Field Test Results for Beam and Null Simultaneous Steering S/T-Equalizer in Broadband Mobile Communication Environment

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Abstract

This paper proposes a beam and null simultaneous steering Space-Time Equalizer (S/T-Equalizer). The proposed S/T-Equalizer performs separated S/T-signal processing in order to reduce computational complexity to a practical level. For spatial signal processing, a new Adaptive Array Antenna algorithm is used that combines the beam and null steering concepts. For temporal signal processing, a conventional delayed decision feedback sequence estimation equalizer may be used. The proposed S/T-Equalizer was prototyped. A series of field tests was then conducted using the 5GHz frequency band to evaluate transmission performance of the proposed system. The results show that the proposed S/T-Equalizer can reduce inter-symbol interference effects while maintaining reasonable signal strength, thereby improving BER performance.

1. Introduction

Mobile multimedia communications demand the creation of broadband signal transmission techniques that offer transmission rates of tens of Mbps. These techniques must overcome problems such as Co-Channel Interference (CCI) and Inter-Symbol Interference (ISI), as well as the relatively large propagation loss inherent to broadband mobile communications. Joint Space-Time-Equalization (S/T-Equalization) is considered most effective in reaching these goals [1], [2].

S/T-Equalization is a unified concept combining conventional adaptive array antennas (AAAs) and temporal equalizers. Temporal equalizers aim to reduce ISI and combine delayed desired signal components, while AAAs suppress CCI and enhance antenna gain towards the desired signal's incident angle. Optimal performance can be achieved through two-dimensional (joint spatial and temporal) optimization of the S/T-Equalizer's parameters [3]. Unfortunately, it is prohibitively complex in many cases to implement the optimal S/T-Equalizer, and a technique that significantly reduces the complexity is required.

This paper proposes a new S/T-Equalization technique that separates spatial and temporal signal processing. This separation reduces the computational complexity of signal processing to a practical level. To avoid conflict between the spatial and temporal equalizers, timing control of equalizer operation is needed. A new AAA algorithm is proposed for spatial equalization. The proposed algorithm combines the beam and null steering concepts; a sharp beam is steered towards the desired signal while nulls are steered towards interferers. The AAA is followed by a temporal equalizer. Although any form of equalizer can be used for temporal equalization, the Delayed Decision Feedback Sequence Estimation (DDFSE) equalizer may be a good choice [4] since it offers a reasonable tradeoff between performance and complexity.

The proposed S/T-Equalizer was prototyped. A series of field tests was then conducted in the 5GHz frequency band to evaluate signal transmission performance of the prototyped system. This paper is organized as follows. Section 2 describes the configuration of the proposed S/T-Equalizer. Section 3 describes details of the prototyping, along with results of the field tests. Section 4 concludes this paper.

2. Configuration of S/T-Equalizer

Figure 1 shows a block diagram of the proposed S/T-Equalizer. Parameter Estimator-1 (PE-1) performs spatial signal processing for the proposed beam and null steering AAA algorithm, and Parameter Estimator-2 (PE-2) performs temporal signal processing for temporal equalization, both take run independently of the other.

2.1. Spatial Equalization

The proposed AAA algorithm first estimates the direction-of-arrival (DOAs) of incident signals. It then forms a beam pattern based on the DOA estimates: a

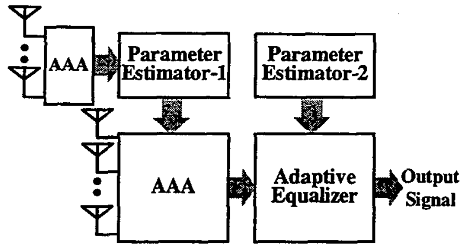

Figure 1. Configuration of proposed S/T-Equalizer

sharp beam is steered towards the desired signal and nulls towards other signals. Figure 2 shows a detailed configuration of PE-1. The DOA estimator in Fig.2 uses a super-resolution algorithm to estimate DOAs and powers of signals impinging on an N-element array antenna. The MUSIC algorithm [5] may be used for DOA estimation. The simple classification used here is that the strongest of the detected signals is the desired signal, and the others are the interferers. This classification is reasonable in relatively simple propagation environments. In the presence of both multi-path and interference components, the strongest signal detected may not be the signal that should be detected but indeed may be the one that should be suppressed. In such complex environments, the true desired could be determined with the help of a higher layer of the system control.

