Relay Communication with Phase Dithering and Intentional Delay in SC-FDE Systems

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***Abstract*—This paper proposes an amplify-and-forward (AF) relay technique for wireless single carrier frequency domain equalizer (SC-FDE) systems. The relaying scenario assumes that there are many nodes densely distributed, allowing two or more relay nodes to participate in relaying. The proposed method aims to enhance time and frequency diversity gain in slow fading channels. To this end, we propose to use random phase rotation and random intentional delay at each relay over time. Performance validation is conducted through simulation. By increasing the number of relay nodes, the simulation results demonstrate a notable enhancement in the bit error rate (BER) performance.**

Keywords—SC-FDE; Two-hop relay; Phase dithering; Intentional delay; Time diversity; frequency diversity

I. Introduction

In terrestrial tactical communication environments, device-to-device communication without a base station is common. In such environments, direct 1:1 communication between the source and destination can often encounter issues when the distance is too far to reach. To ensure communication reliability, the use of relay nodes is a popular solution [1].

There are two types of relay communication techniques: decode-and-forward (DF) relay and amplify-and-forward (AF) relay. AF relay simply amplifies the source's signal and transmits to the destination while the DF relay decodes the source's signal and transmits after re-encoding. The AF relay is much simpler to implement than the DF relay at the cost of risk of noise amplification [2]. Another problem of AF relay is that the relaying does not always guarantee better signal to noise ratio (SNR) at the destination. For instance, assume that several relays participate for relaying. The transmitted signals are combined in the air and arrived at the destination. Depending on the communication environments, the strength of the combined signal can be significantly low due to destructive combining. The same phenomenon may occur in multipath fading channels.

This work proposes a technique for AF relaying with multiple relays in single carrier frequency domain equalizer (SC-FDE) systems. SC-FDE systems are designed for frequency-selective channels and are preferred for wideband 1:1 communication because the equalization requires simple computation, like orthogonal frequency division multiplexing (OFDM). In the proposed technique, one communication packet (or frame) is divided into many blocks. Before transmission, each relay applies phase dithering and random Intentional delay to each block. Phase dithering and random delay create an artificial effect of fast fading, i.e., the effective channel between the multiple relays and the destination changes abruptly from block to block. Random phase and random delay may increase time and frequency diversity gains, respectively. Together with forward error correction (FEC) code, reliable communication can be achieved due to the diversity gains.

The proposed technique is validated through computer simulations using a frequency selective channel model between all links. Specifically, the ITU-R Pedestrian A model is utilized as the 1:1 link channel model. The performance is evaluated for different modulation-and-coding schemes (MCSs) and varying numbers of relays, namely 1, 2, 3, 5, 15, and 25. The MCSs used in the simulation are QPSK with a code rate of 1/3, 16QAM with a code rate of 3/4, and 8PSK with a code rate of 7/8. The simulation results suggest that increasing the number of relays results in an improvement in the bit error ratio (BER) performance. Phase dithering is more effective than intentional random delay, and applying both techniques yield the best performance.

II. Proposed Relay Technique

A. Multi-hop Relay

Fig. 1 shows a multi-hop relay situation. Multi-hop relaying refers to communication between a source and a destination that involves a relay step. A multi-hop relay is a communication network where multiple nodes work together to transmit signals to the destination [3]. In this paper, we consider a communication situation with a two-hop relay that relays once

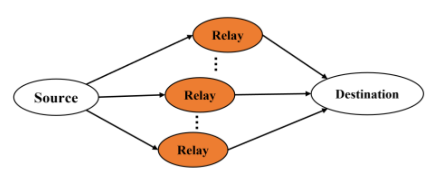

Fig. 1. Two-hop relay in Multi-hop relay.

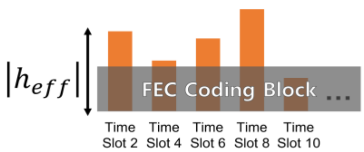

Fig. 2. Received signal at destination after applying phase dithering.

from the source situation with a two-hop relay that relays once from the source and transmits to the destination. The study assumes that the communication path between the source and relay nodes is error-free. The distance between the source and destination varies for each relay node it passes through, and the largest difference is referred to as the "Maximum distance deviation". The maximum distance deviation depends on the MCS used.

B. Phase Dithering

Phase dithering and intentional delay techniques are used to solve the communication degradation that occurs when sending signals over an intermediary. Phase dithering rotates the phase of the signal received by the relay by a random phase.

$$h_{eff} = \sum_{m=1}^{M} h_m\,,\ \left|h_{eff}\right| = \left|\sum_{m=1}^{M} h_m\right| \quad (1)$$

The case of not multiplying random phases at each relay node can be represented by (1). If random phases are not multiplied at each relay node, the effective channel remains constant over time, and if its size is small, it may be difficult to restore data.

$$h_{eff} = \sum_{m=1}^{M} h_m e^{j\theta m(n)}\,,\ \left|h_{eff}\right| = \left|\sum_{m=1}^{M} h_m\, e^{j\theta m(n)}\right| \quad (2)$$

On the other hand, multiplying the signal by random phases at each relay node can cause the effective channel to change over time, which can improve the ability to restore data. The effective channel when multiplied by random phases at each relay node can be represented by equation (2).

