A Spatio-Temporal Equalization Method for Indoor Wireless LANs with Beamforming Criterion Selection

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Abstract— **Spatio-temporal equalization is a technique which utilizes both spatial and temporal information of received signal to compensate intersymbol interference due to multipath fading. Considering application of a spatio-temporal equalizer to high speed wireless communications systems, such as wireless LANs, this paper proposes a new spatio-temporal equalization method using a cascade configuration of an adaptive array and a DFE (Decision Feedback Equalizer), which can be realized with small number of weights, and hence, low computational complexity. However, it has to pay a price for the simplicity, namely, the error performance surface becomes a fourth-order function of the weights, and possibly has two minima. In order to avoid wrong trap by a local minimum during the adaptation of MMSE (Minimum Mean-Squared Error) based adaptation algorithm with any initial values, the proposed equalizer calculates the weights of the adaptive array and the DFE separately in two steps, and the adaptive array selects a path or paths to capture depending on channel conditions.**

Computer simulation results show that the proposed method can achieve good performance in various channel models, which are based on measurement reports, in low computational complexity.

I. INTRODUCTION

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[1]-[5]. However, though the equalization methods can achieve good performance, they require high computational complexity. This is because almost all the methods employ an adaptive array which has temporal filter at each sensors, i.e. adaptive TDL array (ATDLA), 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, considering the application of a spatio-temporal equalizer to high speed wireless communications systems, we propose a spatio-temporal equalizer which employs a cascade configuration, such that an adaptive array is followed by a DFE (Decision Feedback Equalizer)(Fig.1). The spatio-temporal equalizer with the cascade configuration requires small number of weights, and hence, low computational complexity, however, it needs to pay a price for the simplicity. Since the output signal of the equalizer consists of input signals multiplied by the weights twice (the weights of the adaptive array and the DFE), the output signal is a second-order function of the weights. This means that the cost function in the MMSE (Minimum Mean-Squared Error) based weight calculation algorithm becomes a fourth-order function of the weights and that the error performance surface of the equalizer possibly has two minima. In order to avoid wrong trap by a local minimum during the adaptation of the MMSE based adaptive algorithm, the proposed equalizer calculates the weights of the adaptive array and the DFE separately in two step. Moreover, the adaptive array can selects a path or paths to capture, in other words, the beamforming criterion, depending on channel conditions. Owing to the beamforming criterion selectability, the proposed equalizer can achieve good performance using the MMSE based adaptive algorithm with any initial values. We show the BER performance of the proposed equalizer in various channel models, which are based on measurement reports[6], [7], and compare the performance between a ATDLA and the proposed spatio-temporal equalizer.

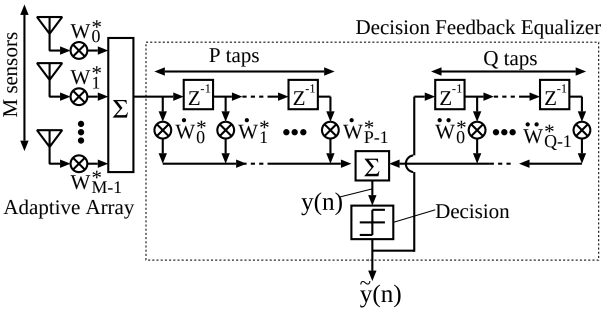

Fig. 1. Cascade Configuration of Spatio-Temporal Equalizer

II. ERROR PERFORMANCE SURFACE

In this section, we show a unique problem of the spatio-temporal equalizer with the cascade configuration (Fig.1) from a view point of the error performance surface, and discuss how to overcome the problem.

When the inputs of the spatio-temporal equalizer at time n are $x_0(n), \ldots, x_{M-1}(n)$, the output $y(n)$ can be written as

$$y(n) = \sum_{m=0}^{M-1} \sum_{p=0}^{P-1} w_m^* \dot{w}_p^* x_m(n-p) + \sum_{q=0}^{Q-1} \ddot{w}_q^* \tilde{y}(n-q-1), \tag{1}$$

where *, M, P, Q, w_m, $\dot{w}_p$, $\ddot{w}_q$ and $\tilde{y}(n)$ denote the complex conjugate, the number of sensors, the length of the feedforward filter in the DFE, the length of the feedback filter, the weights of adaptive array, the weights of the feedforward filter, the weights of the feedback filter and the detected signal at time n, respectively. Using the desired signal $d(n)$, the cost function J of the MMSE based adaptive algorithm can be represented by