Let DOA of the desired signal be denoted by θ_0, and DOAs of interferers by θ_i ($1 \le i \le L$-1), where L is the number of signals detected by the DOA estimator. Let σ_0^2 denote the detected desired signal power, and σ_i^2 ($1 \le i \le L$-1) the powers of the others. The M-element array antenna's weight vector can be calculated by using θ_i ($0 \le i \le L$-1) and σ_i^2 ($0 \le i \le L$-1) so that it forms a beam steered towards the desired signal while forming nulls towards the interferers.

Let $\boldsymbol{c} = (c_1, c_2, \cdots, c_{m_1})^{\mathrm{T}}$ denote the m_1-element array antenna's weight distribution that forms a specific beam pattern. The Taylor or Chebyshev distributions may be used as $\boldsymbol{c}$. It follows that the m_1-element array antenna's weight vector for beam steering, $\boldsymbol{W}_{beam}$, can be calculated by using θ_0 of the desired signal's DOA as

$$\boldsymbol{W}_{beam} = (c_1 s_{b,1}(\theta_0), c_2 s_{b,2}(\theta_0), \cdots, c_{m_1} s_{b,m_1}(\theta_0))^{\mathrm{T}}, \quad (1)$$

where $\mathbf{s}_b(\theta_0) = (s_{b,1}(\theta_0), s_{b,2}(\theta_0), \cdots, s_{b,m_1}(\theta_0))^{\mathrm{T}}$ is the steering vector for θ_0.

An m_2-element array antenna's weight vector for null steering, $\boldsymbol{W}_{null}$, can be calculated by using the DOAs of the desired signal and the interferers. If the number of interferers (L-1) is larger than the null steering array antenna's degree-of-freedom m_2-1, not all the interferers

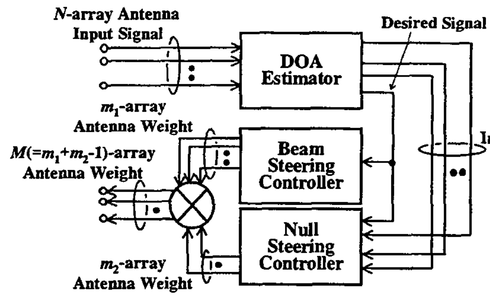

Figure 2. Configuration of Parameter Estimator-1

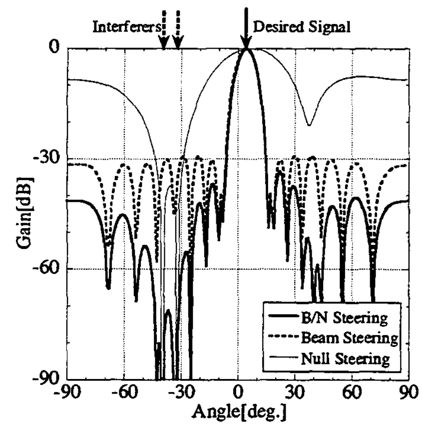

Figure 3. Example of the beam pattern

can be canceled. In such cases, the m_2-1 strongest interferers are selected and canceled. In order to calculate the array antenna's weight vector that has nulls towards m_2-1 interferers, the Howell-Applebaum algorithm [6] can be used. The array correlation matrix $\boldsymbol{R}$ is defined as;

$$\boldsymbol{R} = \sum_{i=1}^{m_2-1} \sigma_i^2 s_n(\theta_i) s_n^{\mathrm{H}}(\theta_i) + \sigma^2 \boldsymbol{I}_{m_2}, \quad (2)$$

where $s_n(\theta_i)$, σ_i^2, and σ^2 represent the m_2-element steering vectors associated with the directions θ_i ($1 \le i \le m_2$-1), powers of interferers and noise, respectively. $\boldsymbol{I}_{m_2}$ denotes an $m_2 \times m_2$ unit matrix.

