Time-Reversal Based Routing in Dispersion Code Multiple Access (DCMA)

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Abstract—**An adaptive Dispersion Code Multiple Access (DCMA) system is proposed and demonstrated using numerical calculations. Compared to conventional static DCMA, where channels between access points are fixed unless adaptive phasers are used, the proposed system employs a base-station which allows users with distinct but fixed phasers to form arbitrary adaptive channels between the access points. The base-station first records the channel responses in the sounding stage, and then uses this information to route the data between arbitrary user pairs in the communication stage.**

I. Introduction

A multiple access scheme allows several data streams or signals to share the same communication channel or a physical medium and is of particular importance in dense wireless communication environments. Typical techniques include frequency domain multiplexing (FDM), time-domain multiplexing (TDM), code division multiple access (CDMA) and space division multiple access (SDMA) [1]. The conventional techniques are primarily based on digital technologies, which are inherently prohibitive at high frequencies due to large power consumption and poor performance. Recently, a purely analog and real-time multiple access technique called Dispersion Code Multiple Access (DCMA) has been proposed [2], [3], which can accommodate ultra-broadband signals, using efficient dispersive devices called phasers [4]. The DCMA technology has an optical counterpart in optical fibre network for optical communication systems [5], and it may be efficiently applied at microwave and millimeter-wave frequencies using recently developed Radio Analog Signal Processing (R-ASP) technology [4].

The reported R-ASP applications, to name a few, include dispersion code multiple access (DCMA) system [2], [3], enhanced SNR transceiver [6], time expansion systems [7], [8] for enhanced sampling, time compression and reversal system [9], distortion-less real-time spectrum sniffer [10], compressive receiver using CRLH dispersive delay line [11]. The core of R-ASP is phaser, which is essentially a dispersive delay structure (DDS) providing a prescribed group delay response $\tau(\omega)$. Different technologies used to realize phasers include periodic EBG structures [12], all-pass network based transmission-type [13] and reflection-type [14] phasers, nonuniform C-section phaser [15], CRLH C-section phaser [16], etc.

A conventional DCMA system forms wireless channels between transmit-receive user pairs using dispersion-matched phaser pairs, where the receive phaser has a complementary group delay versus frequency response, so as to perfectly equalize the transmit-receive group delay over all frequencies. This leads to an $N \times N$ DCMA system with N fixed transmit-receive channels between $2N$ users.

While the aforementioned DCMA system is simple and efficient, it is static in the sense that transmit-receive pairs are fixed and cannot be changed over time, unless each access point would use reconfigurable phasers, that are still unavailable at the time of this writing. However, in most practical applications, the wireless network needs to be reconfigured dynamically in time to allow switching between different transmit-receive pairs. This issue is addressed in this paper. Using a smart base-station between the users, an adaptive DCMA system is proposed. The base-station uses time-reversal technique [17], [18] to characterize the wireless environment in a sounding phase and next uses this information to set up the desired wireless channels between pairs.

II. Conventional Static DCMA System

Consider the 2×2 DCMA system depicted in Fig. 1, consisting of 2 transmitters and 2 receivers. Each transmitting terminal is equipped with a phaser exhibiting a unique group delay versus frequency response as its identification. In the illustrated example, users A and B have positively sloped and negatively sloped group delay responses, and wish to securely communicate with users C and D, respectively. In a DCMA system, such a secure channel between A and C, and between B and D, is established by providing the users C and D with group delay responses that are the complementary (phase conjugated) to those of the corresponding transmitters, as is the case with negatively and positively sloped group delay responses.

