Space-Time-Frequency Trellis Coding for Multiband OFDM Ultra Wideband Wireless Systems

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Abstract— **In this paper, the application of space time trellis codes to multiband orthogonal frequency division multiplexing ultra-wideband (MB-OFDM UWB) systems is investigated. We propose a coding scheme that could fully exploit all the available channel diversity, including space diversity, frequency diversity and inter-subband diversity. Performance of the proposed system is compared with that of the conventional MB-OFDM UWB system in terms of packet error rate (PER). Simulation results show that this system outperforms the conventional one. As an example, an improvement of at least 5 dB at PER=10^{-2} could be achieved over the IEEE 802.15.3a channel models of CM1 and CM2 in the system equipped with only two transmit antennas and one receive antenna. Moreover, the system performance could be further improved when the number of antennas and/or the number of trellis states is increased.**

Keywords- STTCs; Space-Time-Frequency coding; MB-OFDM UWB; IEEE 802.15.3a

I. INTRODUCTION

Ultra wideband (UWB) wireless systems have attracted extensive attention to provide high data rates with low cost and low power consumption [1]. One of the promising candidates for the physical layer of UWB is Multiband OFDM (MB-OFDM) [2]. On the other hand, Multiple Input Multiple Output (MIMO) technique which is based on space time codes, such as space time block codes (STBC) or space time trellis codes (STTC), could significantly improve system capacity [3]. Therefore, the combination of these technologies may be an attractive solution to satisfy the demand of future personal wireless applications.

One of the efficient schemes for incorporating space time codes into OFDM systems is in the form of space time frequency (STF) coding [4]. The investigations of STF coded MB-OFDM UWB systems have been mentioned in the literature, such as [5] and [6]. In [5], the authors proposed a coding framework for MIMO UWB systems. They quantified the system performance regardless of specific coding schemes in the case of Nakagami-*m* frequency selective fading channels. The authors in [6] examined the performance and derived the design criteria for STF codes in the proposed STF coded MB-OFDM UWB system under the channels with the log-normal distribution. However, this work was basically based on the space time block codes.

It is well known that STTC could offer both coding gain and full diversity while STBC provide no coding gain [7]. To take advantage of coding gain, there have been some works considering the application of STTC in OFDM systems, such as [8], [9]. However, in all these systems, the space frequency coding scheme rather than space time frequency coding is implemented. Intuitively, when considering STTC coding for the MB-OFDM UWB system, the implementation of space frequency coding scheme may not fully exploit the available inter-subband diversity provided by the hopping mechanism.

In this paper, we propose a Space-Time-Frequency Trellis coded MB-OFDM UWB (STFTC MB-OFDM UWB) system by incorporating STTC into the standard MB-OFDM UWB system for the middle data-rate ranges of 100Mbps, 160Mbps and 200Mbps. Utilizing the time-domain spreading factor of two and the subband hopping characteristic, we implement a coding scheme that could exploit all the channel diversities richly inherent in ultra wideband environments. We also propose a modified brand metric that is used in the Viterbi algorithm for decoding signals. It will be shown via simulation that the STFTC MB-OFDM UWB system achieves a significant improvement in performance compared to the conventional system.

The rest of the paper is organized as follows. In Section II, we briefly review space time trellis codes and the WiMedia MB-OFDM PHY specifications. In Section III, we describe in detail the proposed STFTC MB-OFDM UWB system. Simulation results are then provided in Section IV. Finally, Section V concludes the paper.

II. BACKGROUNDS

A. Space Time Trellis Codes

Space time trellis code (STTC) is a joint design of channel coding, modulation and transmit diversity, which could

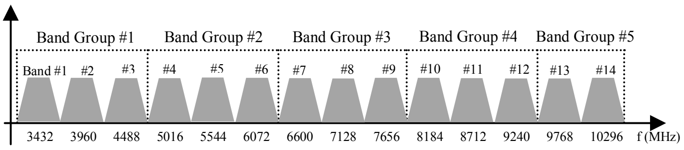


Fig. 1 MB-OFDM band group allocation

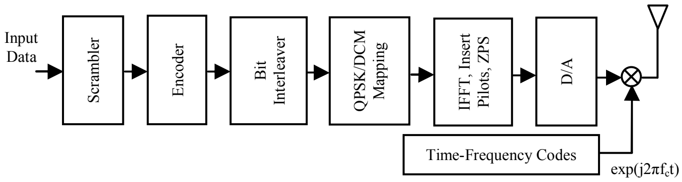


Fig. 2 Transmit architecture for a MB-OFDM system

achieve a large diversity, high spectral efficiency as well as significant coding gain. STTC was first introduced by Tarokh *et al.* for narrowband systems over flat fading channels [10]. However, the codes in [10] were manually derived and not optimal with respect to coding gain. Consequently, optimal codes for different system configurations and channel conditions have been reported, such as in [11]-[14].