The null steering array antenna's weight vector $\boldsymbol{W}_{null}$ can then be expressed as

$$\boldsymbol{W}_{null} = \boldsymbol{R}^{-1} s_n(\theta_0), \quad (3)$$

where $s_n(\theta_0)$ represents the m_2-element steering vector associated with the direction θ_0. An M ($=m_1+m_2$-1)-element array antenna's weight vector for beam and null steering can finally be obtained from $\boldsymbol{W}_{beam}$ and $\boldsymbol{W}_{null}$ as

$$\boldsymbol{W} = \boldsymbol{W}_{beam} * \boldsymbol{W}_{null}, \quad (4)$$

where * denotes a convolution between the two matrixes. Eq.(4) can be folded into $\boldsymbol{W}$=$\boldsymbol{B}$ $\boldsymbol{W}_{null}$, where matrix $\boldsymbol{B}$ is given by

$$
B = \begin{pmatrix} w_{b,1} & 0 & \cdots & 0 \\ w_{b,2} & w_{b,1} & \cdots & 0 \\ \vdots & \vdots & & \vdots \\ w_{b,m_1} & w_{b,m_1-1} & \cdots & 0 \\ 0 & w_{b,m_1} & \cdots & 0 \\ 0 & 0 & \cdots & 0 \\ \vdots & \vdots & & \vdots \\ 0 & 0 & \cdots & w_{b,1} \\ 0 & 0 & \cdots & w_{b,2} \\ \vdots & \vdots & & \vdots \\ 0 & 0 & \cdots & w_{b,m_1} \end{pmatrix}. \qquad (5)
$$

Figure 3 shows a typical beam pattern obtained as a result of the proposed algorithm, where three signals are assumed to have been impinging on the antenna. The thick, thin, and dashed lines represent the beam patterns corresponding to $\boldsymbol{W}$, $\boldsymbol{W}_{beam}$, and $\boldsymbol{W}_{null}$, respectively. The beam pattern with $\boldsymbol{W}$ inherits both $\boldsymbol{W}_{beam}$ and $\boldsymbol{W}_{null}$'s designed beam patterns: the sharp main beam is steered towards the desired signal's DOA θ_0 and the nulls towards the interferers.

2.2. Temporal Equalization

Even though the spatial equalizer with the proposed beam and null steering algorithm can eliminate the effects of interference and most of the delayed desired signal components, some of the delayed desired signal components, having incident angles very close to the desired signal, may also be captured by the main beam. These components cause ISI distortion on the received desired signal at the output of the spatial equalizer. The primary purpose of the temporal equalizer following the spatial equalizer is to eliminate the ISI caused by the delayed desired signal components captured by the main beam.

For temporal equalization, Maximum Likelihood Sequence Estimation (MLSE) equalizers [7] are known to achieve optimal performance. Unfortunately, the computational complexity of MLSE equalizers is exponential to the delay spread on the received desired signal, and hence it is impractical to use MLSE in ISI-rich broadband mobile communication environments. Therefore, some type of complexity-reduced sub-optimal detector is needed for temporal equalization.

2.3. Timing Control

If the taps of the spatial and temporal equalizers are changed asynchronously, updating the spatial equalizer taps may interfere with the signal reception using the temporal equalizer. Hence, spatial and temporal signal processing should be separated such that the equalizers can update their taps independently. An advantage of the DOA-based spatial equalizer is that DOAs of the incident signals basically stay constant over several milliseconds, which corresponds to a couple of data frames. Hence the spatial equalizer taps can be kept constant over a couple of frames, while those of the temporal equalizer have to be updated frame-by-frame. This allows, without causing severe performance degradation, the taps of the spatial equalizer to be updated in the gap between frames. The proposed separated S/T-Equalizer utilizes this concept, and so demands timing control of operation.

3. Field Test Results

3.1. Specifications of Prototyped System

A prototype of the proposed S/T-Equalizer was built for 1.5Mbps×4channels GMSK signal transmission. Because of the overhead for some implementation purposes, the signal transmission baudrate was 14Mbps. A series of field tests was conducted using the prototyped system. Table 1 summarizes major specifications of the prototyped system. For DOA estimation, an 8-element linear array was used. The MUSIC algorithm was run on the prototyped system using the 8-element linear array output vector to detect DOAs. A 19-element linear array, which was located separately from but close enough in space to the DOA detection's 8-element array, was used for beam-forming. Of the 19 antenna elements, 16 were used for beam steering and 4 for null steering, which satisfies $m_1+m_2-1=M$. Taylor distribution was used as the array antenna's weight distribution for beam steering.

For temporal equalization, a DDFSE equalizer [4] was used. The DDFSE equalizer combines the concepts of the MLSE equalizer and the Decision Feedback Equalizer (DFE); by eliminating some of the MLSE states from the trellis diagram for the channel, its complexity remains feasible. The DDFSE equalizer has two sets of taps: one for MLSE, the other for DFE. In the prototyped system, MLSE has 4 taps and DFE 11 taps, resulting in 15 taps in total, which, with the symbol duration T, covers delay spread of up to 14T. In addition to signal detection, the temporal equalizer also outputs an estimate of the delay profile as a result of channel estimation.

