A Spatio-Temporal Equalization Method for 60 GHz Indoor Wireless Local Area Networks

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Abstract— This paper proposes a spatio-temporal equalization method, which employs a cascade configuration of an adaptive array and a decision feedback equalizer (DFE). With the configuration, the proposed equalizer requires small numbers of weights, and hence, low computational complexity, however, it has to pay a price for the simplicity, namely, noise enhancement due to high sidelobe levels in certain radio propagation environments. In this paper, we have settled the problem by introducing beamforming criterion selectability. The proposed equalizer changes a criterion in beam-weight calculation depending on estimated channel condition, therefore, it can achieve good performance even in the channel models where directions of arrival (DoAs) of incoming waves are randomly determined.

This paper investigates the bit error rate (BER) performance of the proposed equalizer in various channel models, which are based on measurement reports, in comparison with the performance of a adaptive tapped-delay-line (TDL) array.

I. INTRODUCTION

The millimeter-wave frequency band is considered to be a promising candidate to provide broadband services in an indoor wireless local area network (LAN), because of its availability of required bandwidth (more than hundreds of MHz spectral space) and the severe attenuation of the walls. Especially, the band around 60 GHz is advantageous since there is a specific attenuation characteristic due to atmospheric oxygen of about 15 dB/km. It has been shown that a considerable performance enhancement is obtained by using the 60 GHz band[1]. However, even when the 60 GHz band is employed, the radio channel becomes frequency selective, if the signal bandwidth exceeds several dozens MHz[2], therefore, in such high speed communications systems, some countermeasures have to be taken to cope with the frequency selective fading.

Spatio-temporal equalization is a technique which utilizes both spatial and temporal information of received signal to compensate intersymbol interference due to multipath fading. So far, a considerable number of studies have been made on spatio-temporal equalization, and a lot of the equalization methods have been proposed[3]-[7]. However, though the equalization methods can achieve good performance, they require high computational complexity. This is because almost all the methods employ an adaptive antenna array which has temporal filter at each antenna element, i.e. adaptive TDL array (ATDLA)(Fig.1), or maximum likelihood sequence estimation (MLSE) approach in weights calculation. With such methods, real time processing could be hardly possible in high speed communications systems, such as broadband wireless LANs.

In this paper, attaching greater importance to computational complexity, we propose a spatio-temporal equalizer which employs a cascade configuration, such that **an adaptive antenna array without temporal filter** is followed by a DFE(Fig.2). Moreover, in the equalizer, the weights are determined depending not on the MLSE criterion but on the MMSE (Minimum Mean-Square-Error) criterion. Therefore, the proposed equalizer requires less computational complexity than ATDLA or MLSE based spatio-temporal equalizer. On the other hand, the cascade configuration needs to pay a price for the simplicity. When DoA of a desired wave is almost the same as that of an undesired wave, SNR (Signal to Noise Ratio) of the received signal could be degraded, because of high sidelobe levels and spatial whiteness of the noise (Fig.3 pattern A), and it is difficult to improve the performance with the temporal processing in the latter part. In this paper, we have settled the problem by introducing **beamforming criterion selectability**. To be concrete, the proposed equalizer forms
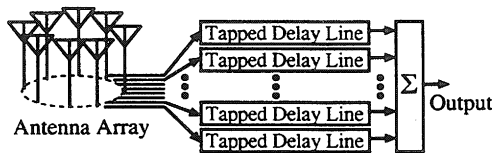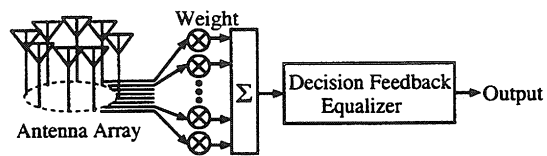