We now describe encoding and decoding operations. We consider a system with M-PSK constellation, n_T transmit antennas and n_R receive antennas. At the transmitter, an input data stream is divided into $m = log_2 M$ parallel streams. The M-PSK STTC encoder, which consists of m branches, takes these streams as its input. Denote a vector of m binary input bits that were fed into the STTC encoder at time t to be $\mathbf{c}^t = (c_1^t, c_2^t, ..., c_m^t)^T$, where the operation $(.)^T$ represents the transpose. The vector of symbols generated by the encoder at time t is $\mathbf{w}^t = (w_1^t, w_2^t, ..., w_{n_T}^t)^T$, where each symbol is computed as $w_i^t = \sum_{k=1}^{m} \sum_{s=1}^{v_k} g_{s,i}^k c_k^{t-s} \bmod M$, $i = 1,2,...,n_T$. In this formula, $\{g_{s,i}^k\}$ is the generator coefficient of the encoder, v_k is the memory order of the k-th branch and is computed as $v_k = \left\lfloor \frac{v+k-1}{m} \right\rfloor$, where $v = \sum_{k=1}^{m} v_k, k = 1,2,...,m$, is the total memory order of the encoder and $\lfloor . \rfloor$ is the floor function. The symbol $w_i^t, i = 1,...,n_T$ is then mapped onto the M-PSK constellation. The resulting modulated symbol, denoted as $x_i^t, i = 1,...,n_T$, is transmitted through the i-th transmit antenna. Note that all the symbols $\{x_1^t, x_2^t, ..., x_{n_T}^t\}$ are transmitted simultaneously through n_T transmit antennas. This M-PSK STTC code has the total number of states of 2^v and achieves a bandwidth efficiency of m bits/s/Hz.

STTC is often described through a set of m generator coefficient sequences $\{\mathbf{g}^k\}, k = 1,2,...,m$, where

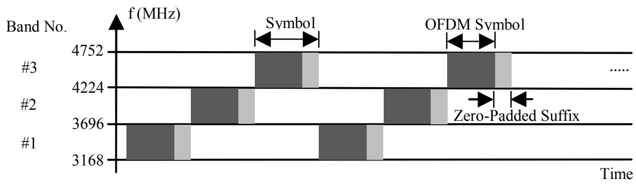


Fig. 3 A time-frequency hopping pattern for a MB-OFDM system

$$\mathbf{g}^k = [(g_{0,1}^k, g_{0,2}^k, ..., g_{0,n_T}^k), ..., (g_{v_k,1}^k, g_{v_k,2}^k, ..., g_{v_k,n_T}^k)]$$

For example, optimal 4-state and 16-state 4-PSK STTCs for a system with two transmit antennas over flat fading channels respectively are [3]