3.2. Field Test Courses

A series of field tests was conducted to evaluate uplink (mobile-to-base) signal transmission performance of the prototyped system. Figure 4 shows the measurement course for the field tests. As a Base Station (BS), the prototyped proposed S/T-Equalizer was located on the top of Building X to receive the signal transmitted from a Mobile Station (MS). BS antenna height was about 20m. An omni-directional monopole antenna was located on the top of the vehicle, and used for signal transmission. Points A and b and their vicinities have Line-Of-Sight (LOS) paths: other locations are non LOS (NLOS) regions due to the presence of Buildings X and Y.

Table 1. Specification of prototyped system

Frequency band	5GHz FDD
Modulation	GMSK
Baudrate	14Mbps
Bit-rate	1.5×4 Mbps
Adaptive Array Antenna	
DOA Estimation(*N*)	8 element array
Algorithm	MUSIC
Beamforming(*M*)	19 element linear array
Beam Steering(m_1)	16 elements Taylor distribution
Null Steering(m_2)	4 elements
Temporal Equalizer	15tap-DDFSE (MLSE:4, DFE:11)

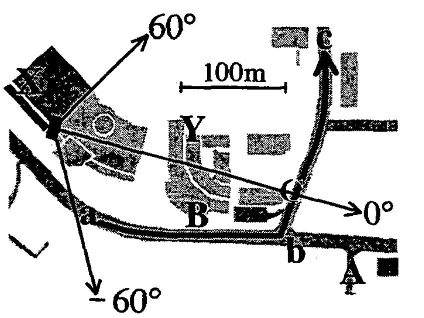

Figure 4. Measurement course for field tests

3.3. BER Performance under LOS Conditions

BER performance was first evaluated with the MS located at Point A. The DOA estimator detected only a single path having 10 degree DOA, which corresponds to the look angle from the BS to Point A. Figure 5 shows measured BERs versus received E_b/N_0 at the array output. In order to change the E_b/N_0 value, the transmission power was controlled. The solid and dashed lines represent the theoretical and simulated BER curves. Delay spread estimated by the temporal equalizer at Point A was less than 1T, and hence no BER floor is observed. The measured BER is 2dB worse than the simulation result. This is reasonable considering the impairments inherent in hardware implementation.

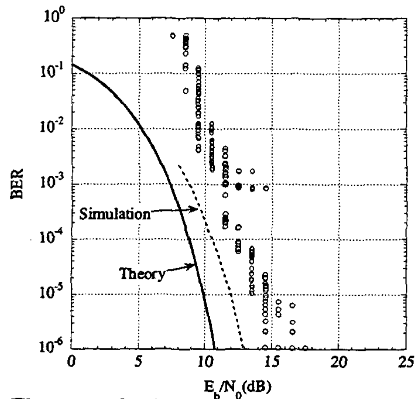

Figure 5. BER performances at Point A

3.4. BER Performance under NLOS Conditions

BER performance was then evaluated when the MS was located at Points B and C, where there were no LOS paths from the BS. Figure 6 shows a MUSIC spectrum and its corresponding beam pattern obtained by the prototyped system when the MS was located at Point B. In this case, three signals having DOAs of -13 degrees, 10 degrees, and 23 degrees were detected. The strongest signal of the three was the one with -13 degree DOA. Hence, the beam was steered towards that direction and the nulls were formed towards the directions of the other signals.

Figure 7 shows measured BERs at Point B. The symbols ● and ○ plot BER performance with and without AAA, respectively. In both cases, the DDFSE temporal equalizer was used. The delay spread evaluated by the temporal equalizer without AAA was about 3.5T, which exceeds MLSE capacity of the DDFSE equalizer. This is a major cause of degradation in the BER performance without AAA. With AAA, the delay spread can be reduced to less than 1T because AAA can suppress delayed signal components. This improves the BER performance.

Due to the blockage from Building Y, Point C is also an NLOS region. Figure 8 shows measured BERs when the MS was located at Point C. The symbols ● and ○ plot BER performance with and without the temporal equalizer, respectively. In both cases, AAA was used. The delay spread estimated by the temporal equalizer was about 2.5T. This indicates the existence of delayed components falling on the AAA's main beam, so the BER is degraded without the DDFSE temporal equalizer. The conclusion is that spatial equalization by itself can not achieve acceptable BERs if delayed desired signal components fall on the antenna's main beam.