$$\begin{aligned} J &= E[|d(n) - y(n)|^2] \\ &= E[|d(n)|^2] \\ &- \sum_{q=0}^{Q-1} \{\dot{w}_q^* E[\tilde{y}(n-q-1) d^*(n)] \\ &\qquad + \dot{w}_q E[\tilde{y}^*(n-q-1) d(n)]\} \\ &- \sum_{m=0}^{M-1} \sum_{p=0}^{P-1} \{w_m^* \dot{w}_p^* E[x_m(n-p) d^*(n)] \\ &\qquad\qquad + w_m \dot{w}_p E[x_m^*(n-p) d(n)]\} \\ &+ \sum_{q=0}^{Q-1} \sum_{k=0}^{Q-1} \ddot{w}_q^* \ddot{w}_k E[\tilde{y}(n-q-1) \tilde{y}^*(n-k-1)] \\ &+ \sum_{m=0}^{M-1} \sum_{p=0}^{P-1} \sum_{q=0}^{Q-1} \\ &\qquad \{w_m^* \dot{w}_p^* \ddot{w}_q E[x_m(n-p) \tilde{y}^*(n-q-1)] \\ &\qquad + w_m \dot{w}_p \ddot{w}_q^* E[x_m^*(n-p) \tilde{y}(n-q-1)]\} \\ &+ \sum_{m=0}^{M-1} \sum_{p=0}^{P-1} \sum_{k=0}^{M-1} \sum_{i=0}^{P-1} \{w_m^* \dot{w}_p^* w_k \dot{w}_i \\ &\qquad\qquad \times E[x_m(n-p) x_k^*(n-i)]\}. \end{aligned} \tag{2}$$

Equation (2) states that the cost function J of the spatio-temporal equalizer with cascade configuration is a fourth-order function of the weights, and possibly has two minima. If we use MMSE based adaptive algorithms with any initial values, in order to calculate the weights, the weights may be trapped by a local minimum during the adaptation.

From a viewpoint of practical operation of the spatio-temporal equalizer, the local minima can be seen when primary and delayed waves, come from almost the same direction. Fig.2 shows examples of the antenna beam patterns (pattern A and B) when a primary wave and a delayed wave come from 50 [deg] and 55 [deg], respectively. Pattern A has a null toward the delayed wave, however, it also has high sidelobe level. Since the thermal noise is white in space, the high sidelobe level results in the degradation of the signal to noise ratio (SNR) at the output of the adaptive array, which can not be recovered with the equalization of the DFE. On the other hand, pattern B does not suffer from the degradation of SNR, though pattern B can not cancel the delayed wave. The component of the delayed wave can be canceled at the DFE, therefore, the spatio-temporal equalizer can achieve good performance with pattern B. In this case, pattern A may be a local minimum of the cost function J and pattern B could be the global minimum.

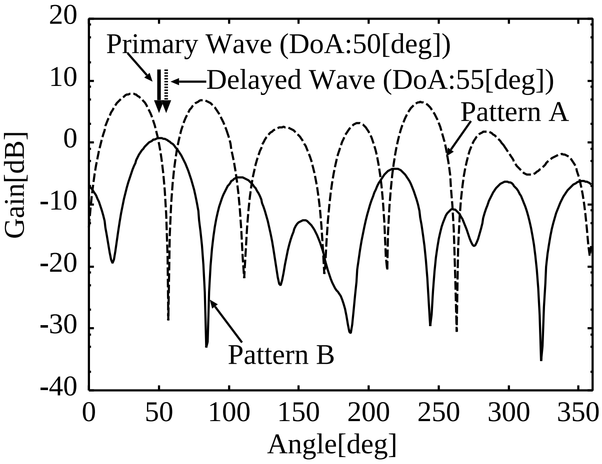

Fig. 2. Example of Antenna Patterns

This example suggests that we could guide the weights to the global minimum by calculating the weights of the adaptive array and the DFE separately in two steps, and by selecting a beamforming criterion depending on the channel condition. In the next section, we propose a spatio-temporal equalization method which is based on the discussion above.

III. Proposed Spatio-Temporal Equalization Method

A. Selective Reception with Adaptive Array

Generally, an adaptive array based on MMSE criterion algorithm captures only one path which is synchronized with the reference signal, however, with the cascade configuration of Fig.1, the adaptive array needs to capture more than one path in order to avoid the degradation of SNR.