$$\mathbf{g}^1 = [(0,2),(1,0)]; \mathbf{g}^2 = [(2,2),(0,1)]$$

$$\mathbf{g}^1 = [(0,2),(1,2),(2,2)]; \mathbf{g}^2 = [(2,0),(1,1),(0,2)]$$

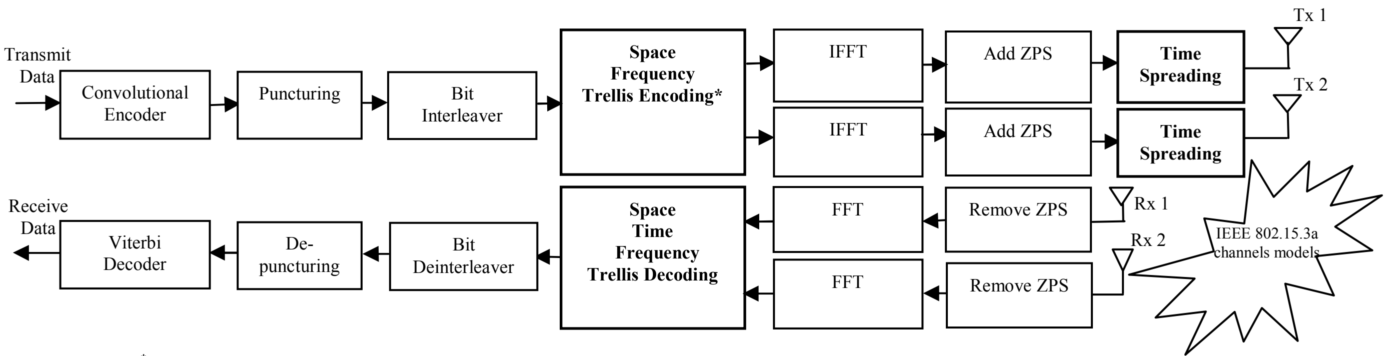
At the receiver, the Viterbi algorithm is employed to perform maximum likelihood decoding. The sequence corresponding to the path with minimum path metric is selected as the received signal.

B. *Overview of MB-OFDM UWB PHY Layer Specifications*

In this subsection, we briefly review the specifications of WiMedia MB-OFDM system [15]. In MB-OFDM approach, the entire UWB spectrum between 3.1-10.6 GHz is divided into 14 subbands, each has a bandwidth of 528 MHz. These subbands are grouped into 5 band groups as shown in Fig. 1.

The physical layer architecture of MB-OFDM system is similar to that of conventional OFDM, except that the carrier frequency changes from one OFDM symbol to another. The block diagram of MB-OFDM transmitter is depicted in Fig. 2. Accordingly, information data are first scrambled, encoded, interleaved, and then mapped onto QPSK or DCM (Dual Carrier Modulation) constellation. The resulting data are fed into an IFFT block to generate OFDM symbol. The total number of subcarriers in each OFDM symbol is 128, of which, there are 100 data subcarriers, 12 pilot subcarriers, 10 guard subcarriers, and the rest are null subcarriers.

With respect to some characteristics the MB-OFDM system differs from the conventional OFDM system. First, a zero-padded suffix of length 37 is used to mitigate the effects of multipath as well as provide a guard interval for transceivers switching from one subband to another. Second, time and/or frequency repetitions are deployed to enhance the system performance. These repetition (or spreading) factors, together with conventional coding rates, determine the different data rates that the system can support, such as 160 Mbps, 200 Mbps, and 480 Mbps. Third, the MB-OFDM system transmits symbols using different subbands specified by time-frequency codes (TFCs). These TFCs are used not only for providing frequency diversity but also for multiple



* The combination between space frequency trellis encoding and time spreading is considered as space time frequency trellis encoding in this system.

Fig. 4 Block diagram of the proposed STFTC MB-OFDM UWB system

access purpose. An example of a frequency hopping pattern within the band group 1 is given in Fig.3. Finally, wireless channels in a MB-OFDM UWB system follow a log-normal distribution, rather than the Rayleigh distribution.

III. STFTC MB-OFDM UWB SYSTEM

In this section, we present the proposed Space-Time-Frequency Trellis coded MB-OFDM UWB (STFTC MB-OFDM UWB) system. We consider a system with *M*-PSK constellation, n_T transmit antennas and n_R receive antennas. Basically, the proposed system is based on the conventional MB-OFDM UWB system for medium data rates. A simplified block diagram of this system with two transmit antennas and two receive antennas is depicted in Fig. 4. As highlighted in the diagram, this system differs from the conventional system with respect to the followings. At the transmitter, a space-frequency trellis encoder that encodes data over space and frequency dimensions is added. As a time domain spreading feature already exists in the considered conventional system, the combination of the space-frequency trellis encoding and time spreading is referred to as a space-time-frequency trellis (STF) encoding scheme. In the diagram, the position of the time spreading block is chosen for the purpose of minimizing computational complexity. At the receiver, a STF trellis decoder is used to decode STF coded signals. In addition, symbol interleavers and deinterleavers are incorporated into this system as an option. Their purpose is to improve the system performance as recommended in [8]. The operation of this system is described below.