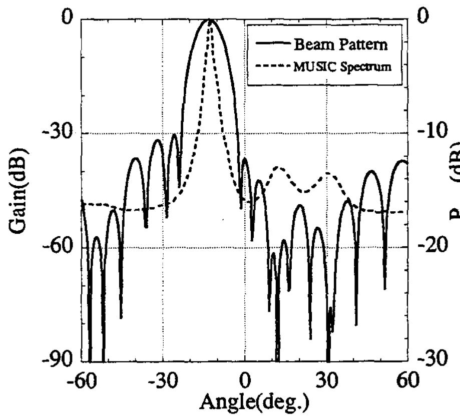

Figure 6. MUSIC spectrum and beam pattern obtained by the prototyped S/T-Equalizer

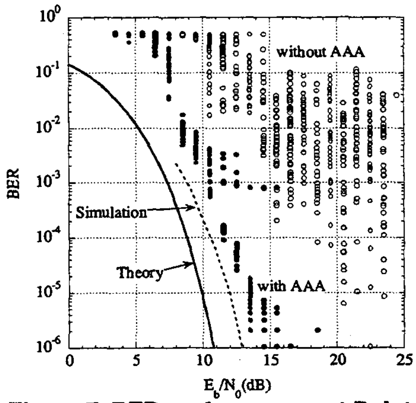

Figure 7. BER performances at Point B

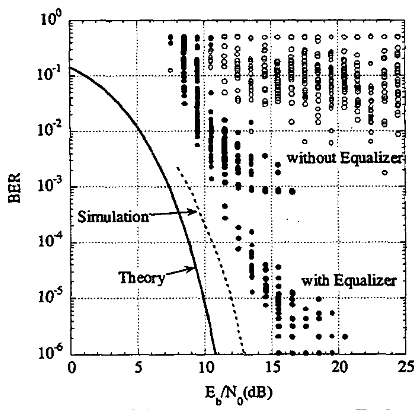

Figure 8. BER performances at Point C

3.5. BER Performance under Dynamic Condition

BER performance was evaluated when the MS moved from Point A to Point C as shown in Fig.4. Figure 9 shows measured BER performance for average vehicle speed of 30km/h. The thick, thin, and dashed lines represent the measured BERs with the proposed S/T-Equalizer, with just the spatial equalizer, and with just the temporal equalizer, respectively. The MS started from Point A; it passed through Point C 15 seconds later, and reached Point C 50 seconds later. At Point B, the BER was smaller than 10^{-6} due to the LOS path. At most of the locations over the entire 400m measured course, the proposed S/T-Equalizer can achieve BERs better than 10^{-4}. With just the spatial equalizer or just the temporal equalizer, the BERs exceeded 10^{-2} over more than 50% of the entire course. This suggests that the joint use of spatial and temporal equalizers can significantly improve BER performance.

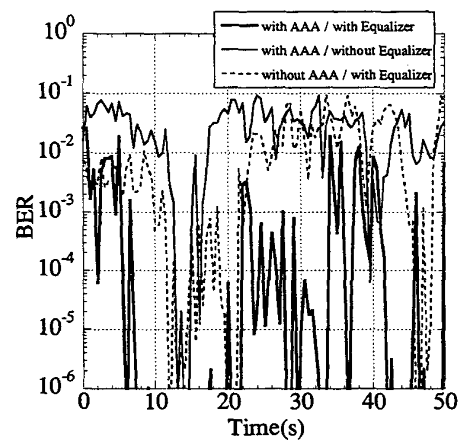

Figure 9. BER performances at the average speed of 30km/h

4. Conclusion

In this paper, we have proposed a new S/T-Equalizer featuring separated spatial and temporal signal processing. This separation reduces computational complexity to a practical level. A simultaneous beam and null steering AAA algorithm was derived for the S/T-Equalizer. The simultaneous beam and null steering AAA algorithm combines the concepts of beam steering and null steering: a sharp beam is steered towards the desired signal and nulls towards other signals. The proposed S/T-Equalizer was prototyped, and field tests were conducted to evaluate uplink transmission performance of the proposed system. BER performance under NLOS and dynamic conditions suggests that the joint use of spatial and temporal equalizers can significantly improve BER performances over the case where either spatial equalizer or temporal equalizer is used alone.

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