DADS with short spreading sequences for high data rate communications or improved BER performance

Vincent Le Nir and Bart Scheers

***Abstract*—In this paper, a method is proposed to improve the performance of the delay and add direct sequence (DADS) modulation scheme. On one hand, the selection of a short pseudo-noise (PN) sequence is used to improve the data rate performance. On the other hand, when high data rates are not required, the same short PN sequence is replicated to form a long PN sequence. In this case, noise reduction by averaging is used to improve the bit error rate (BER) for high spreading factors. Theoretical BER formulas are derived and verified by simulations in additive white Gaussian noise (AWGN) and frequency selective Rayleigh channels. The proposed DADS modulation scheme is implemented using the CogWave software to allow the exchange of video, audio and text between two USRPs through a graphical user interface (GUI) developed in Qt4.**

***Index Terms*—Spread spectrum modulation scheme, transmit reference, non-coherent detection**

I. INTRODUCTION

Delay and add direct sequence (DADS) is a digital modulation scheme in which a pseudo-noise (PN) sequence is used on one hand as an embedded reference signal, and on the other hand for modulating the data information [1], [2]. This modulation scheme provides a processing gain and therefore inherits the advantages of conventional spread-spectrum communications such as multipath mitigation, anti-jamming, and multiple access capabilities. Moreover, the DADS modulation scheme has a very simple receiver structure with no carrier recovery which can exploit the multipath diversity of frequency selective channels, contrary to conventional spread-spectrum receivers in which several Rake fingers are needed along with carrier recovery [3]. However, it can be observed that the bit error rate (BER) performance degrades as the length of the PN sequence increases, making DADS less attractive for high spreading factors.

In this paper, a method is proposed to improve the performance of the DADS modulation scheme. On one hand, the selection of a short pseudo-noise (PN) sequence is used to improve the data rate performance. The use of short PN sequences reduces the advantages of DADS for anti-jamming and multiple access capabilities but keeps the advantages for multipath mitigation and receiver simplicity. On the other hand, when high data rates are not required, the same short PN sequence is replicated to form a long PN sequence. In this case, noise reduction by averaging is used to improve the bit error rate (BER). Theoretical BER formulas are derived for additive white Gaussian noise (AWGN) and frequency selective Rayleigh channels. It is shown that with noise reduction by averaging, the BER performance of DADS no longer degrades as the length of the PN sequence increases. It is also shown that the multipath diversity of frequency selective channels is exploited without any modification in the receiver structure. Theoretical BER formulas are verified by simulations in AWGN and frequency selective Rayleigh channels.

The proposed DADS modulation scheme is implemented using the CogWave software [4]. CogWave is a free and open-source software platform aiming at developing cognitive radio waveforms. The CogWave software allows the exchange of video, audio and text between two USRPs through a graphical user interface (GUI) developed in Qt4/Gstreamer. The USRP hardware driver (UHD) C++ application programming interface (API) allows to receive and transmit IQ samples. Combining CogWave with USRP gives a rapid prototyping platform for physical layer design and algorithm validation through a real-time video, audio and text transmission.

The remainder of this paper is organized as follows. In Section II, we derive the theoretical BER formulas with the selection of a short PN sequence and the selection of a long PN sequence using noise reduction by averaging in AWGN channels. The theoretical BER formulas are compared with simulations. In Section III, we derive the theoretical BER formulas with the selection of a short PN sequence and the selection of a long PN sequence using noise reduction by averaging in frequency selective channels. A comparison between theoretical and simulated BER performance is also performed. In section IV, some details are provided about the implementation of the proposed DADS modulation scheme using the CogWave software to allow the exchange of video, audio and text between two USRPs through a graphical user interface (GUI) developed in Qt4/Gstreamer. Finally, Section V concludes this paper.