Fig.3 shows the principle of the proposed reception method with the adaptive array. In the figure, (A) shows the channel impulse response and the DoA (Direction of Arrival) pattern. The paths a, b, and c in the response correspond to the incoming waves a, b, and c respectively. If we use the received pilot signal as it is to calculate the weights of the adaptive array synchronizing with the path with the maximum power a, the adaptive array forms a null toward the path c, which has almost the same DoA as the path a. This results in the degradation of SNR because of the high sidelobe level. In

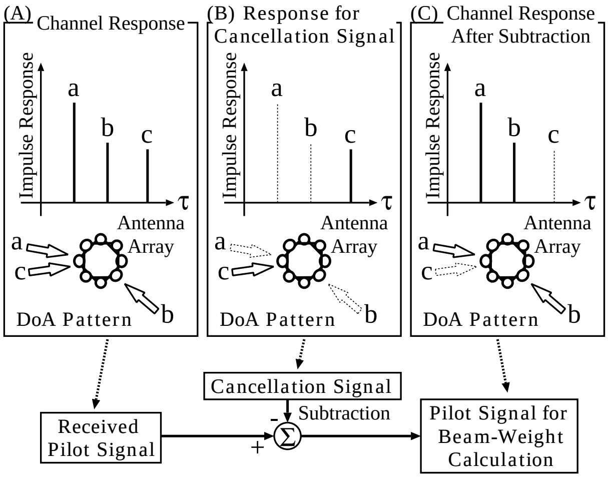

Fig. 3. Selective Reception Method with Adaptive Array

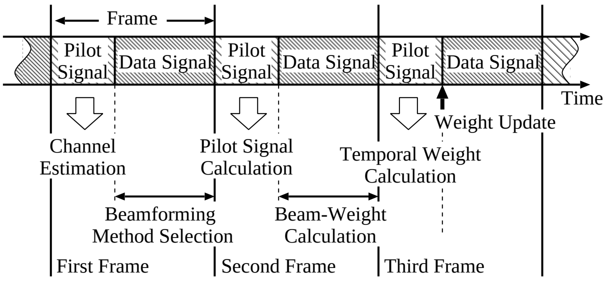

Fig. 4. Frame Format and Weight Calculation Procedure

the proposed method, to capture both the path *a* and *c*, the equalizer generates a signal for cancellation using the response shown in Fig.3 (B). By subtracting the cancellation signal from the received pilot signal, we'll have the signal which is equivalent to the received pilot signal passed through the channel shown in Fig.3 (C). With the equivalent received pilot signal, the adaptive array can form a beam toward both the path *a* and *c* by synchronizing with the path *a*.

B. Procedure of Weights Calculation

Fig.4 shows the frame format and the weights calculation procedure in the proposed method. Each frame consists of a pilot signal, which is composed of PN (Pseudo Noise) sequence with L symbols long, and a data signal. Using the pilot signals of three consecutive frames, the weights of the adaptive array and the DFE are calculated as in the followings:

- *1st. frame:* The complex instantaneous channel impulse response at each sensors is first estimated by correlating the received pilot signal. Using the estimated response, the path(s) to capture is(are) selected. Details of the path selection method are discussed in C. Also, the estimated response is used for the frame synchronization.
- *2nd. frame:* If the path to capture is only the path with the maximum power ($path_{max}$), the received pilot signal is used for the calculation of the weights of the adaptive array as it is. Otherwise, the received pilot signal which is subtracted by the corresponding components of the path to capture excluding the $path_{max}$ will be used for the weights calculation. Here, we employ the RLS (Recursive Least Square) algorithm[8] as the MMSE based adaptive algorithm, and the known pilot signal is used for the reference signal.
- *3rd. frame:* Using the received pilot signal and the weights of the adaptive array, the weights of the DFE are calculated by the RLS algorithm. The known pilot signal is also used as the reference signal. All the weights are updated at the end of the pilot signal of this frame.

C. Path Selection Algorithm

Fig.5 shows the path selection algorithm to realize the beamforming criterion selectability. The equalizer first determines the delay time k_{max} of the $path_{max}$. Then, it calculates the normalized variation of the instantaneous amplitude of the estimated channel response P_{vari}, which is defined as

$$P_{vari}(k) = \frac{1}{M}\sum_{m=1}^{M}\frac{\{|f_m(k)| - \overline{|f(k)|}\}^2}{\overline{|f(k)|}^2}, \tag{3}$$

$$\overline{|f(m)|} = \frac{1}{M}\sum_{m=1}^{M}|f_m(k)|, \tag{4}$$

where $f_m(k)$ denotes the estimated channel response at the mth sensor. Since a large angular spread of the path results in low correlation of the received signals among the sensors, the equalizer can tell the angular spread of the each path by comparing the value of $P_{vari}(k)$ with a threshold Th_{vari}. If the angular spread of the $path_{max}$ is large, or else if the angular spreads of all the other paths are large, the equalizer selects only the $path_{max}$ as the path to capture, since the adaptive array can capture only the $path_{max}$ without noise enhancement regardless of DoA patterns of the other paths. This is because the adaptive array operates like a diversity system in such situations. Otherwise, the equalizer calculates the DoA of each paths which have small angular spread from the phase differences of the estimated channel impulse responses. If there exists no path whose DoA is within Th_{DoA} from the $path_{max}$, the equalizer selects only the $path_{max}$ as the path to capture, otherwise, the $path_{max}$ and the path(s) whose DoA is(are) within Th_{DoA} from the $path_{max}$.