Fig. 1. Adaptive TDL Array
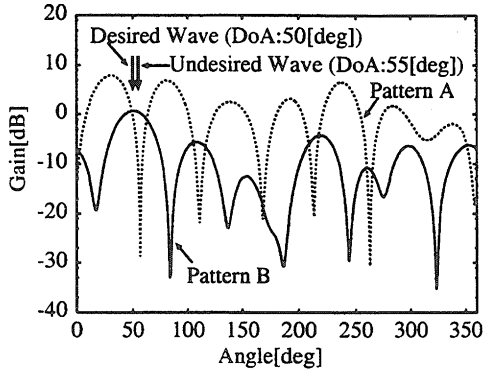

Fig. 2. Proposed Configuration

Fig. 3. Example of antenna patterns

(a)Transmitter

(b)Receiver

Fig. 4. Transmitter/Receiver Structure

such a beam pattern as to capture both the desired wave and the undesired wave (Fig.3 pattern B) when the desired and the undesired waves have almost the same DoA, and the remaining undesired components are equalized in the temporal processing. Owing to the beamforming criterion selectability, the proposed equalizer can achieve good performance even in the channel models where DoAs of incoming waves are randomly determined.

We also show the BER performance of the proposed equalizer in various channel models, which are based on measurement reports[8], [9], and compare the performance between a ATDLA and the proposed spatio-temporal equalizer.

II. SYSTEM CONFIGURATION

Assume that the proposed spatio-temporal equalizer is applied to the down link of a 60 GHz indoor wireless LAN. Fig.4 shows the transmitter and receiver structure. In our method, we prepare two types of channels; a traffic channel and a pilot channel. The traffic channel is used to convey information signals, and the pilot channel is for the pilot signal which is used to estimate the channel impulse response. In the receiver, the incoming wave is received by an antenna array with N_{ary} sensors. After then, the received signal is processed in the data signal processing section and in the pilot signal processing section independently. In the data signal processing section, the outputs from the matched filters are multiplied by the weights of the beamformer which are calculated in the pilot signal processing section. After symbol timing synchronization, pilot signal extraction and equalization with DFE which has N_{ftap} taps in the feedforward filter and N_{btap} taps in the feedback filter, the data are recovered. In the pilot signal processing section, the complex instantaneous channel impulse response at each sensor is first estimated by correlating the received pilot signal. Then, using the estimated
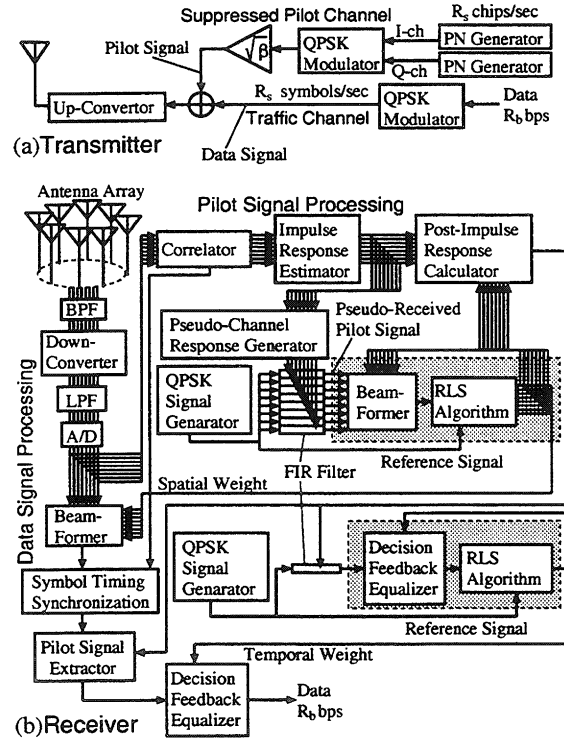
channel impulse response, the receiver selects a suitable beamforming criterion for the channel condition. In our method, the equalizer calculates the weights of beamformer using the pseudo-received pilot signal which is generated in the receiver, and the equalizer can change its beamforming criterion by selecting an appropriate impulse response for the pseudo-received pilot signal generation. Details of the selection of beamforming criterion, in other words, impulse response for the pseudo-received pilot signal generation, are discussed in section III. The weights of the beamformer are calculated by the recursive least square (RLS) algorithm with the pseudo-received pilot signal. The weights of DFE are also determined in the same manner as the beam-weights calculation using the pseudo-received pilot signal which is generated from the estimated channel response including the beamformer.

