signals to the desired MSs from neighboring BS without the CDD principle (i.e. all $\delta_m^{\text{cyc}} = 0$) results in pure macro-diversity within a broadcasted region.

In the following simulation results in Figure 10, a reference OFDM system (without TX diversity) is given for comparison in which two BSs transmit their own signals

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independently. Therefore, the performances degrades by approaching the cell border (carrier-to-interference ratio \(C/I\), \(C/I = 0\ dB\)). The simulation results show the BER performance characteristics by using the standard C-CDD. A large performance gain is given directly at the cell border due to increased TX diversity. For \(C/I = −4.7\ dB\), the elimination of the used cyclic delay \(\delta_1^{\text{cyc}} = 30\) and the inherent delay \(\delta(d_1) = −30\) occurs \(\Rightarrow \delta_1 = 0\), and therefore, a performance degradation exists. Using no cyclic delay \(\delta_1^{\text{cyc}} = 0\), that is pure macro-diversity, results in a performance degradation at the cell border. A random choice of the cyclic delays as described in Subsection 3.1 can compensate the performance loss in the area around \(C/I = −4.7\ dB\). Further details can be found, for example in Reference [20].

4.4. Adaptive bit loading

In this section, we show the benefits of TX-antenna diversity for ABL compared to UBL. In case of UBL, we constantly use 16-QAM modulation. For ABL, we chose a modulation alphabet out of 4-QAM, 16-QAM and 64-QAM (each with Gray mapping) for each subcarrier of an OFDM symbol dependent on the quality of the subcarrier, that is its subcarrier fading coefficient. The constraint for the adaptive allocation of the modulation schemes is to keep the number of transmitted bits equal to UBL for each OFDM frame. For details about the bit loading algorithm, we refer to Reference [21].

We consider a small office environment and use the 802.11n C channel model [11] with NLOS propagation, \(\tau_{\text{max}} = 200\) ns, and bell-shaped Doppler power spectrum (maximum Doppler frequency \(f_{\text{D, max}} ≈ 29\) Hz at a carrier frequency of \(f_c = 5.25\) GHz).

A coded OFDM scheme is assumed employing a rate \(R = 1/2\) convolutional code with generators \((23, 37)_8\), \(N_c = 990\) active subcarriers with \(F_s = 20\) kHz occupying a bandwidth of 19.8 MHz. The resulting OFDM symbol duration is \(T_s = 50\) µs and the sampling time \(T_{\text{samp}} = !T_s/N_{\text{FFT}} = 48.828\) ns, where \(N_{\text{FFT}} = 1024\). We choose a guard interval \(T_{\text{GI}} = 21 \times T_{\text{samp}} ≈ 1.03\) µs. The system transmits \(N_t = 101\) OFDM symbols per frame resulting in a frame duration of 5.15 ms and a data rate of 38.8 Mbps. We assume perfect knowledge of the channel state at both the transmitter and the receiver.

Figure 11 displays the average BERs at the decoder output as a function of the SNR \(E_b/N_0\) for ABL and UBL using Gray mapping. \(E_b/N_0\) is averaged over all subcarriers. Since the total number of bits per frame is the same for ABL and UBL, the mapping of \(E_b/N_0\) to the subcarrier SNR \(E_S/N_0\) is the same for ABL and UBL as well. For an average BER of \(10^{-6}\) and a system without diversity, we observe an SNR gain of about 1.2 dB for the ABL as compared to the UBL. This relative gain increases by using CDD and CDD combined with discontinuous Doppler diversity (DDoD [13]). For \(N_T = 4\), we create two pairs of antennas, where within each pair the second TX signal is cyclically delayed by \(\delta_1^{\text{cyc}} = 10 \times T_{\text{samp}}\). The first pair experiences a discontinuous Doppler shift of \(\Delta f_0 = −583\) Hz and the second one a shift of \(\Delta f_1 = 583\) Hz. The results indicate also that for increasing the number of TX antennas with CDD+DDoD, we approach the lower bounds given by ABL and UBL over an independent Rayleigh (IR) fading channel. Clearly, as the subcarriers are less correlated, ABL exhibits an increasing performance gain compared to UBL, as more independent optimisation choices become available. For an IR fading channel, ABL outperforms UBL by 2.5 dB at an average BER of \(10^{-6}\).

5. SUMMARY

In this paper, we have introduced the principle of CDD. Several modifications and variants have been discussed. Simulation results for a broad variety of wireless communications systems have shown significant gains when applying CDD and its variants compared to single antenna systems. These achievable gains for numerous kinds of wireless communications systems together with its simplicity, flexibility and standard compatibility let CDD appear as an appropriate candidate for both already existing and future wireless communications systems.

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