II. THEORETICAL VS SIMULATED BER PERFORMANCE OF DADS IN AWGN CHANNELS

A. Selection of a Short Pseudo Noise Sequence for DADS

The transmission chain of the DADS modulation scheme with the selection of a short PN sequence is shown in Figure 1. Assuming that K bits have to be transmitted, the PN sequence of length M is repeated K times to form the reference signal. The transmitted signal is the sum of two signals, namely the reference signal and its delayed version multiplied by the information signal. Considering an AWGN channel, the received signal r_i can be modeled as

$$r_i = d_k x_{i-D} + x_i + n_i \tag{1}$$

with D the delay (in chips), d_k the information bits taking values in {-1,1} with data rate $1/M$, x_i the transmitted chip of the PN sequence and n_i the AWGN with variance $N_0/2$ per dimension. The selection of a short PN sequence whose length M is twice the delay D used in the modulation scheme

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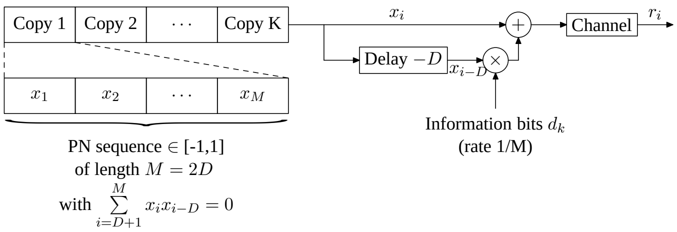


Fig. 1. Transmission chain of the DADS modulation scheme with the selection of a short PN sequence

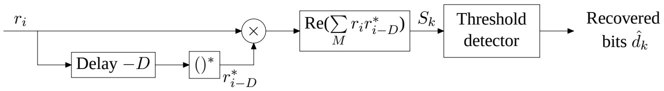


Fig. 2. Reception chain of the DADS modulation scheme

($M = 2D$) is given by [2]

$$\text{select } \{x_i\} = \begin{cases} x_i = x_{i-2D} & \forall i \\ \sum_{i=D+1}^{M} x_i x_{i-D} = 0 & \end{cases} . \quad (2)$$

A PN sequence satisfying this criterion can be easily generated from the 2^M possible codes. The ratio between the number of codes satisfying the auto-correlation criterion and the total number of codes 2^M for delays $D = 2, 4, 6, 8$ are 0.5, 0.375, 0.3125, and 0.2734 respectively. The reception chain of the DADS modulation scheme is shown in Figure 2. The correlator output is given by

$$S_k = \mathrm{Re}\left(\sum_{i=(k-1)M+D+1}^{kM} r_i r^*_{i-D} \right) \quad (3)$$

with

$$\begin{aligned} r_i r^*_{i-D} = & \underbrace{d_k(x^2_{i-D} + x^2_i)}_{\text{useful part } a_i} + \underbrace{2 x_i x_{i-D}}_{\text{interference part } b_i} \\ & \underbrace{+(d_k x_{i-D} + x_i) n^*_{i-D} + n_i(d_k x_i + x_{i-D}) + n_i n^*_{i-D}}_{\text{noise part } c_i} \end{aligned} . \quad (4)$$

The correlator output can be divided into a useful, interference and noise parts

$$\{A_k, B_k, C_k\} = \mathrm{Re}\left(\sum_{i=(k-1)M+D+1}^{kM} \{a_i, b_i, c_i\} \right) . \quad (5)$$

Assuming that the correlator output approaches a Gaussian distribution, the bit error rate (BER) performance can be expressed analytically as [5]

$$\begin{aligned} BER &= \frac{1}{2}\Big[\mathrm{Prob}(S_k < 0 | d_k = +1) \\ &\quad + \mathrm{Prob}(S_k \geq 0 | d_k = -1) \Big] \\ &= \frac{1}{4} \operatorname{erfc}\left(\frac{E[S_k | d_k = +1]}{\sqrt{2(var[S_k | d_k = +1])}} \right) \\ &\quad + \frac{1}{4} \operatorname{erfc}\left(\frac{-E[S_k | d_k = -1]}{\sqrt{2(var[S_k | d_k = -1])}} \right) \end{aligned} \quad (6)$$

with erfc(.) the complementary error function. A_k and B_k are deterministic values. For large M, the correlator output approaches a Gaussian distribution with mean and variance

$$\begin{aligned} E[S_k] &= A_k + B_k + E[C_k] \\ var[S_k] &= var[C_k] \end{aligned} . \quad (7)$$