IV. COMPUTER SIMULATION

Computer simulations are conducted to evaluate the performance of the proposed method in comparison with the ATDLA.

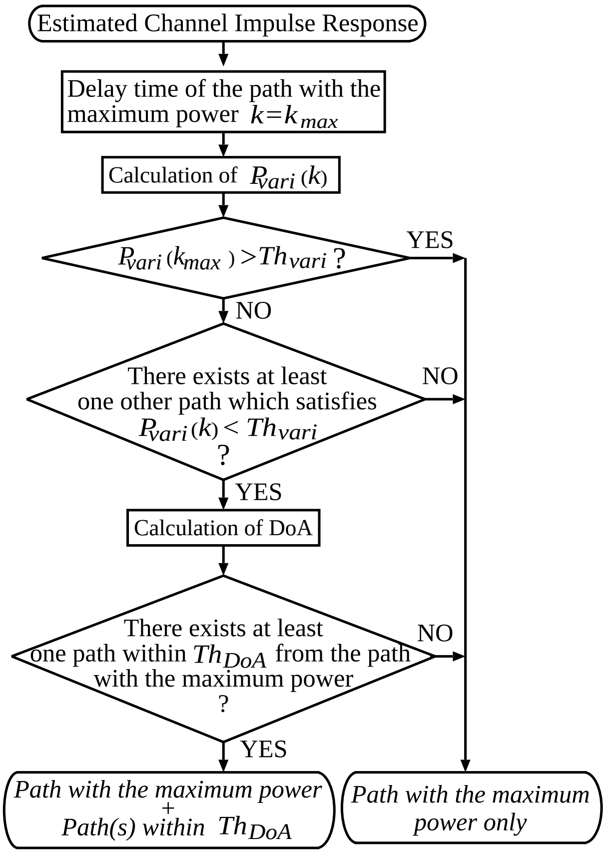

Fig. 5. Path Selection Algorithm

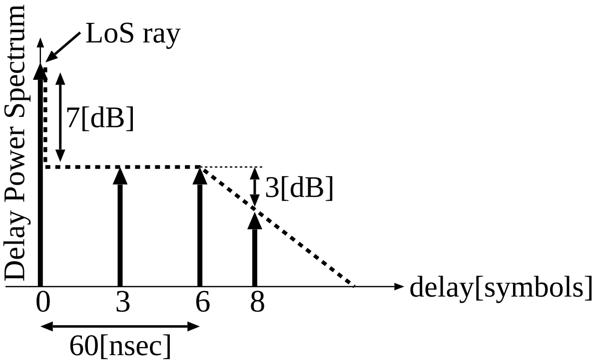

Fig. 6. Model of the Delay Power Spectrum

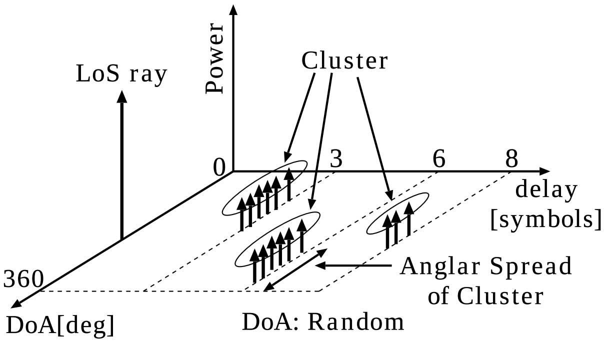

Fig. 7. Space-Time Channel Model

A. Space-Time Channel Model

In agreement with measurements reported in [6], 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 in Fig.7, which depicts a space-time channel model (Model A), where delayed incoming rays form clusters shown in [7]. In the case of no LoS channel (Model B), LoS rays in Fig.6 and 7 will be omitted. Also, in the case of LoS channel with no angular spread (Model C), each clusters has only one incoming wave. 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]. We have chosen the Doppler spectrum of flat and the maximum Doppler shift of 150 [Hz].