Fig. 2 shows the magnitude of the signal received at the receiving end when multiple nodes participate in the relay but retransmit with randomized phase multiplication at each time slot. The magnitude of the combined signal changes randomly every time slot due to the random phase when signals from multiple nodes participating in a relay are combined and received. This has the same effect as experiencing fast fading. Therefore, even in a slow-fading environment, it is possible to obtain the time diversity gain of a fast-fading channel.

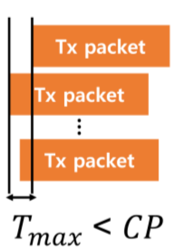

Fig. 3. Received signals at destination with random delay.

C. Intentional Delay

Intentional delay refers to the practice of applying a random delay to the signal received from a source by multiple relay nodes before retransmitting it. By introducing such a delay, the signal that reaches the destination arrives with a time delay for each transmitted packet, as illustrated in Figure 3. Here, T_{max} represents the maximum deviation in time between the arrival of transmitted packets. If T_{max} exceeds the length of the cyclic prefix (CP), communication may not be possible, and should not be exceeded. When a signal with a wide bandwidth is received by a receiver with sufficient time resolution, all of the received signals can be used to obtain frequency diversity gain, as shown in Figure 3.

III. Simulation Environments

A. SC-FDE Transmission Method and Symbol Structure

SC-FDE is a technique that is utilized in combination with Orthogonal Frequency Division Multiplexing (OFDM) to address the issue of multipath delay spread in wideband wireless channels. Both methods use CP to avoid inter-block and intra-block interference, and the length of CP is set greater than the channel's delay range [4]. SC-FDE has an advantage over OFDM in terms of having a lower Peak-to-Average Power Ratio (PAPR) and being less sensitive to Carrier Frequency Offset (CFO) [5]. Fig. 4 shows the SC-FDE symbol structure of this paper. The SC-FDE symbol structure has a CP at the very front, followed by data and pilots. In this case, the pilots are in the middle of the data, as a characteristic. If the pilots are in the middle of the data, it shows superior performance in time-variant fading channels [6]. N is the size of Fast Fourier Transform (FFT), and the length of CP is L_{cp}, and the length of the pilot is L_p.

B. Transmitter/Receiver Block Diagram

Fig. 5 depicts the overall architecture of the proposed relay-based communication system. Binary messages are first generated at the transmitter, followed by forward error correction (FEC) encoding using convolutional turbo coding (CTC). Random interleaving is then performed to prevent burst errors, and the interleaved signal is mapped to the chosen modulation and coding scheme (MCS). Subsequently, single-carrier frequency-domain equalization (SC-FDE) modulation is applied to the signal for transmission. The relay applies intentional delay and phase dithering to the received signal, which then passes through a fading channel before being re-transmitted to the receiver. At the receiver, the relayed signal undergoes channel estimation in the time domain, followed by demodulation. The signal is then demapped, randomly deinterleaved, and subjected to FEC decoding to recover the original message. The relay stage, highlighted in orange in Fig. 5, is the main focus of this paper.

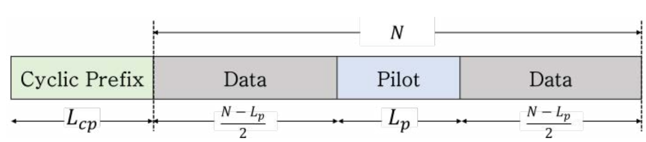

Fig. 4. SC-FDE symbol structure.

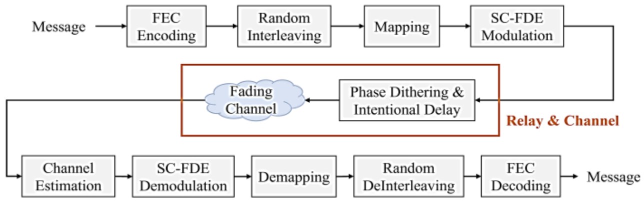

Fig. 5. Transmitter/Receiver Structure Block Diagram.

IV. Simulation

A. Simulation Environment

The simulation and performance evaluation in this paper are conducted using MATLAB. The parameters used in this paper's simulation are presented in Table 1. The bandwidth is 4 MHz, and the FFT size is 512. The length of the CP is 64 symbols, and the length of the pilot is 256 symbols. The paper assumes a mobile speed of 20 km/h. Three MCS are used: QPSK with R=1/3, 16QAM with R=3/4, and 8PSK with R=7/8. The maximum distance deviation e is 4 km for QPSK and 2 km for 16QAM or 8PSK. The phase rotation angle range for phase dithering is -π to π, and it is performed randomly within this range. The maximum intentional delay is 5 clocks, which applies a random delay of 1 to 5 clocks to the signal. The number of relay nodes used in the simulation is 1, 2, 3, 5, 15, and 25.