The integrated useful part A_k, interference part B_k and the mean of the noise part C_k are given by

$$\begin{aligned} A_k &= 2 d_k (M - D) P_s \\ B_k &= 0 \\ E[C_k] &= 0 \end{aligned} \quad (8)$$

with P_s the energy per chip and the variance of the noise part C_k is given by

$$var[C_k] = 4(M - D) P_s \tfrac{N_0}{2} + (M - D) \tfrac{N_0^2}{2} . \quad (9)$$

Knowing that a transmitted data bit is the sum of two sequences of length M, the energy per bit E_b can be written as $E_b = 2MP_s$, the derivation of the BER formula leads to the following expression [2]

$$BER = \frac{1}{2} \operatorname{erfc}\left(\sqrt{ \frac{\frac{M-D}{M} E_b}{2N_0 \left(1 + \frac{MN_0}{2E_b}\right)} } \right) . \quad (10)$$

Figure 3 shows the BER performance of the DADS modulation scheme with the selection of a short PN sequence for different values of M in AWGN channels. For small values of M (4 and 16), theoretical and simulated curves do not match since the Gaussian approximation is not satisfied. In this case, simulated curves perform better than theoretical ones. For large values of M (64 and 256), theoretical and simulated curves are similar.

B. Selection of a Long Pseudo Noise Sequence for DADS and noise reduction by averaging

The transmission chain of the DADS modulation scheme with selection of a long PN sequence is shown in Figure 4. The selection of a long PN sequence can be easily generated from the repetition of the short PN sequence selected with criterion (2) whose length N is twice the delay D used in the modulation scheme ($N = 2D$). The selected short PN sequence is repeated T times to form the long PN sequence of length M.

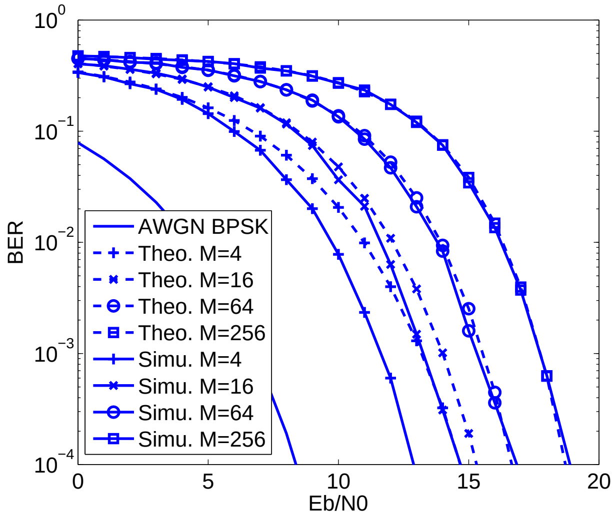


Fig. 3. Comparison between theoretical and simulated DADS modulation scheme with the selection of a short PN sequence in AWGN channels

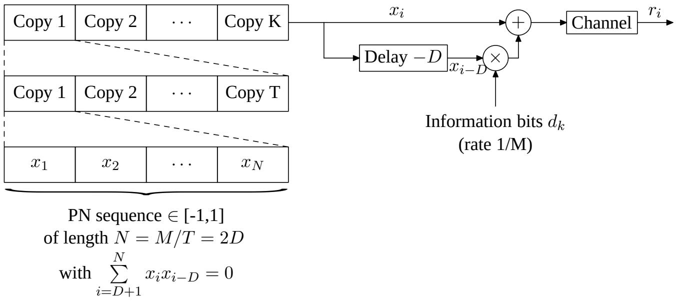


Fig. 4. Transmission chain of the DADS modulation scheme with selection of a long PN sequence

The demodulation algorithm can exploit the redundancy of the PN sequence by averaging the received noisy chips in the same bit as shown in Figure 5. The idea is then to correlate the delayed version of the received signal with its enhanced version. Assuming that the PN sequence of length N has been repeated T times, the enhanced received signal can be generated by averaging the T chips

$$\begin{aligned}\hat{r}_i &= \frac{1}{T}\sum_{t=1}^{T} r_{j+(t-1)N} \\ \hat{r}_i &= \frac{1}{T}\sum_{t=1}^{T} (d_k x_{j+(t-1)N-D} + x_{j+(t-1)N} + n_{j+(t-1)N})\end{aligned} \tag{11}$$

with $j = i \mod N$. Knowing that $x_i = x_{i-2D}$ and $N = 2D$, this can be rewritten as

$$\hat{r}_i = d_k x_{i-D} + x_i + \frac{1}{T}\sum_{t=1}^{T} n_{j+(t-1)N} \quad . \tag{12}$$

