Abstract

An adaptive antenna array or a smart antenna is named a software antenna because it can form a desired antenna pattern and adaptively control it if an appropriate set of antenna weights is provided and updated in software. It can be a typical tool for realizing a software radio. An adaptive antenna array can be considered an adaptive filter in space and time domains for radio communications, so the communication theory can be generalized from a conventional time domain into both space and time domains. This article introduces a spatial and temporal communication theory based on an adaptive antenna array, such as spatial and temporal channel modeling, equalization, optimum detection for single-user and multi-user CDMA, precoding in transmitter, and joint optimization of both transmitter and receiver. Such spatial and temporal processing promises significant improvement of performance against multipath fading in mobile radio communications.

Spatial and Temporal Communication Theory Using Adaptive Antenna Array

Ryuji Kohno, Yokohama National University

Recent research interests in the field of wireless personal communications have been moving to the third-generation cellular systems for higher quality and variable speed of transmission for multimedia information [1, 2]. For the demand in the third-generation wireless personal communications, however, there are several problems which must be addressed. Signal distortion is one of the main problems of wireless personal communications. It can be classified as intersymbol interference (ISI) due to the signal delay of going through the multipath channel, and co-channel interference (CCI) due to the multiple access. There are already many measures for combatting signal distortion. A traditional equalizer in the time domain is useful for short time delay signals [3, 4]. However, when the delay time is long, the complexity of the equalization system increases.

An antenna array, on the other hand, is defined as a group of spatially distributed antennas. The output of the antenna array is obtained by properly combining each antenna output. By this operation, it is possible to extract the desired signal from all received signals, even if the same frequency band is occupied by all signals. An antenna array can reduce the interference according to the arrival angles or directions of arrival (DOA) [5, 6]. Even if the delay time is large, the system complexity does not increase because the antenna array can reduce the interference by using the antenna directivity. Thus, the combination of an antenna array and a traditional equalizer will be able to yield good performance by compensating for each other's drawbacks [7–14]. It is possible to increase the user capacity (i.e., the number of available users at one base station) by using an antenna array not only in the time domain but also in the space or angular space domain. Therefore, spatial and temporal (i.e., two-dimensional) signal processing based on an antenna array will become a breakthrough technique for the third generation of wireless personal communications. This concept has been also successfully used for a long time in many engineering applications such as radar and aerospace technology [15].

Much research on spatial and temporal signal processing using an adaptive antenna array has been pursued in recent years [16–21]. Research of adaptive algorithms for deriving optimal antenna weights in the time domain, such as Least Mean Squares (LMS), Recursive Least Squares (RLS), and the Constant Modulus Algorithm (CMA) [17], has been proposed from a viewpoint of extending techniques of an adaptive digital filter. On the other hand, there is also research based on DOA estimation from the viewpoint of spectral analysis in the space domain, such as discrete Fourier transform (DFT) [22], the maximum entropy method (MEM) [23], MUSIC [24], and ESPRIT [25, 26]. Adaptive schemes to obtain the optimal weights are classified into these two groups.

SDMA, that is, space-division multiple access, a new access scheme concept, is comparable with frequency-division multiple access (FDMA), time-division multiple access (TDMA), and code-division multiple access (CDMA), and can be com-

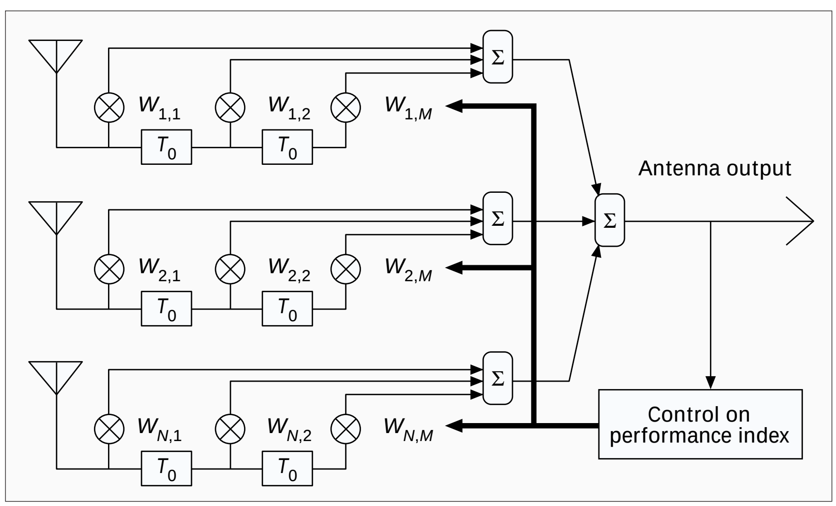

Figure 1. *An adaptive TDL antenna array with* N *element antenna and* M *taps in each element.*