At the transmitter, the data bit stream is first encoded, punctured, and interleaved. The resulting signal is then fed into a space-frequency trellis coding encoder. This encoder encodes signals frame by frame. For each frame, the encoder adds tail bits into the data frame to make sure that it always starts from state zero and finishes at state zero. We now consider a data frame of $L\times m$ information bits, where L is the number of information data subcarriers in an OFDM symbol and $m = log_2 M$. At the encoder, the input data bit sequence of the l-th data frame is first converted into m parallel data sequences. Next, the space time trellis encoding process, as described in Section II.A, takes these data sequences, and produces n_T complex-valued sequences, denoted as $\mathbf{x}_i^l = [x_i^l(0), x_i^l(1),..., x_i^l(L+Q-1)],\ i = 1,2,..,n_T$, where Q is the number of trellis transitions that occurs due to adding tail bits. If the system employs the symbol interleavers, the interleaving activity applies directly to each of these symbol sequences. The output sequence from each interleaver is then fed into each 128-point IFFT block. Note that the transmitter will insert pilot and guard subcarriers before taking IFFT operation. The IFFT output is added with a zero-padded suffix (ZPS) to form a MB-OFDM symbol. In this system, there are only L subcarriers that carry information data within each MB-OFDM symbol. Denote $\mathbf{s}_i^l, i = 1,2,..,n_T$ to be the MB-OFDM symbol transmitted at the i-th transmit antenna. The time domain spreading is achieved by repeating the same MB-OFDM symbol over two different subbands.

At the receiver, the signal received at the j-th antenna over the n-th transmission of the same symbol $\mathbf{s}_i^l$ is given by

$$\mathbf{r}_j^{l,n} = \sum_{i=1}^{n_T} (\mathbf{s}_i^l \otimes \mathbf{h}_{j,i}^{l,n}) + \mathbf{n}_j^{l,n},\ j = 1,...,n_R;\ n = 1,2.$$

where $\otimes$ denotes a linear convolution, $\mathbf{h}_{j,i}^{l,n}$ is the impulse response of the link between the i-th transmit antenna and the j-th receive antenna in the n-th transmission of the l-th MB-OFDM symbol, and $\mathbf{n}_j^{l,n}$ are independent noise samples modelled as Gaussian random variables. The received signal at each antenna is fed into the FFT block after the ZPS is removed. The symbols from the FFT block are put through the deinterleaver if the interleaver exists at the transmitter. The resulting signal, after the pilot and guard are discarded, denoted as $\mathbf{y}_j^{l,n} = [y_j^{l,n}(0), y_j^{l,n}(1),..., y_j^{l,n}(L+Q-1)]$, is taken by the decoder. This signal could be expressed as [6]

$$\mathbf{y}_j^{l,n} = \sum_{i=1}^{n_T} \mathbf{H}_{j,i}^{l,n} \bullet \mathbf{x}_i^l + \mathbf{N}_j^{l,n},\ j = 1,2,...,n_R;n = 1,2.$$

where $\mathbf{H}_{j,i}^{l,n} = [H_{j,i}^{l,n}(0),..., H_{j,i}^{l,n}(L+Q-1)]$ is the channel frequency response associated with the impulse response $\mathbf{h}_{j,i}^{l,n}$, $\mathbf{N}_j^{l,n} = FFT\{\mathbf{n}_j^{l,n}\}$, and $\bullet$ denotes the Hadamard product.

In the STF decoder, the Viterbi algorithm is employed for

TABLE I. SIMULATION PARAMETERS.

Parameter	Value
Data rate	200 Mbps
Convolutional code	K=7, Rc= 5/8
Modulation	QPSK
Number of states of STTC	4 or 16
FFT size	128
Number of information data subcarriers	100
Channel models	CM1, CM2, CM3, CM4
Number of channel realizations	100

estimating transmitted sequences. Because the same MB-OFDM symbol is transmitted repeatedly twice at the transmitter, the decoding process need to be performed jointly during each pair of two consecutive symbol periods across n_R receive antennas. To take that requirement into account, we propose a modified branch metric that is computed as the squared Euclidean distance between the hypothesised received signals and the actual ones over two MB-OFDM symbol periods. Define $\hat{x}_i^l(k), i=1,2,...,n_T, k=1,2,...,(L+Q-1)$ to be the output complex-valued symbol from the trellis branch associated to the i-th transmit antenna and the k-th subcarrier. Assuming that the perfect channel state information is available at the receiver, the proposed metric is calculated as