The correlator output becomes

$$S_k = \mathrm{Re}\left(\sum_{i=(k-1)M+D+1}^{kM} \hat{r}_i r^*_{i-D}\right) \tag{13}$$

with

$$\hat{r}_i r^*_{i-D} = \underbrace{d_k(x^2_{i-D} + x^2_i)}_{\text{useful part } a_i} + \underbrace{2x_i x_{i-D}}_{\text{interference part } b_i} \\ \underbrace{+ d_k x_{i-D} n^*_{i-D} + x_i n^*_{i-D} + \frac{1}{T}\sum_{t=1}^{T} n_{j+(t-1)N}(d_k x_i + x_{i-D}) + \frac{1}{T}\sum_{t=1}^{T} n_{j+(t-1)N} n^*_{i-D}}_{\text{noise part } c_i} \quad . \tag{14}$$

We assume that $D \ll M$. The integrated useful part A_k, interference part B_k and the mean of the noise part C_k are given by

$$\begin{aligned} A_k &= 2d_k M P_s \\ B_k &= 0 \\ E[C_k] &= 0 \end{aligned} \tag{15}$$

with P_s the energy per chip and the variance of the noise part C_k given by

$$var[C_k] = 4MP_s\frac{N_0}{2} + 2N\frac{N_0^2}{2} \tag{16}$$

leading to the following BER

$$BER = \frac{1}{2}\,\mathrm{erfc}\left(\sqrt{\frac{E_b}{2N_0\left(1 + \frac{NN_0}{E_b}\right)}}\right) \quad . \tag{17}$$

Figure 6 shows the BER performance of the DADS modulation scheme with the selection of a long PN sequence for $M = 4096$ and different values of N in AWGN channels. The difference between theoretical and simulated BER curves is very small. Simulations show that the same performance is obtained for any value of $M = NT$. With noise averaging, the BER performance no longer degrades as M increases. As the BER performance still degrades as N increases, the delay D should be kept as small as possible.

III. THEORETICAL VS SIMULATED BER PERFORMANCE OF DADS IN FREQUENCY SELECTIVE RAYLEIGH CHANNELS

A. *Short Pseudo Noise Sequence for DADS*

We consider a frequency selective channel with AWGN. The received signal r_i can be modeled as

$$r_i = \sum_{l=0}^{L-1} h_l\left(d_k x_{i-l-D} + x_{i-l}\right) + n_i \tag{18}$$

with L the number of taps and h_l the complex-valued channel attenuation for the l^{th} tap. (4) can be re-written as