TABLE I. Simulation Environment Parameters

Simulation Parameters	
Parameter	***Values***
Bandwidth	4 MHz
FFT size	512
CP length	64 symbols
Pilot length	256 symbols
Moving speed	20 km/h
Modulation and coding scheme	QPSK with R=1/3
	16QAM with R=3/4
	8PSK with R=7/8
Maximum distance deviation	4 km or 2 km
Phase dithering range	$[-\pi, \pi]$
Maximum Intentional delay	5 clock
Number of relay node	1, 2, 3, 5, 15 and 25

B. Simulation Results

The simulation evaluation metric checks the required signal-to-noise ratio (SNR) when the bit error ratio (BER) is 10^{-5}. In all simulation results, blue dashed line represents the baseline, which is the result of only relaying without applying phase dithering or intentional delay. The pink solid line represents the result with only phase dithering applied, and the green solid line intentional delay applied. And in all simulation results for all MCS, the number of relay nodes are 1, 2, 3, 5, 15 and 25 starting from the rightmost BER curve. Represents the result with only intentional delay applied. The red solid line represents the result with both phase dithering and Fig. 6 shows the simulation results for QPSK, R=1/3. Fig. 7 shows the simulation results for 16QAM, R=1/3, and Fig. 8 shows the simulation results for 8PSK, R=7/8. As the number of relay nodes increases, the simulation results show a significant improvement in the performance of all MCSs. By applying phase dithering or intentional delay in relaying, can observe that the performance is improved compared to the baseline. The performance improvement due to phase dithering and intentional delay is greater for 16QAM and 8PSK than for QPSK. The performance improvement for QPSK is about 1dB, but for the other MCS, it is about 2dB. From the simulation results, it can be observed that phase dithering and intentional delay have a performance improvement effect in broadband relay communication.

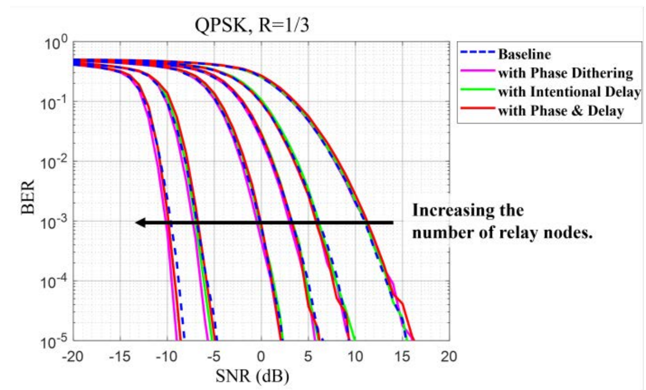

Fig. 6. Simulation result for QPSK, R=1/3.

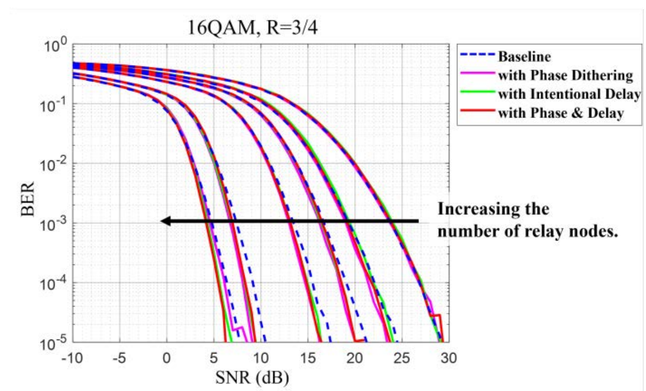

Fig. 7. Simulation result for 16QAM, R=3/4.

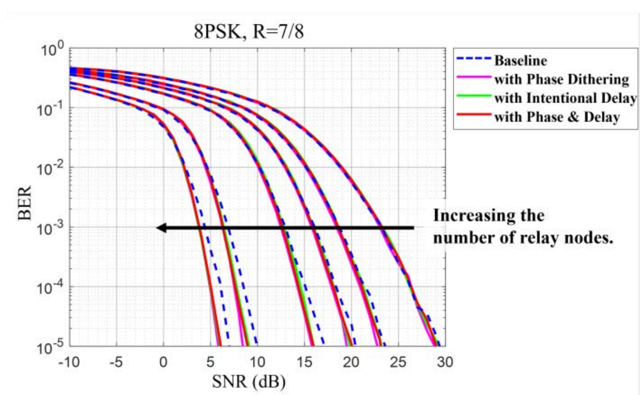

Fig. 8. Simulation result for 8PSK, R=7/8.

V. Conclusion

This paper proposes using AF relay technology in an SC-FDE system environment and confirms its performance. The proposed relay technology involves transmitting signals by applying phase dithering and intentional delay in the relay. Phase dithering is rotates the phase of the signal to obtain time diversity, and intentional delay is delays and transmits the signal to obtain frequency diversity gains. Performance verification was conducted through simulation using a total of three MCSs. The simulation results show that the BER performance improves as the number of relays increases. Additionally, using the relay technology improves BER performance in all MCSs compared to not using it. These results suggest that the proposed relay technology can improve communication performance by obtaining diversity gains. In future studies, removing the diversity gain obtained by the delay caused by the distance deviation may more clearly confirm the performance of the relay technology.

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