Time-Reversal Wideband Communications

Yan Chen, Yu-Han Yang, Feng Han, and K. J. Ray Liu

***Abstract*—With the advance of semiconductor technologies, the performance of analog-to-digital converter (ADC) has been improved a lot during the past decade in terms of both sampling rate and resolution. The cost has gone down dramatically that makes the wideband communication much affordable. Under such circumstances, a natural question to ask is: Is there a low complexity high energy-efficient solution to high throughput wideband communications? In this letter, we explore this question by studying time-reversal communications. We find that compared with that of OFDM system, the computational complexity of a time-reversal system at the transmitter side is lower since it requires similar additions but no multiplications. Furthermore, the computational complexity of a time-reversal system at the receiver side is negligible since only onetap detection is performed, which means that the overall computational complexity of time-reversal system is much lower than that of OFDM system. Moreover, we find that when the bandwidth is large enough, time-reversal system can achieve much higher achievable rate than OFDM system. Therefore, time-reversal technique is a desired solution to low complexity high throughput wideband communications when more bandwidth is available.**

***Index Terms*—Energy-efficient, low complexity, OFDM, time-reversal, wideband communications.**

I. Introduction

IN RECENT years, we have witnessed an explosive growth of the number of wireless users along with wide variety of wireless communication applications and services. Such a phenomenon calls for future high-speed broadband wireless communication solutions. Multi-carrier modulation techniques such as orthogonal frequency division multiplexing (OFDM) are possible solutions and have drawn great attentions due to their capability to provide high data rate even with limited bandwidth, i.e., extremely high spectral efficiency. However, in spite of many advantages, the high computational complexity, high energy consumption and interference at both transmitter and receiver prohibit them from end-user equipments and wireless terminals in many applications.

On the other hand, due to the advance of semiconductor technologies, ADC has been costed down dramatically. In addition, the performance of ADC has been improved a lot during the past decade in terms of both sampling rate and resolution. For example, there have been 17 different commercial off-the-shelf ADCs from Texas Instrument with sampling rate at least 1 GHz and resolution at least 8 bits [1]. Moreover, according to the Moore's law, the sampling rate and resolution of commercial ADCs will continue to be improved. Such developments and progresses in the field of ADC make the wideband communication much affordable. When the bandwidth is wide enough, the advantage of high spectral efficiency of OFDM-based scheme becomes less significant and the cost of high computational complexity and high energy consumption at both transmitter and receiver becomes major drawbacks, due to which OFDM-based scheme may not be a desirable solution when the bandwidth is much broader than the current 4-G systems. A natural question to ask is: when the ADC becomes cheaper and cheaper while the bandwidth becomes wider and wider, is there a low-complexity, high energy-efficient and high data rate wideband communication solution? As pointed out in [2], time-reversal (TR) signal transmission is an ideal paradigm for low-complexity, low energy consumption green wireless communication because of its inherent nature to fully harvest energy from the surrounding environment by exploiting the multi-path propagation to re-collect all the signal energy that could be collected.

The history of the research on time-reversal transmission dates back to early 1990's [3], where the main focus was on acoustics and ultrasound fields. In [4]–[6], it is shown that, with TR, acoustic energy can be refocused on the source with very high resolution. The focusing effect was then validated in the real underwater acoustics experiments in the oceans [7]–[9]. Since TR can make full use of multi-path propagation without complicated channel processing and equalization, it has been also investigated in wireless communication systems [10]–[12]. When only one symbol is transmitted or the symbol duration is not smaller than the channel delay spread, the time-reversed waveform can guarantee the optimal bit error rate (BER) performance by virtue of its maximum signal-to-noise ratio (SNR). However, when the symbol duration is smaller than the channel delay spread, which is generally the case in high speed communication systems, the transmitted waveforms are overlapped and thus interfere with each other. Such inter-symbol interference (ISI) can be notably severe and causes crucial performance degradation, especial with very high symbol rate.

The problem becomes even more challenging in multi-user transmission scenario, e.g., the Time-Reversal Division Multiple Access (TRDMA) system [13], where the inter-user interference (IUI) is introduced due to the non-orthogonality of the channel impulse responses among different users. To address this problem, we can utilize the degree of freedom provided by the environment, i.e., the abundant multipaths, to combat the interference, which is known as waveform/signature design. The basic idea of waveform design is to carefully adjust the amplitude and phase of each tap of the waveform based on the channel information such that the signal at the receiver can retain most of the useful signal while suppress the interference as much as

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The authors are with Origin Wireless Communications, and also with Department of Electrical and Computer Engineering, University of Maryland, College Park, MD 20742 USA (e-mail: yan@umd.edu; yhyang@umd.edu; hanf@umd.edu; kjrliu@umd.edu).