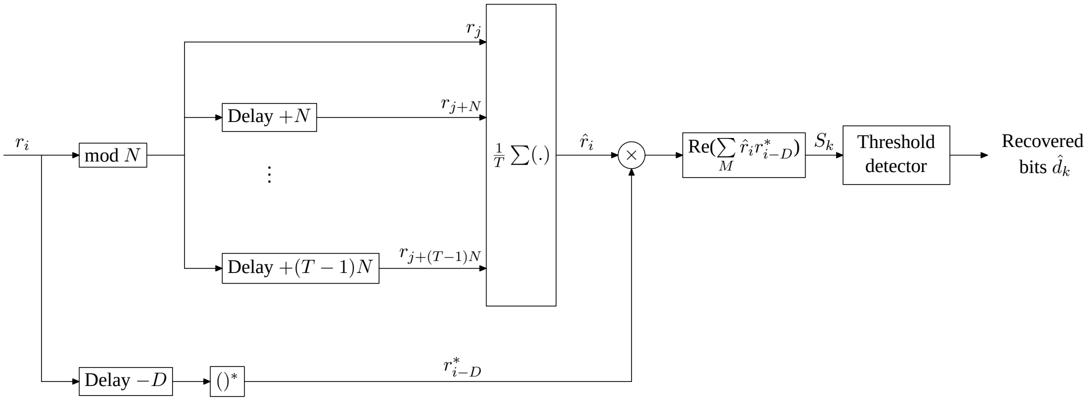


Fig. 5. Generic receiver exploiting noise reduction by averaging in DADS

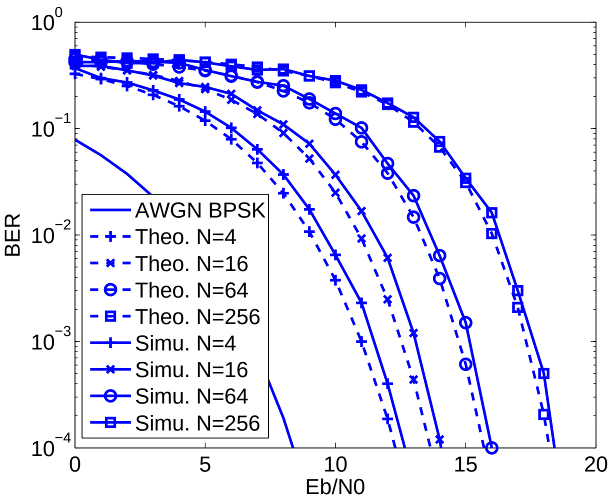


Fig. 6. Comparison between theoretical and simulated DADS modulation scheme with the selection of a long PN sequence in AWGN channels

$$\begin{aligned} r_i r^*_{i-D} = & \underbrace{d_k \sum_{l=0}^{L-1} |h_l|^2 (x^2_{i-l-D} + x^2_{i-l})}_{\text{useful part } a_i} \\ & \underbrace{+2 \sum_{l=0}^{L-1} |h_l|^2 x_{i-l} x_{i-l-D} + \sum_{l=0}^{L-1} \sum_{l' \neq l} h_l h^*_{l'} (d_k x_{i-l-D} + x_{i-l})(d_k x_{i-l'} + x_{i-l'-D})}_{\text{interference part } b_i} . \\ & \underbrace{+ \sum_{l=0}^{L-1} h_l n^*_{i-D} (d_k x_{i-l-D} + x_{i-l}) + \sum_{l=0}^{L-1} h^*_l n_i (d_k x_{i-l} + x_{i-l-D}) + n_i n^*_{i-D}}_{\text{noise part } c_i} \end{aligned} \tag{19}$$

A_k is a deterministic value. We assume that the cross-correlation between the interference part B_k and the noise part C_k is zero and we assume that $\tau_{max} \leq D$ with τ_{max} the maximum delay spread. The correlator output approaches a Gaussian distribution for large M with mean and variance

$$\begin{aligned} E[S_k] &= A_k + E[B_k] + E[C_k] \\ var[S_k] &= var[B_k] + var[C_k] \end{aligned} \tag{20}$$

The integrated useful part A_k, the mean of the interference part B_k and the mean of the noise part C_k are given by

$$\begin{aligned} A_k &= 2 d_k \sum_{l=0}^{L-1} |h_l|^2 (M-D) P_s \\ E[B_k] &= 0 \\ E[C_k] &= 0 \end{aligned} \tag{21}$$

with P_s the energy per chip and the variance of the interference part B_k and the variance of the noise part C_k are given by

$$\begin{aligned} var[B_k] &= 4 \sum_{l=0}^{L-1} |h_l|^4 (M-D) P_s^2 \\ &\quad +4 \sum_{l=0}^{L-1} \sum_{l' \neq l} |h_l|^2 |h_{l'}|^2 (M-D) P_s^2 . \\ var[C_k] &= 4 \sum_{l=0}^{L-1} |h_l|^2 (M-D) P_s \tfrac{N_0}{2} + (M-D) \tfrac{N_0^2}{2} \end{aligned} \tag{22}$$

The derivations of the BER formula give the following expression

$$BER = \frac{1}{2} E_{h_l} \left[\text{erfc} \left(\sqrt{ \frac{ \frac{M-D}{M} \sum_{l=0}^{L-1} |h_l|^2 E_b }{ 2 N_0 \Gamma } } \right) \right] \tag{23}$$

with

$$\Gamma = 1 + \frac{ \sum_{l=0}^{L-1} |h_l|^4 E_b }{ \sum_{l=0}^{L-1} |h_l|^2 M N_0 } + \frac{ M N_0 }{ 2 \sum_{l=0}^{L-1} |h_l|^2 E_b } + \frac{ \sum_{l=0}^{L-1} \sum_{l' \neq l} |h_l|^2 |h_{l'}|^2 E_b }{ \sum_{l=0}^{L-1} |h_l|^2 M N_0 } . \tag{24}$$