Under these conditions, the system operates as follows. An input pulse at the phaser A is positively chirped and radiated to the environment. Both users B and D receive this signal, but only user C is able to recompress it owing to its negatively sloped group delay response, and thereby successfully receives the signal from user A. User D on the other hand, further disperses the signal from user A, and is unable to detect it due to its resulting reduced amplitude. Users A and C are thus dispersion matched, due to their complementary group delay responses, and form a single wireless channel. In a similar way, user B and user D form another wireless channel based on another set of complementary group delay responses. Such a system thus establishes two secure wireless channels between 4 users, where each channel accesses the full spectrum and other communications resources simultaneously with other existing channels. This is the concept of DCMA, which may be easily extended to $N \times N$ users with N complementary phaser pairs.

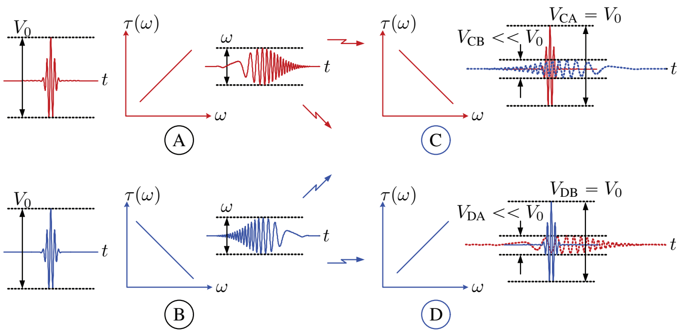

Fig. 1: Principle of a conventional DCMA system proposed in [3].

While DCMA system represents a simple and an analog multiple access technique in a *static* environment, it suffers from fundamental issue in a *dynamic* environment. Consider again the 2×2 DCMA system of Fig. 1, where user A communicates with user C, and user B communicates with user D. One can naturally ask the question: Can user A switch its communication in real-time, to user D instead of user C?

To enable such dynamic communication in a multi-user environment to achieve an adaptive DCMA system, there are two possible approaches: 1) Each user has a reconfigurable phaser, which can transform its group delay response in real-time to dispersion match with the user it wants to communicate with. 2) There is a mediator that negotiates the communication requests from different users and route them to their requested destined users. This work selects the second approach is proposed and described, whereas the first solution will be reported elsewhere.

III. Proposed Adaptive DCMA System

A. Principle

Consider the 2×2 DCMA system depicted in Fig. 2, where each user has a fixed phaser with a group delay response $\tau_n(\omega)$, where the subscript n denotes user n. In addition, a base-station establishes the requested channel between any pair of users, in a dynamic fashion. The overall operation principle is described next.

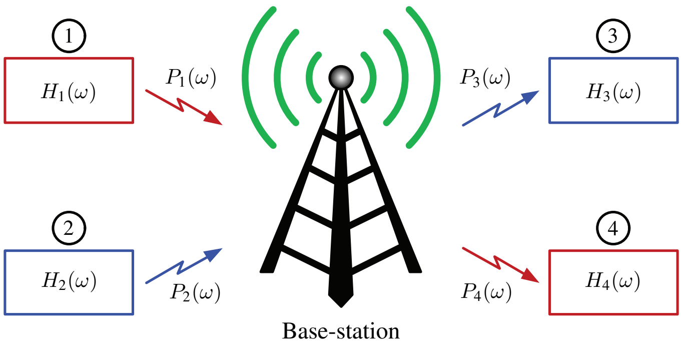

Fig. 2: Proposed time-reversal based DCMA system.

Let us assume that each user has a phaser which exhibits an all-pass response with transfer function $H_n(\omega) = \exp\{j\phi_n(\omega)\}$, where $\tau_n(\omega) = -\partial\phi_n(\omega)/\partial\omega$. Also, the transfer function between each user and the base-station is $P_n(\omega)$, where n denotes the user index. The proposed system operates in two phases:

1) *Sounding phase:* In this phase, each user registers to the base-station by sending a known sounding signal $S(\omega)$. The received sounding signal at the base-station is $R_n(\omega) = S(\omega)C_n(\omega)$, where $C_n(\omega) = H_n(\omega)P_n(\omega)$, and $P_n(\omega)$ is the transfer function of the corresponding channel between user n and the base-station. With measured $R_n(\omega)$ and known sounding signal $S(\omega)$, the base-station deduces the transmitter-channel response $C_n(\omega)$ of user n in real-time, which includes the identifying dispersion response of this user. The base-station then stores this channel information in the form of its complex conjugate $C_n^*(\omega)$. This operation is also known as time-reversal and in a practical scenario, may be realized in a digital fashion by flipping the sampled signal in time, or in analog fashion by using a “time lens” incorporating two or three dispersive lines and one mixer [7], [9], [19].
2) *Communication phase:* After the sounding phase, once every channel transfer function has been determined and stored at the base-station, data communication is initiated between arbitrary user pairs. Suppose user n wishes to communicate with user m, and they have unique phasers with different and *not necessarily dispersion*

matched group delay versus frequency responses. User n sends the information signal $S_n(\omega)$ towards the base-station first. The signal received at the base-station is $R_n^{\text{BS}}(\omega) = S_n(\omega)C_n(\omega)$. The base station retrieves the information signal $S_n(\omega)$ by multiplying $R_n^{\text{BS}}(\omega)$ with the conjugate of channel response $C_n^*(\omega)$ gathered from the sounding stage. It then preconditions $S_n(\omega)$ by multiplication with the conjugate of $C_m^*(\omega)$, as a preparation to route it to intended user m. This signal $[S_n(\omega)C_m^*(\omega)]$ is re-transmitted back in the environment and the signal received at user k is then given by

$$R_k(\omega) = S_n(\omega)C_m^*(\omega)C_k(\omega). \tag{1}$$

Clearly, only when $k = m$, $R_m(\omega) = S_n(\omega)$, i.e. the m^{th} user successfully retrieves the signal from user n as $|C_m^*(\omega)C_m(\omega)| = 1$ or maximally correlated channel. All the other users receive a reduced amplitude signal as $|C_m^*(\omega)C_k(\omega)| < 1$. The degree of channel discrimination thus depends on the contrast between the auto-correlations and cross-correlations between concerned channel transfer functions.

The above described two-stage communication process thus enables DCMA between two users in real-time with arbitrary dispersion profiles instead of dispersion matched phaser pairs. Compared to a static DCMA system of Sec. II, the adaptive DCMA requires two communication phases, and a base-station to mediate between channel users.

B. Results

Let us take an example of an adaptive 3×3 DCMA system with 6 users. To provide a maximal channel diversity based on phaser dispersion responses, a critical choice of group delay versus frequency response is important. An attractive choice is a set of Chebyshev polynomials, which are characterized by a fixed min-max amplitude range in a given region, ensuring that the dispersed pulses are always contained within one bit period [15]. The corresponding group delay response of the k^{th} transmitting phaser can be written $\tau_k(\omega) = \Delta\tau[\tau_k(\omega')] + \tau_0$, with $\omega' = 2(\omega - \omega_0)/(\omega_2 - \omega_1)$, where $\tau_k(\omega')$ is the k^{th} Chebyshev polynomial of the first kind, $\Delta\tau$ is the group delay swing, and $(\omega_2 - \omega_1)$ is the bandwidth of the phasers. The first 6 Chebyshev group delay codes corresponding to 6 users are plotted in Fig. 3 along with the intended user pairs for data communication.