III. BEAMFORMING CRITERION SELECTION ALGORITHM

The proposed equalizer selects a suitable impulse response for pseudo-received pilot signal generation which is used to calculate beam-weights depending on the channel conditions, and the channel conditions are judged from the estimated channel impulse

response. In the followings we show the classification of the channel conditions, and discuss suitable beamforming criterion for the each channel condition.

- **Small Angular Spread of Each Incoming Wave**
  In this case, DoAs of incoming waves can be estimated from phase differences of the estimated channel response. According to DoA patterns, the channel conditions can be further classified into the following two situations;
  - *DoA of the desired wave $\neq$ DoA of the undesired wave*
    The adaptive array can capture only the desired wave (the path with the maximum power), therefore, the equalizer utilizes **the estimated channel response as it is** (*Response 1*) for the pseudo-received pilot signal generation.
  - *DoA of the desired wave $\cong$ DoA of the unesired wave*
    The equalizer utilizes **the estimated channel response without the undesired component** (*Response 2*) for the pseudo-received pilot signal generation, in order to capture both the desired and the undesired waves.
- **Large Angular Spread of Each Incoming Wave**
  In this case, DoAs of incoming waves cannot be estimated from the channel impulse response, however, the adaptive array operates as a diversity system because of low correlation of the received signals among the sensors. Therefore, the equalizer can select *Response 1* for the pseudo-received pilot signal generation.

Fig.5 shows the impulse response selection algorithm to realize the beamforming criterion selection mentioned above. The receiver first determines the delay time k_{max} of the desired wave. Then, it calculates the normalized variation of the instantaneous amplitude of the estimated channel response P_{vari}, which is defined as

$$P_{vari}(k) = \frac{1}{N_{ary}} \sum_{n=1}^{N_{ary}} \frac{\{|f_n(k)| - \overline{|f(k)|}\}^2}{\overline{|f(k)|}^2}, \quad (1)$$

$$\overline{|f(k)|} = \frac{1}{N_{ary}} \sum_{n=1}^{N_{ary}} |f_n(k)|, \quad (2)$$

where $f_n(k)$ denotes the estimated channel impulse response at the nth antenna sensor, and the receiver judges the angular spread of the incoming wave is large if $P_{vari}(k)$ exceeds a threshold Th_{vari}.

If the angular spread of the desired wave is large, or else if the angular spreads of all the undesired waves are large, the equalizer selects *Response 1*, since the adaptive array can capture only the desired wave regardless of DoA patterns of the undesired waves. Otherwise, the equalizer calculates the DoA of each
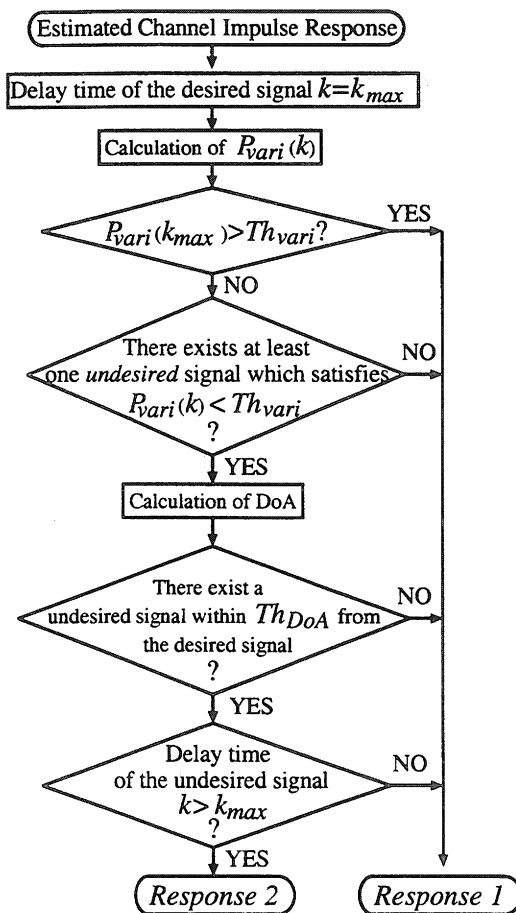

Fig. 5. Beamforming Criterion Selection Algorithm

incoming wave from the phase differences of the estimated channel impulse responses. If there exists at lease one undesired wave whose DoA is within Th_{DoA} from the DoA of the desired wave, and if the delay time of the desired wave is smaller than that of the undesired wave, the equalizer selects *Response 2*, otherwise, *Response 1*.