Figure 7 shows the BER performance of the DADS modulation scheme with the selection of a short PN sequence $M = 64$ for different values of L in frequency selective Rayleigh channels. The maximum delay spread τ_{max} is set to the number of taps L. Theoretical and simulated curves are very similar. One can observe that the DADS modulation scheme can exploit the multipath diversity of frequency selective channels without any modification in the receiver structure. The performance of the DADS modulation scheme with the selection of a short PN

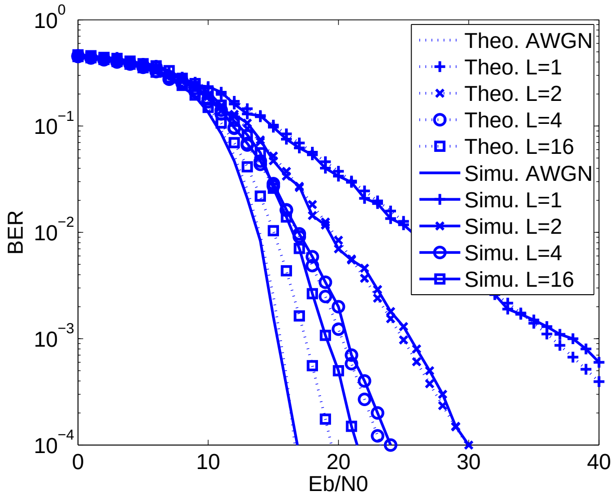


Fig. 7. Comparison between theoretical and simulated DADS modulation scheme with the selection of a short PN sequence in frequency selective Rayleigh channels ($M = 64$)

sequence in frequency selective Rayleigh channels approaches the AWGN performance as L increases.

B. Long Pseudo Noise Sequence for DADS

The enhanced received signal can be generated by averaging the T chips leading to the following formula

$$\hat{r}_i = \sum_{l=0}^{L-1} h_l(d_k x_{i-l-D} + x_{i-l}) + \frac{1}{T}\sum_{t=1}^{T} n_{j+(t-1)N} \quad (25)$$

The enhanced received signal multiplied by the conjugate delayed version of the received signal gives

$$\begin{aligned}\hat{r}_i r^*_{i-D} \;=\; & \underbrace{d_k \sum_{l=0}^{L-1} |h_l|^2 (x^2_{i-l} + x^2_{i-l-D})}_{\text{useful part } a_i} \\ & \underbrace{+2\sum_{l=0}^{L-1} |h_l|^2 x_{i-l} x_{i-l-D} + \sum_{l=0}^{L-1}\sum_{l'\neq l} h_l h^*_{l'} (d_k x_{i-l-D} + x_{i-l})(d_k x_{i-l'} + x_{i-l'-D})}_{\text{interference part } b_i} \\ & \underbrace{+\sum_{l=0}^{L-1} h_l (d_k x_{i-l-D} + x_{i-l}) n^*_{i-D} + \frac{1}{T}\sum_{t=1}^{T}\sum_{l=0}^{L-1} h^*_l n_{j+(t-1)N}(d_k x_{i-l} + x_{i-l-D}) + \frac{1}{T}\sum_{t=1}^{T} n_{j+(t-1)N} n^*_{i-D}}_{\text{noise part } c_i}\end{aligned} \quad (26)$$