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bined with them for more user capacity. Its research interest is to investigate how much capacity is improved by using an antenna array. Moreover, since communications technology continues its rapid transition from analog to digital and from narrowband to broadband, the fundamental processes (i.e., modulation, equalization, demodulation, etc.) have been integrated and implemented in software. This is referred to as *software radio architecture* [27, 28]. Since an adaptive antenna array can form various antenna patterns and adaptively control the pattern with software, it is also named a *smart antenna* or *software antenna*. Thus, the analysis of radio communication systems can be well simulated on a computer. The design of a radio communication system, which includes an air interface, has to consider the combination of each fundamental process. Furthermore, hardware implementation of an adaptive antenna array has recently been reported to ensure performance improvement and to evaluate complexity of implementation [29, 30]. A typical software antenna is a digital beamformer which is implemented by the combination of a phased array, downconverter, A/D converter, and field programable arrays or digital signal processors [20, 31, 32].

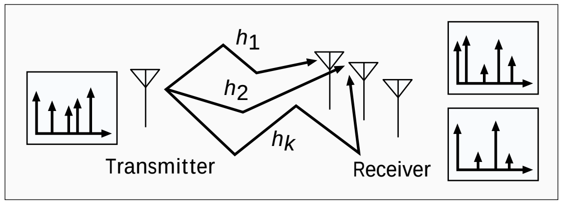


Figure 2. *Spatial and temporal multipath channel model (2D channel model with paths defined by DOAs and time impulse responses of the paths).*

As a result of the above-mentioned trend, the research area for an adaptive antenna array is expanding to many subjects of spatial and temporal signal processing in wireless personal communications. However, there is no communication theory covering the entire subject based on adaptive antenna arrays. Therefore, the author's group has been researching a spatial and temporal communication theory based on adaptive antenna arrays [33–36]. This article briefly introduces an overview of spatial and temporal communication theory for the design and analysis of wireless communication systems using adaptive antenna arrays from a viewpoint of extending a traditional communication theory. I hope this article will spur further interest in adaptive antenna array and its role in realizing a software radio for wireless personal communications.

Adaptive Antenna Array

An adaptive antenna array is an antenna array that continuously adjusts its own pattern by means of feedback control. Its comprehensive explanation can be found in much excellent literature [16–20]. An adaptive tapped delay line (TDL) antenna array in Fig. 1, which has a digital filter in each antenna element, can also control their own frequency response [10]. The pattern of an array is easily controlled by adjusting the amplitude and phase of the signal from each element before combining the signals.

When the input signal to the TDL antenna array is $x(t)$, the array output is represented by

$$y(t) = \sum_{n=1}^{N} \sum_{m=1}^{M} x(t - mT_0) w_{n,m} \exp(-jn\varphi), \tag{1}$$

where T_0 is the delay between adjacent taps, $w_{n,m}$ is the mth complex tap coefficient of the nth antenna, and N and M are the number of elements and taps at each element antenna respectively. The total number of taps are $N \times M$. φ is the phase difference between the received signal at adjacent antenna elements in a uniform linear array and is given by

$$\varphi = \frac{2\pi S \sin\theta}{\lambda}, \tag{2}$$

where λ, S, and θ are the wavelength of an incoming signal, the distance between adjacent elements or interelement spacing, and the DOA of the received signal, respectively. The antenna transfer function in both spatial frequency or angular space domain, θ, and temporal frequency domain, $f = \omega/2\pi$, is given by

$$H(\omega, \theta) = \sum_{m=1}^{M} \exp(-jm\omega T_0) \sum_{n=1}^{N} w_{n,m} \exp(-jn\varphi) \tag{3}$$

Equation 3 represents the antenna pattern when ω is a constant, while it represents the frequency response when θ is a constant.

Therefore, the adaptive TDL antenna array can be employed as a tool for signaling, equalization and detection in space and time domains.

Spatial and Temporal Channel Model

In order to design and analyze an antenna array, a radio transmission model should be modeled in both the space and time domains, while traditional communication theory represents it as a delay profile in the time domain. The spatial characteristics (e.g., the angular profile) are important as well as the temporal ones (e.g., the delay profile) [37]. The spatial and temporal characteristics of a radio transmission channel are dependent on propagation environments such as indoor, outdoor, and various urban and rural areas. A comprehensive discussion on spatial and temporal channel modeling can be found in [20, 38].

For the sake of simplicity, the simple and deterministic model of a multipath channel is employed in this article to introduce a basic concept of the spatial and temporal communication theory. If the time variation and stochastic properties of delay and angular spread are taken into account, the channel model can be extended to a more practical one. The directional considerations are restricted to the horizontal plane (i.e., azimuth) without loss of generality. These do not mean a severe restriction of generality when dealing with radio transmission scenarios.

A multipath fading channel, such as a mobile radio channel, is modeled in which a transmitted signal from one signal source arrives at the receiver with different angles and delays. The received signal is represented by using two variables (i.e., time t and arrival angle θ).