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possible. In the literature, there have been many studies investigating the problems of designing advanced waveforms to suppress the interference [12], [14]–[18]. In [12], an MMSE-like waveform was proposed to suppress ISI for single user scenario where, however, the rate back-off factor was not taken into account in the optimization. In [14], multi-user joint power allocation and waveform design for sum rate optimization was investigated in the downlink TR systems.

In this paper, we study the TRDMA system and find that when the bandwidth is wide enough, TRDMA is an ideal low-complexity, high energy-efficient solution that can provide high data rate communications. Specifically, we compare the TRDMA system with the OFDM system in terms of achievable rate and computational complexity. We find that compared with that of OFDM system, the computational complexity of TRDMA system at the transmitter side is lower since it requires similar additions but no multiplications. Furthermore, the computational complexity of TRDMA system at the receiver side is negligible since only onetap detection is performed [13]. Therefore, the overall computational complexity of TRDMA system is much lower than that of OFDM system. Moreover, we show that when the bandwidth is wide enough, TRDMA system can achieve much higher achievable rate than OFDM system.

The rest of this paper is organized as follows. In Section II, we discuss the achievable rate of OFDM system and TRDMA system. Then, in Section III, we compare the computational complexity between OFDM system and TRDMA system. Finally, we conduct simulations in Section IV.

II. Achievable Rate

In this paper, we consider a downlink communication system with one transmitter and M receivers, and the transmission is over a wireless channel with bandwidth W. We assume that the channel is slow fading with a large delay spread, and the channel impulse response (CIR) at time k between the transmitter and the receiver m in the discrete time domain is modeled as

$$h_m[k] = \sum_{l=0}^{L-1} h_{m,l}\delta[k-l], \tag{1}$$

where $h_{m,l}$ is the k-th tap of the CIR between the transmitter and the receiver m, L is the number of channel taps, i.e., channel length, and $\delta[.]$ is the Dirac delta function. We assume that $h_m[k]$'s are independent with each other.

A. Achievable Rate of OFDM System

In OFDM system, the transmitted signals are modulated over different subcarriers. Let us assume that there are N subcarriers. Then, the corresponding channel fading coefficient $\mathbf{h}_m^f = [h_{m,1}^f, h_{m,2}^f, \ldots, h_{m,N}^f]^T$ can be computed as follows [19]

$$h_{m,n}^f = \sum_{l=0}^{L-1} h_{m,l}\exp\left(\frac{-j2\pi nl}{N}\right), \forall n \in [1, N]. \tag{2}$$

From (2), we can see that $\mathbf{h}_m^f$ is the N-point Discrete Fourier Transform (DFT) of the L-tap channel $\mathbf{h}_m = [h_{m,1}, h_{m,2}, \ldots, h_{m,L}]^T$, scaled by $\sqrt{N}$.

As shown in [20], the optimal subcarrier assignment to maximize the total data rate is to assign each subcarrier to only one user with the best channel gain. By utilizing the guard interval, there is no interference among different subcarrier, i.e., each subcarrier can be treated as an AWGN channel, and thus the achievable rate of the OFDM system can be written as follows

$$R_{OFDM} = \frac{W}{N}\frac{N}{N+L}\sum_{i=1}^{N}\log_2\left(1 + p_{m_i}^{\star}|h_{m_i,i}^f|^2\frac{N}{W\sigma_0^2}\right), \tag{3}$$

where $m_i = \arg\max_m |h_{m,i}^f|^2$ for all $i = 1, \ldots, N$, σ_0^2 is the noise power spectral density, and $p_{m_i}^*$ is the optimal power allocation among different subcarriers which can be computed through the following optimization problem

$$\begin{aligned} \max_{p_{m_i}} \quad & \sum_{i=1}^{N}\log_2\left(1 + p_{m_i}|h_{m_i,i}^f|^2\frac{N}{W\sigma_0^2}\right) \\ s.t. \quad & \sum_{i=1}^{N} p_{m_i} = \frac{N}{N+L}\bar{P}, \end{aligned} \tag{4}$$

with $\bar{P}$ being the total transmit power constraint. Note that the introduction of cyclic prefix, i.e., the guard interval, leads to a loss of time and power utilization with a factor of $\frac{L}{N+L}$ [19], due to which there is a factor $\frac{N}{N+L}$ in (3) and (4).

B. Achievable Rate of TRDMA System

In the TRDMA system, the transmitter has a specific waveform $\mathbf{g}_m$ designed for each receiver m. Such waveforms can be the basic TR waveforms or optimal waveforms designed by a certain criterion. When the transmitter has some information to transmit to the receivers, it first loads the data stream on the waveforms and then concurrently transmits the signal into the wireless channel with

$$\mathbf{s} = \sum_{j=1}^{M}(\sqrt{p_j}\mathbf{g}_j) * \mathbf{x}_j^{[D]}, \tag{5}$$

where $\mathbf{x}_j^{[D]}$ are up-sampled version, with a backoff factor of D, of the sequence that is to be transmitted to receiver j, and p_j is the power allocated to receiver j.