$$\sum_{j=1}^{n_R}\sum_{n=1}^{2}\left|y_j^{l,n}(k)-\sum_{i=1}^{n_T}H_{j,i}^{l,n}(k)\hat{x}_i^l(k)\right|^2$$

where $y_j^{l,n}(k)$ and $H_{j,i}^{l,n}(k)$ are the received symbol and the channel frequency response at the k-th subcarrier, respectively. The Viterbi algorithm will solve the minimization problem

$$\arg\min \sum_{k=0}^{L+Q-1}\sum_{j=1}^{n_R}\sum_{n=1}^{2}\left|y_j^{l,n}(k)-\sum_{i=1}^{n_T}H_{j,i}^{l,n}(k)\hat{x}_i^l(k)\right|^2$$

Finally, the estimated sequence obtained from the decoder is deinterleaved, and decoded to get the transmitted information.

IV. SIMULATION RESULTS

In this section, Monte Carlo simulations of the proposed STFTC MB-OFDM UWB system described in Section III are presented. We measure the system performance in terms of packet error rate (PER) over the IEEE 802.15.3a channel models defined in [16]. There are four channel models, namely CM1, CM2, CM3, and CM4, corresponding to different scenarios. The CM1 channel is based on a measurement of a Line of Sight (LOS) scenario where the distance between the transmitter and the receiver is up to 4 m. The others are CM2 (0-4m, Non Light of Sight-NLOS), CM3 (4-10m, NLOS), CM4 (4-10m, NLOS, rms delay spread of 25 ns). Moreover, the multipath gains are modeled as independent log-normally distributed random variables in these models. The simulation

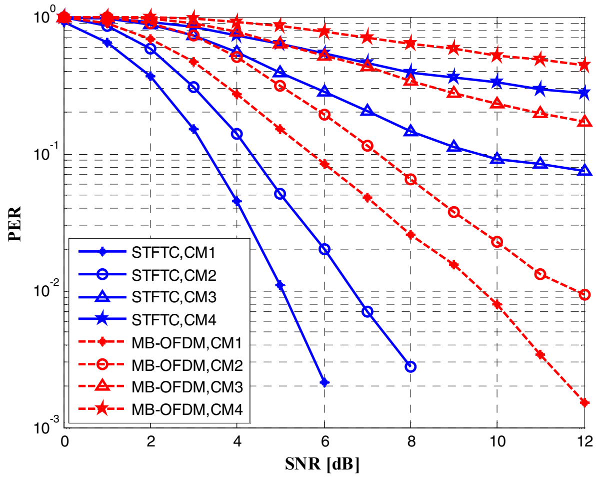


Fig. 5 Performance comparison between MB-OFDM UWB system and STFTC MB-OFDM UWB system with 1 Rx antenna

parameters are chosen based on the WiMedia specifications for the data rate of 200 Mbps, and are listed in Table I. The 4-state and 16-state STTC codes mentioned in Section II.A are adopted in our simulation. We assume that perfect channel state information is available at the receiver. We also assume that fading channels are independent not only for different transmitter-receiver links but also for different subbands. For the conventional MB-OFDM UWB system, a maximum ratio combiner is employed for combining signals at the receiver.

Fig. 5 compares the PER performance of the STFTC MB-OFDM UWB system with two transmit antennas and one receiver antenna, (2 Tx, 1 Rx) STFTC MB-OFDM UWB, with that of the conventional system. It is clear that there is a significant improvement in performance over all four channel models. For example, a gain of about 5 dB at PER=10^{-2} could be attained over the CM1 and CM2 channel models. Similar observations can be made in the case of two receive antennas as depicted in Fig. 6. Moreover, the PER performance of 10^{-2} could be achieved at low SNR values with this system even in the highly dispersive channel models of CM3 and CM4.

Fig. 7 shows the PER performance of the (2 Tx, 1 Rx) STFTC MB-OFDM UWB system with different number of trellis states. It can be seen that, by increasing the number of trellis states from 4 to 16, the system performance is improved in all channel models. This is due to the fact that there is more redundancy, or equivalently more coding gain, offered by the trellis codes with higher number of states.

The system performance could be further improved if the random interleavers and deinterleavers are added to the system as shown in Fig. 8. For instance, there are about 0.6 dB and 1.0 dB improvements at PER=10^{-2} in the system with interleavers, compared to the one without interleavers over the CM1 and CM2 channel models, respectively.