IV. COMPUTER SIMULATION

Computer simulations are conducted to evaluate the performance of the proposed spatio-temporal equalizer in comparison with that of the ATDLA.

A. Space-Time Channel Model

In agreement with measurements reported in [8], we use delay power spectrum (DPS) of a line-of-sight (LoS) channel defined in Fig.6. We have further assumed the spatial properties of the channel as depicted in Fig.7 and Fig.8. Fig.7 depicts a space-time channel model (Model A), where delayed incoming rays form clusters shown in [9]. In the case of no
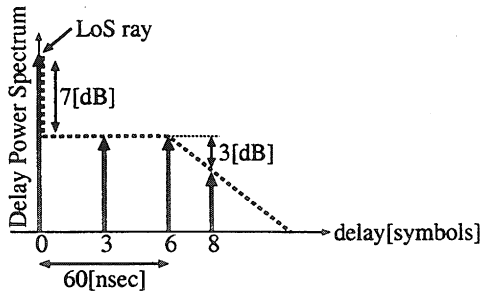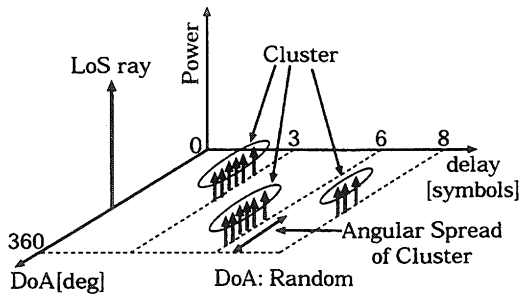
Fig. 6. Model of the Delay Power Spectrum

Fig. 8. Space-Time Channel Model (Model C)

Fig. 7. Space-Time Channel Model (Model A and B)

TABLE I

SYSTEM PARAMETERS

# of sensors N_{ary}	8 (circular array)
Symbol rate R_s	100[Msymbols/sec]
Carrier frequency f_c	60[GHz]
Roll-off factor α	0.5
Oversampling factor N_{smp}	4
RLS Repetitions N_{cal}	50

LoS channel (Model B), LoS rays in Fig.6 and 7 will be omitted. Fig. 8 is a space-time channel model to evaluate the performance in the environment where the angular spread of incoming waves is quite small (Model C). DoAs of a LoS ray and clusters follow a uniform distribution of [0,360)[deg], whereas distribution of the individual clusters is assumed to be a uniform distribution of [-45,45][deg], which corresponds to standard deviation of 26[deg]. Taking account of an indoor environment, we have chosen the Doppler spectrum of flat and the maximum Doppler shift of 150Hz.

B. System Parameters

System parameters used in all the computer simulations are summarized in Table I. Both the proposed system and the ATDLA have a circular array with 8 sensors, whose sensor spacing is half of the carrier wavelength. The proposed system employs an DFE which has 17taps (N_{ftap}=9, N_{btap}=8), while the ATDLA has totally 72taps (or 24taps) in the TDLs. In the proposed system, thresholds of the DoA Th_{DoA} and the normalized variation Th_{vari} were chosen to be 10.0[deg] and 0.07, respectively.

C. Simulation Results

Figs.9, 10, and 11 show the BER performance versus the ratio of the average energy per symbol to the noise power density ($\overline{E_s/N_0}$) for in the channel model
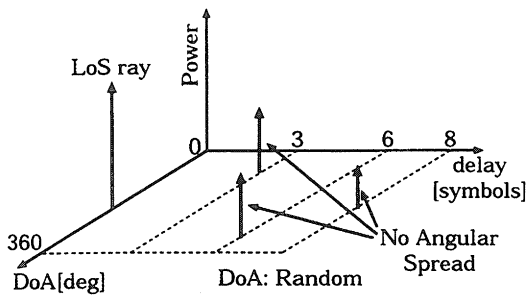
A, B, and C, respectively. The BER performances of the ATDLA with 72taps and 24taps are also plotted in the same figures.