The received signal at receiver m can be written as

$$\mathbf{y}_m = \sum_{j=1}^{M}\mathbf{h}_m * (\sqrt{p_j}\mathbf{g}_j) * \mathbf{x}_j^{[D]} + \mathbf{n}_m, \tag{6}$$

where $\mathbf{n}_m$ are the additive white Gaussian noise with zero mean and noise power spectral density σ_0^2.

Since only onetap detection is used at the receiver [13], according to (6), the Signal to Interference plus Noise Ratio (SINR) of receiver m can be written as in (7), shown at the top of the next page.

With (7), the total achievable rate of the TRDMA system can be calculated as follows

$$R_{TRDMA} = \frac{W}{D}\sum_{m=1}^{M}\log_2(1 + SINR_m). \tag{8}$$

$$SINR_m = \frac{p_m \left|(\mathbf{h}_m * \mathbf{g}_m)[L-1]\right|^2}{p_m \sum\limits_{i=-(L-1)/D, i\neq 0}^{(L-1)/D} \left|(\mathbf{h}_m * \mathbf{g}_m)[Di+L-1]\right|^2 + \sum\limits_{j=1}^{M} p_j \sum\limits_{i=-(L-1)/D}^{(L-1)/D} \left|(\mathbf{h}_m * \mathbf{g}_j)[Di+L-1]\right|^2 + W\sigma_0^2} \quad (7)$$

Notice that due to the backoff factor D, for fair comparison with OFDM system, the power allocated to different receivers in (5)–(7) should satisfy the following constraint

$$\sum_{m=1}^{M} p_m = D\bar{P}. \quad (9)$$

In the basic TR scheme, we use equal power allocation and set the waveform as the time-reversed conjugate of the CIR as follows

$$g_{m,l} = \frac{h^{\star}_{m,L-1-l}}{\sqrt{\sum\limits_{l=0}^{L-1} |h_{m,l}|^2}}, l = 0, \ldots, L-1. \quad (10)$$

However, the basic TR scheme may not be able to provide desired performance. To improve the performance, the allocated power p_m and waveform $\mathbf{g}_m$ should be carefully designed to maximize the achievable rate as follows [14]

$$\max_{p_m, \mathbf{g}_m} \quad \frac{W}{D} \sum_{m=1}^{M} \log_2(1 + SINR_m)$$
$$s.t. \quad \sum_{m=1}^{M} p_m \leq D\bar{P}, \mathbf{g}_m^H \mathbf{g}_m = 1, p_m \geq 0, \forall m. \quad (11)$$

III. Computational Complexity

In this section, we discuss the computational complexity of the OFDM and TRDMA systems. We will omit the common components shared by both systems such as Automatic Gain Control (AGC) and frequency error corrections, and focus on the unique components of each system.

For the OFDM system, there are three unique components, which are power allocation, Fast Fourier Transform (FFT) at the transmitter and FFT at the receivers. Note that the channel is assumed to be stationary, due to which we do not need to perform power allocation every time slot. Instead, power allocation is re-computed only when the channel changes. Thus, the computational complexity of power allocation is treated as overhead complexity, which will not be discussed in this paper. In such a case, the computational complexity mainly comes from the FFT component at the transmitter and receiver. When the number of subcarrier N is a power of 2, with the well-known radix-2 Cooley-Tukey algorithm [21], the FFT component requires $\frac{N}{2}\log_2 N$ complex multiplications and $N\log_2 N$ complex additions. When there are M receivers, an N-point FFT is required at the transmitter and M N-point FFTs are required at the receivers. In such a case, when $\mathcal{N} \leq N$ symbols are transmitted over N subcarriers, the computational complexity per symbol is: $\frac{N}{2\mathcal{N}}\log_2 N$ complex multiplications and $\frac{N}{\mathcal{N}}\log_2 N$ complex additions at the transmitter; and $\frac{MN}{2\mathcal{N}}\log_2 N$ complex multiplications and $\frac{MN}{\mathcal{N}}\log_2 N$ complex additions at the receivers.