We assume that the cross-correlation between the interference part B_k and the noise part C_k is zero and we assume that $\tau_{max} \leq D \ll M$. The integrated useful part A_k, the mean of the interference part B_k and the mean of the noise part C_k are given by

$$\begin{aligned} A_k &= 2 d_k \sum_{l=0}^{L-1} |h_l|^2 M P_s \\ E[B_k] &= 0 \\ E[C_k] &= 0 \end{aligned} \quad (27)$$

with P_s the energy per chip and the variance of the interference part B_k and the mean of the noise part C_k are given by

$$\begin{aligned} var[B_k] &= 4\sum_{l=0}^{L-1}\sum_{l'\neq l} |h_l|^2 |h_{l'}|^2 M P_s^2 \\ var[C_k] &= 4\sum_{l=0}^{L-1} |h_l|^2 M P_s \tfrac{N_0}{2} + 2N\tfrac{N_0^2}{2} \end{aligned} \quad (28)$$

leading to the following BER

$$BER = \frac{1}{2} \underset{h_l}{E}\left[\operatorname{erfc}\left(\sqrt{\frac{E_b}{2N_0\Gamma}}\right)\right] \quad (29)$$

with

$$\Gamma = 1 + \frac{\sum_{l=0}^{L-1}\sum_{l'\neq l} |h_l|^2 |h_{l'}|^2 E_b}{\sum_{l=0}^{L-1} |h_l|^2 M N_0} + \frac{N N_0}{\sum_{l=0}^{L-1} |h_l|^2 E_b} \quad (30)$$

Figure 8 shows the BER performance of the DADS modulation scheme with the selection of a long PN sequence with $N = 64$ and $M = 4096$ for different values of L in frequency selective Rayleigh channels. Theoretical and simulated BER curves are very similar. Simulations show that the same performance is obtained for any value of $M = NT$. The multipath diversity of frequency selective channels is also exploited without any modification in the receiver structure. Moreover, with noise averaging, the BER performance no longer degrades as M increases. As the BER performance still degrades as N increases, the delay D should be kept as small as possible but larger than the maximum delay spread τ_{max}. The performance of the DADS modulation scheme with the selection of a long PN sequence in frequency selective Rayleigh channels approaches the AWGN performance as L increases.

IV. IMPLEMENTATION OF THE PROPOSED DADS MODULATION SCHEME USING THE COGWAVE SOFTWARE

The proposed DADS modulation scheme is implemented using the CogWave software [4]. CogWave is a free and open-source software platform aiming at developing cognitive radio waveforms. The CogWave application allows the exchange of video, audio and text between two USRPs through a graphical user interface (GUI) developed in Qt4/Gstreamer and cognitive radio waveforms developed in IT++. The USRP hardware driver (UHD) C++ application programming interface (API) allows to receive and transmit IQ samples. Combining CogWave with USRP gives a rapid prototyping platform for physical layer design and algorithm validation through a real-time video, audio and text transmission.

Figure 9 shows the demonstrator setup of 2 host PCs connected to 2 USRPs and the exchange of data with the CogWave software using the DADS modulation scheme in FDD mode. The sampling rates for both USRPs are 1 Msps. The carrier frequencies are 433.92 MHz and 443.92 MHz respectively. A short PN sequence of length $M = 4$ is chosen. At the transmitter, the CogWave software takes some text, audio or

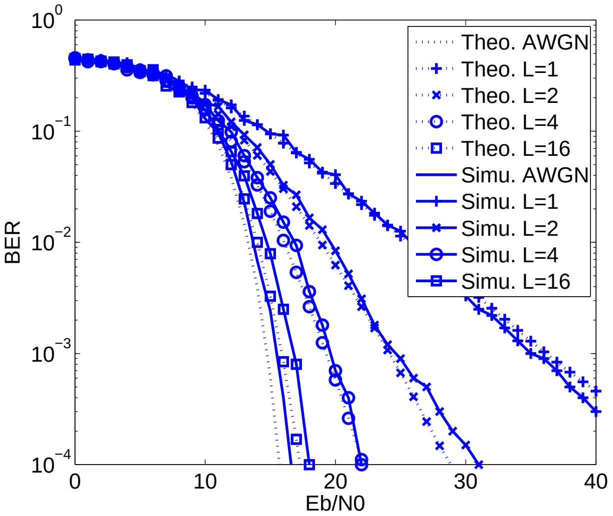
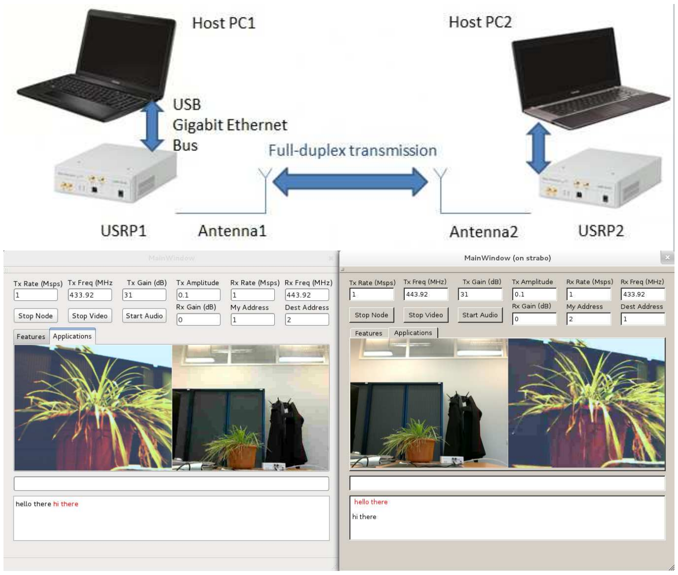