In the model A, the ATDLA with 72taps can achieve the best performance among the three equalizers, though the BER of the proposed system is the lowest at low $\overline{E_s/N_0}$. Also, the inclination of the BER of the ATDLA with 72taps is larger than the proposed system. This is because the temporal processing section of the ATDLA can operate as a combining diversity system, whereas the temporal processing in the proposed equalizer is essentially a selection diversity system.

In the model B, all the curve of the BER have almost the same inclination. This means that, in such a situation where all the incoming signals have angular spread, the performance of the adaptive array dominantly determines the overall performance. The reason why the BER of ATDLA with 72taps is higher than that of ATDLA with 24taps is that the ATDLA with 72taps suffers from slow rate of convergence in weight calculation due to the large numbers of weights.

In the model C, the BER performance of the ATDLA with 24taps degrades exceedingly. This means that even spatio-temporal equalizer, which has both the spatial and the temporal processing, has to have the temporal filter which can deal with the maximum time delay of the incoming waves when the waves have small angular spread. The proposed equalizer can achieve good performance in this model, too.

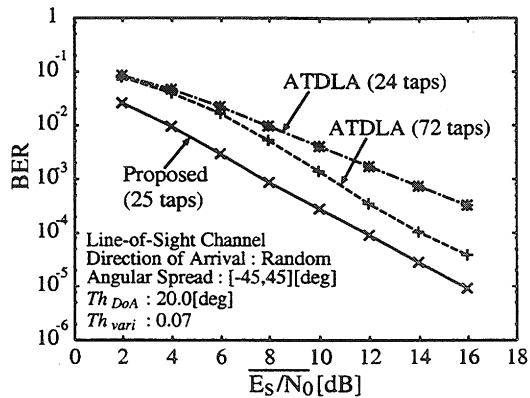From all the results, it can be concluded that the

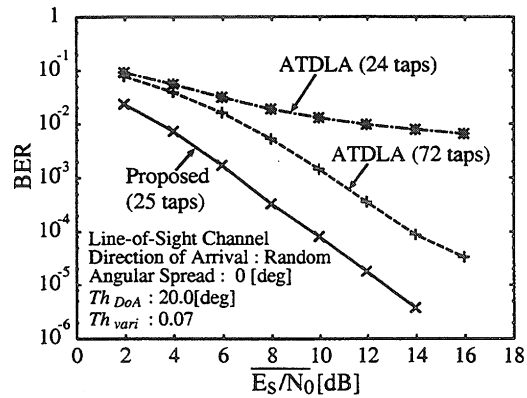Fig. 9. Bit Error Rate in Channel Model A

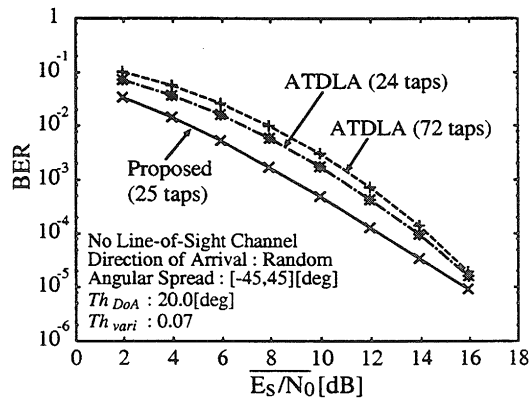Fig. 11. Bit Error Rate in Channel Model C

Fig. 10. Bit Error Rate in Channel Model B

proposed equalizer can achieve good performance for all the channel models with small numbers of weights, and hence, low computational complexity.

V. CONCLUSION

In this paper, we have proposed a spatio-temporal equalization method, which employs a cascade configuration of an adaptive array without temporal filter and a DFE, and evaluated its performance comparing with the ATDLA. What is especially important about the proposed equalizer is that it selects a suitable beamforming criterion depending on the channel condition, therefore, **the proposed equalizer can manage low computational complexity and good performance at the same time.**

We have shown the BER performance in the three space-time channel models, which are based on measurement reports. From all the results, we have confirmed that the proposed system can achieve good performance with low computational cost.

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