TABLE I
Complexity Comparison Between OFDM and TRDMA

	OFDM	TRDMA
Tx	$\frac{N}{2\mathcal{N}}\log_2 N$ complex multiplications $\frac{N}{\mathcal{N}}\log_2 N$ complex additions	$\frac{2M-1}{M}L - 1$ complex additions
Rx	$\frac{MN}{2\mathcal{N}}\log_2 N$ complex multiplications $\frac{MN}{\mathcal{N}}\log_2 N$ complex additions	no additions or multiplications

For the TRDMA system, there are two unique components, which are power allocation and waveform design as well as signal mixing. Similar to the power allocation in the OFDM system, the power allocation and waveform design in the TRDMA system do not need to re-compute every time slot and thus the corresponding computational complexity is treated as overhead complexity. In such a case, the computational complexity of TRDMA system mainly comes from the signal mixing at the transmitter. The signal mixing is due to waveform overlapping among different symbols and the concurrent transmissions to multiple receivers. For a TRDMA system with M receivers, backoff factor D and channel length L, the signal mixing requires $\sum_{i=0}^{D-1}\left(\lceil\frac{L-i}{D}\rceil - 1\right) + \frac{(M-1)L}{MD}$ complex additions per symbol. The computational complexity of the worst-case scenario when $D = 1$ is $\frac{2M-1}{M}L - 1$ complex additions at the transmitter. Here, we assume that the waveforms with modulations are pre-computed during the waveform design step, due to which no multiplications are needed. Moreover, since onetap detection is used at the receiver (the equalization is done on the air where the signature is convolved with the channel), there is zero computational complexity at the receiver, i.e., no additions or multiplications are needed at the receivers.

From the above discussions, we can see that compared with OFDM system, the computational complexity of TRDMA system at the transmitter side is lower since it requires similar additions but no multiplications, while the computational complexity of TRDMA system at the receiver side is negligible since only onetap detection is performed. Therefore, the overall computational complexity of TRDMA system is much lower than that of OFDM system. A summary of the computational complexity comparison between OFDM and TRDMA is shown in Table I.

IV. Simulation

In this section, we conduct simulation to evaluate the achievable rate performance of OFDM and TRDMA systems. Specifically, we will show that TRDMA is the ideal solution that is low-complexity and high energy-efficient but can achieve higher throughput than OFDM system when the bandwidth is abundant.

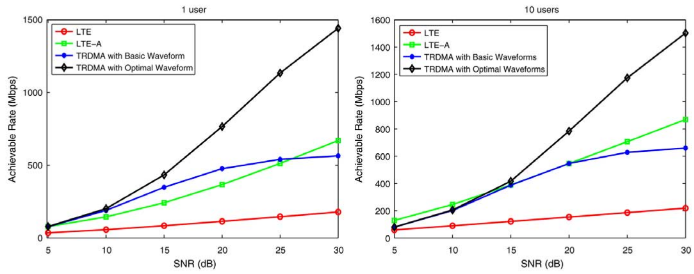

Fig. 1. Achievable rate comparison: (a) 1 user case; (b) 10 users case.

In the following simulations, the bandwidth of the TRDMA system is set to be 500 MHz. We compare the TRDMA system with two OFDM systems: one is LTE system with 20 MHz bandwidth and the other is LTE-A system with 100 MHz bandwidth. The number of subcarriers N in both OFDM systems is set to be 1201, which are chosen from the output of a 2048-point FFT [22]. The channels we use in this paper is the UWB channel model proposed in [23].

The simulation results are shown in Fig. 1. We can see that for one user case, even with basic TR waveform, the TRDMA scheme can achieve much better performance than LTE in all SNR region and better performance than LTE-A in most SNR region. With optimal waveform, the performance of TRDMA can be further improved. When there are 10 users, due to the selectivity among different users, the achievable rate of LTE and LTE-A can be enhanced, due to which LTE-A can achieve comparable and even slightly better performance than TRDMA with basic TR waveform. Nevertheless, with optimal waveform, TRDMA can still outperform LTE and LET-A in most SNR region, which demonstrates that TRDMA can achieve higher throughput than OFDM systems when the bandwidth is abundant, e.g., 5 times in the simulations.

We also evaluate the computational complexity. In this evaluation, as discussed in section III, we omit the common components shared by both systems such as Automatic Gain Control (AGC) and frequency error corrections. We assume that one symbol is transmitted over one subcarrier in LTE and LTE-A, i.e., $\mathcal{N} = 1201$ and $N = 2048$. Based on [23], the channel length for the spectrum with 500 MHz is around 100, and thus we set $L = 100$ for TRDMA. Note that the channel length for LTE and LTE-A will be different due to different bandwidth. Nevertheless, according to Table I, the complexity of LTE and LTE-A is independent of channel length. With Table I, when there is only one user, i.e., $M = 1$, the complex multiplications and complex additions needed for LTE, LTE-A, and TRDMA at the transmitter is (11,22), (55,110), and (0,99), respectively, while the complexity at the receiver is (11,22), (55,110), and (0,0), respectively. When there is 10 users, i.e., $M = 10$, the complex multiplications and complex additions needed for LTE, LTE-A, and TRDMA at the transmitter is (11,22), (55,110), and (0,189), respectively, while the complexity at the receiver is (110,220), (550,1100), and (0,0), respectively. Therefore, we can see that the overall complexity of TRDMA is much lower than LTE-A especially for multiple users scenario.

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