We have simulated the system with the maximum number of transmit and/or receive antennas of two, the FFT size of 128, the constellation scheme of QPSK, and the number of trellis states up to 16. Considering this system with other parameters is straightforward. Better performance may be expected with the penalty of higher complexity using other configurations.

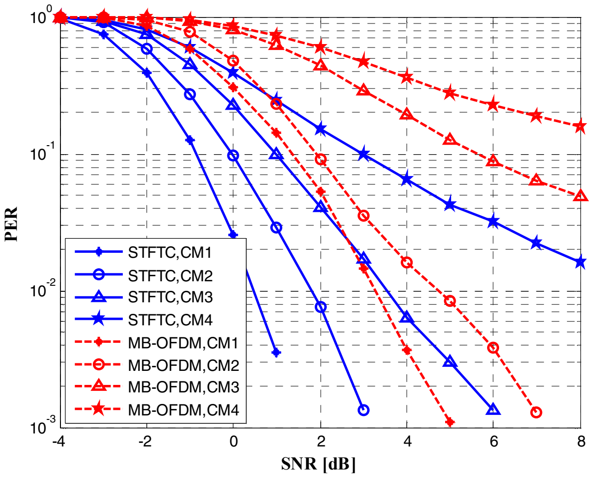


Fig. 6 Performance comparison between MB-OFDM UWB system and STFTC MB-OFDM UWB system with 2 Rx antennas

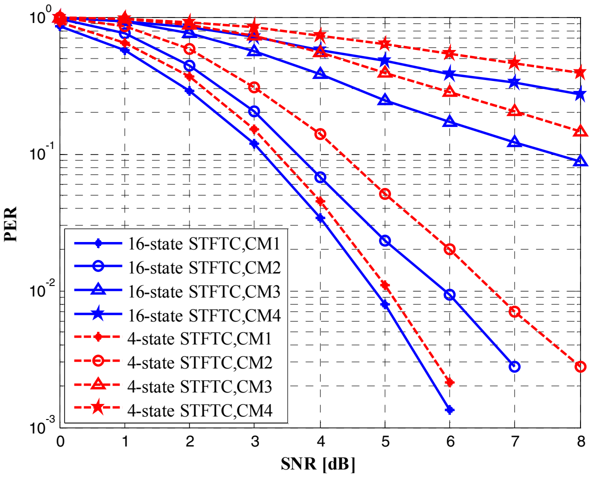


Fig. 7 Performance comparison between 4-state and 16-state trellis codes in STFTC MB-OFDM UWB system with 1 Rx antenna

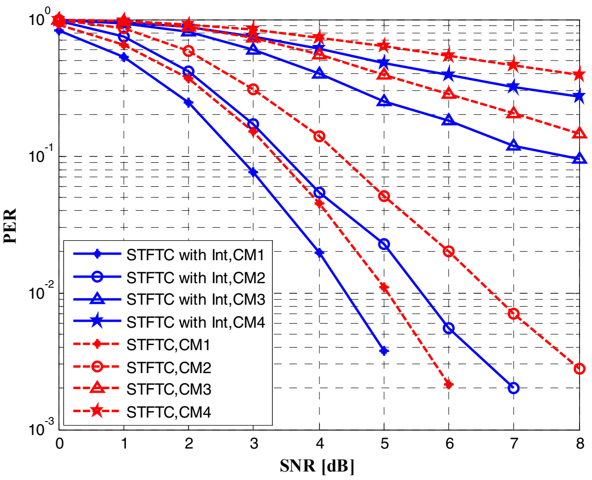


Fig. 8 Performance of 4-state STFTC MB-OFDM UWB system with and without symbol interleaver (Int), 1 Rx antenna

V. CONCLUSIONS

The proposed STFTC MB-OFDM UWB system, which incorporates space time trellis code into the WiMedia MB-OFDM UWB system, has been examined in this paper. From the simulation results, it can be concluded that this system could achieve a significant improvement in terms of PER performance compared to the conventional MB-OFDM UWB one. It is worth noting that the optimal STTCs in the context of single carrier systems over flat fading channels have been used in our simulation. However, it is no certain that these codes would still be optimal in the proposed system. Developing design criteria for obtaining optimal STTCs specific to the proposed system would be our future work.

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