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 a DFE which has 17taps (P=9, Q=8), while the ATDLA has totally 72taps (or 24taps). In order to make the computational complexity of all the systems the same amount, the number of RLS repetitions of the proposed system, the ATDLA with 24taps and the ATDLA with 72taps are set to be 200, 200 and 30. In the proposed system, thresholds of the DoA Th_{DoA} and the normalized variation Th_{vari} were chosen to be 25.0 [deg] and 0.08, respectively.

C. Simulation Results

Figs.8, 9, and 10 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 and the spatio-temporal equalizer with the cascade configuration without the selection algorithm are also plotted in the same figures.

In the model A, the proposed system can achieve the best performance among the four equalizers. The BER of the ATDLA with 72taps is higher than that with 24taps at low $\overline{E_s/N_0}$. This is because the weights of the ATDLA with 72taps do not converge well due to small number of RLS repetitions.

In the model B, all the system can achieve almost the same performance. This means that the adaptive array dominantly determines the overall performance in such a situation where all the incoming signals have angular

TABLE I

System Parameters

# of sensors M	8 (equi-spaced circular array)
Symbol rate	100 [Msymbols/sec]
Carrier frequency	60 [GHz]
Roll-off factor	0.5
PN sequence	M sequence (L=255 [symbols])

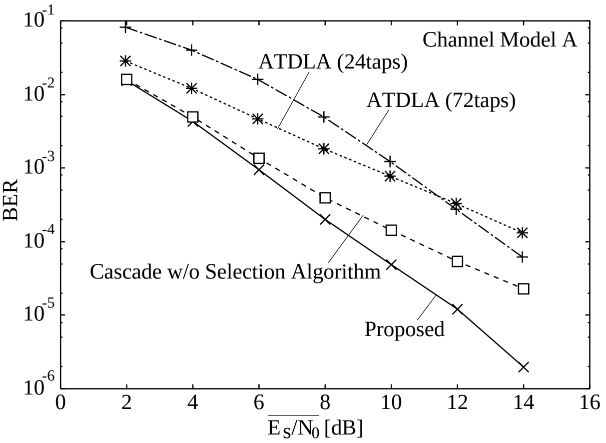

Fig. 8. Bit Error Rate in Channel Model A

spread.

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 the best performance in this model, too.

V. Conclusion

In this paper, we have proposed a spatio-temporal equalization method, which employs a cascade configuration of an adaptive array and a DFE, and evaluated its performance comparing with the ATDLA. In the proposed method, in order to avoid wrong trap by a local minimum, the weights of the adaptive array and the DFE are calculated separately in two steps, and the adaptive array selects a path or paths to capture depending on channel conditions. 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.

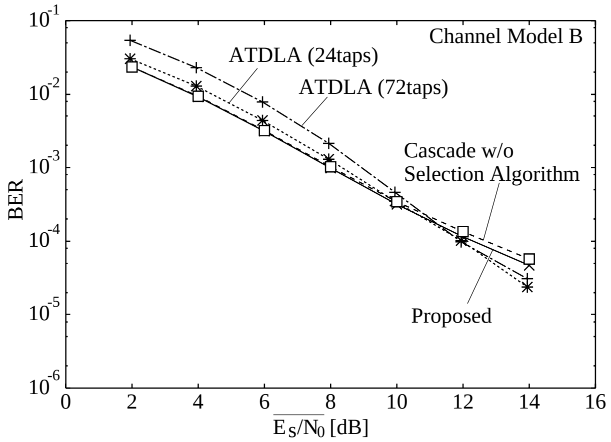

Fig. 9. Bit Error Rate in Channel Model B

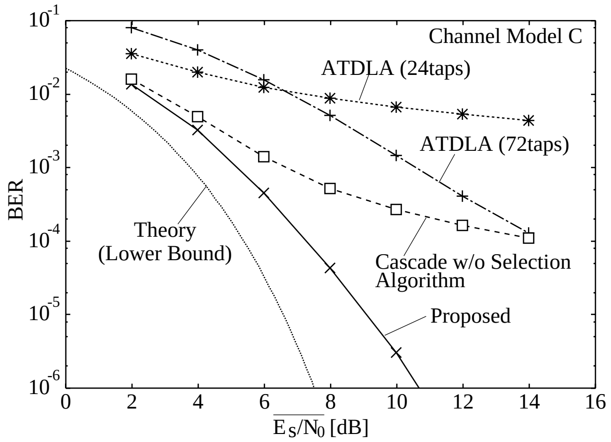

Fig. 10. Bit Error Rate in Channel Model C

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