In order to estimate the bit-error rate (BER) of the proposed DCMA system, the following assumptions were made: 1) line-of-sight communication, i.e. no multiple reflections, 2) non-dispersive channels, i.e. $H_n(\omega) = \text{const.} = 1$, and 3) noiseless environment. Figure 4 shows the numerically computed BERs for different Chebyshev codes of Fig. 3 and group delay swings of $\Delta\tau = 5$ ns and 9 ns. A 20-bit information stream is specified

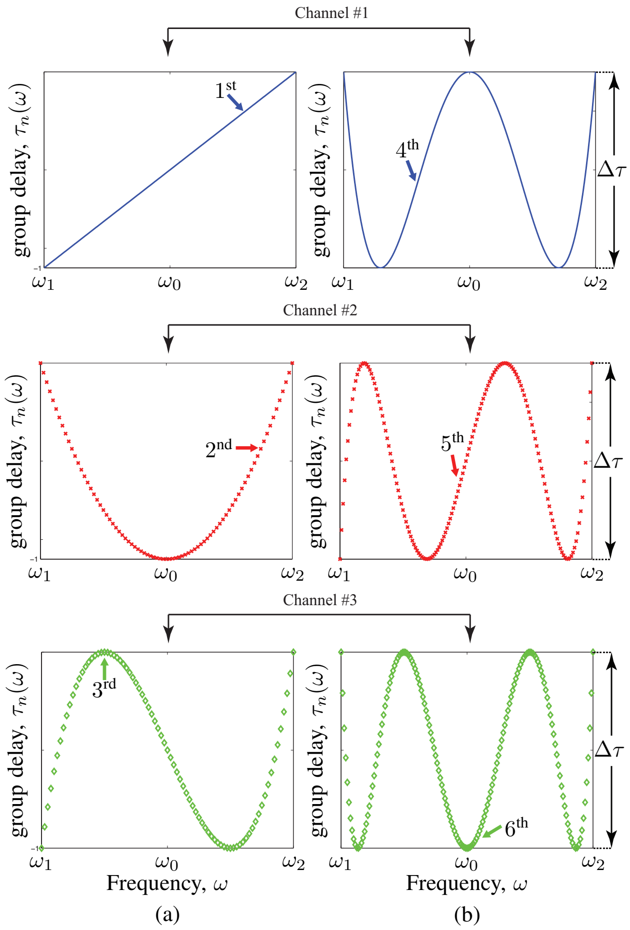

Fig. 3: First 6 Chebyshev dispersion codes for different users considered in an adaptive DCMA system example. Intended user pairs exhibiting non-matched group delay responses are indicated.

at each transmitting terminal, and the corresponding BER is computed as an average of multiple simulation (5000 bits in total) results.

The BER results of Fig. 4(a) show excellent channel performances even when the two users in the intended channels do not exhibit dispersion-matched profiles, thereby validating the proposed system of adaptive DCMA. The BER is further improved when the group delay swing $\Delta\tau$ is increased to 9 ns, as is expected to create better frequency discriminating characteristics.

IV. Conclusion

An adaptive DCMA system has been proposed and demonstrated using numerical calculations. Compared to the conventional static DCMA system, the proposed system employs a base-station to form in real-time, multiple wireless channels between users with non-complementary dispersion profiles.

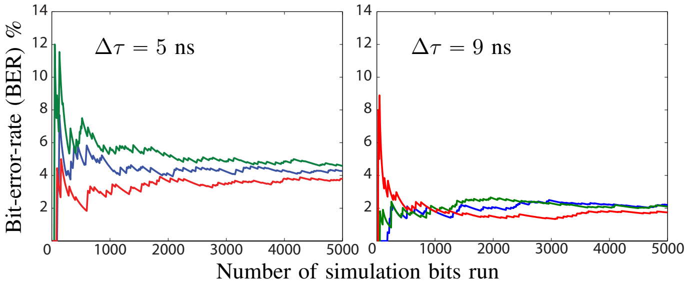

Fig. 4: Bit-error-rate (BER) performance at the three receiving terminals of a 3×3 DCMA system with the dispersion codes of Fig. 3 when the group delay swing $\Delta\tau$ is (a) 5 ns and (b) 9 ns. All the transmitters are communicating simultaneously.

The base-station first characterizes the channel responses in the sounding stage, and use this information to route the information stream between intended users. The proposed technique thus provides a practical solution to reconfigurability and versatility in an otherwise static DCMA system.

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