Fig. 8. Comparison between theoretical and simulated DADS modulation scheme with the selection of a long PN sequence in frequency selective Rayleigh channels ($N = 64$)



Tx Rate (Msps)	Tx Freq (MHz	Tx Gain (dB)	Tx Amplitude	Rx Rate (Msps)	Rx Freq (MHz)
1	433.92	31	0.1	1	443.92
			Rx Gain (dB)	My Address	Dest Address
			0	1	2

hello there hi there

Tx Rate (Msps)	Tx Freq (MHz)	Tx Gain (dB)	Tx Amplitude	Rx Rate (Msps)	Rx Freq (MHz)
1	443.92	31	0.1	1	433.92
			Rx Gain (dB)	My Address	Dest Address
			0	2	1

hello there

hi there

Fig. 9. Demonstrator setup and CogWave software using the DADS modulation scheme

video from keyboard, microphone or web-cam input sources. Cyclic redundancy check (CRC) and forward error correction (FEC) are used to detect and to correct errors between a frame's preamble and postamble. Each bit is multiplied with a delayed version of the PN sequence and added to the same PN sequence. The resulting data is passed to the USRP via UHD for continuous transmission at the selected carrier frequency, sampling rate and transmit gain. At the receiver, the received samples are captured by the USRP via UHD in continuous mode at the selected carrier frequency, sampling rate and receive gain. The received buffer is set to the number of samples in a frame. The demodulation multiplies the received samples by their conjugate delayed version. Noise reduction by averaging is used in the case of long PN sequences. A time offset correction is then performed by estimating the offset corresponding to the maximum energy of the soft bit sequence.

The hard bit sequence is then used to detect the frame's preamble and postamble, and within the frame to detect and to correct errors by CRC and FEC. Once the start of frame is detected, the received buffer is adjusted such that the start of frame is also the start of received buffer. Finally, the CogWave software puts some text, audio or video to the display or speaker output sinks. The same operation is done in opposite direction on a different carrier frequency for a FDD mode.

V. CONCLUSION

In this paper, a method has been proposed to improve the performance of the delay and add direct sequence (DADS) modulation scheme. On one hand, the selection of a short pseudo-noise (PN) sequence has been used to improve the data rate performance. The use of short PN sequences has reduced the advantages of DADS for anti-jamming and multiple access capabilities but has kept the advantages for multipath mitigation and receiver simplicity. On the other hand, when high data rates are not required, the same short PN sequence has been replicated to form a long PN sequence. In this case, noise reduction by averaging has been used to improve the bit error rate (BER) for higher spreading factors. Theoretical BER formulas have been derived and verified by simulations in additive white Gaussian noise (AWGN) and frequency selective Rayleigh channels. It has been shown that with noise reduction by averaging, the BER performance of DADS no longer degrades as the length of the PN sequence increases. It has also been shown that the multipath diversity of frequency selective channels is exploited without any modification in the receiver structure. The proposed DADS modulation scheme has been implemented using the CogWave software to allow the exchange of video, audio and text between two USRPs through a graphical user interface (GUI) developed in Qt4. Future work will focus on the addition of cognitive features to the DADS modulation scheme, such as the capability to adjusts dynamically the spreading factor M for more robustness or the central frequency used for transmission by sensing its operational electromagnetic environment.

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