Each propagation path in a channel is defined by its delay profile or impulse response for a particular DOA θ of the received signal. Thus, the channel can be represented by a spatial and temporal 2D model like Fig. 2. Figure 3 illustrates such a spatial and temporal or 2D profile of a multipath channel measured by a practical measurement system [38]. From this figure, it is noted that individual propagation paths defined by DOAs have different impulse responses.

Therefore, the impulse response of the kth path $h_k(t)$ with DOA θ_k, $(k = 1, 2, \ldots, K)$ is represented by

$$h_k(t) = \sum_{i=1}^{I_k} g_{k,i} \delta(t - \tau_{k,i}) \exp(j\psi_{k,i}), \tag{4}$$

where $g_{k,i}$, $\tau_{k,i}$, and $\psi_{k,i}$ denote path amplitude, path delay, and path phase of the ith delayed signal through the kth path, respectively. I_k is the number of delayed signals or delay spread in the kth path, and $\delta(t)$ is the Dirac delta function.

An equivalent complex baseband representation of the received signal $R_n(t, \theta_k)$ in the nth antenna element is

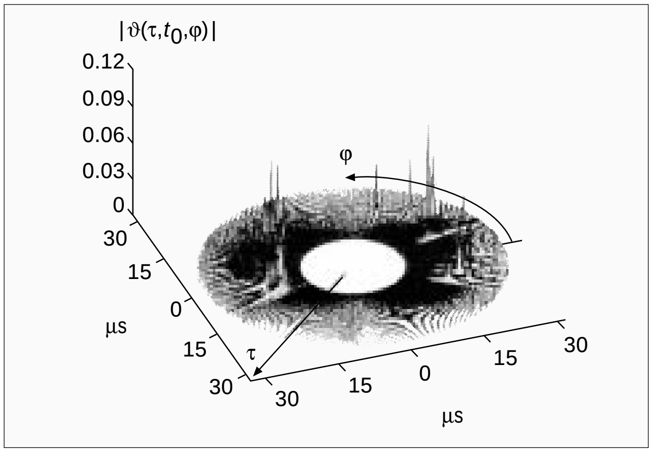


Figure 3. *A real measured impulse response according to DOA (from [36]).*

$$R_n(t,\theta_k) = \sum_{i=1}^{I_k} g_{k,i} S_b(t-\tau_{k,i}) \times \exp\left(-j2\pi nS\frac{\sin\theta_k}{\lambda}\right)\exp(j\phi_{k,i}), \tag{5}$$

where $S_b(t)$ is the complex baseband transmitted signal and $\phi_{k,i}$ is the net phase offset.

Spatial and Temporal Equalization

By using the above-mentioned spatial and temporal channel model, we can derive an extended Nyquist theorem for a known channel [39]. Moreover, for unknown or time-varying channels, various algorithms for updating antenna weights are discussed.

Spatial and Temporal Nyquist Criterion

The Nyquist criterion in space and time domains can be derived from Eqs. 1 and 2. The array output $y(t)$ can be replaced by $y(t, \Theta)$ because the array output depends on time t and arrival angle set $\Theta = (\theta_1,\theta_2,\ldots,\theta_K)$. The array output is rewritten as

$$y(t,\Theta) = \sum_{k=1}^{K} p(t,\theta_k), \tag{6}$$

where $p(t, \theta_k)$ is defined as

$$p(t,\theta_k) = \sum_{n=1}^{N}\sum_{m=1}^{M}\sum_{i=1}^{I_k} w_{n,m} g_{k,i} \exp(j\phi_{k,i}) \exp\left(-j2\pi nS\frac{\sin\theta_k}{\lambda}\right) S_b(t-\tau_{k,i}-mT_0).$$

Suppose that θ_1 represents the desired arrival angle. If $p(t, \theta)$ equals the symbol s_l at $t = lT_d$ and $\theta = \theta_1$, and equals zero elsewhere, ISI must be zero. This condition is named the generalized Nyquist criterion in both space and time domains. Then the criterion is represented by

$$p(lT_d, \theta) = s_l\delta'(t - lT_d, \theta - \theta_1), \tag{7}$$

where $\delta'(t, \theta)$ is the 2D Dirac delta function and sl represents the transmitted symbol at $t = lT_d$. This includes the usual Nyquist criterion when $p(t, \theta_k)$ is a function of time only.

Adaptive Spatial and Time Equalization for Reducing ISI

Several criteria for spatial and temporal equalization such as ZF (zero forcing) and MMSE (minimum mean square error) are available to update the weights and tap coefficients. The ZF criterion satisfies the generalized Nyquist criterion in the noise-free case if there are an infinite number of taps and elements. Since a finite number of taps and elements is available in practical noisy multipath channels, there may be some equalization errors in adaptive equalization based on temporal updating algorithms. If the permissible equalization error is given, there may be several combinations of taps and elements which achieve the same equalization error. Therefore, the number of antenna elements can be reduced by increasing the number of taps in some cases (e.g., when the difference in arrival angles is large) [39].

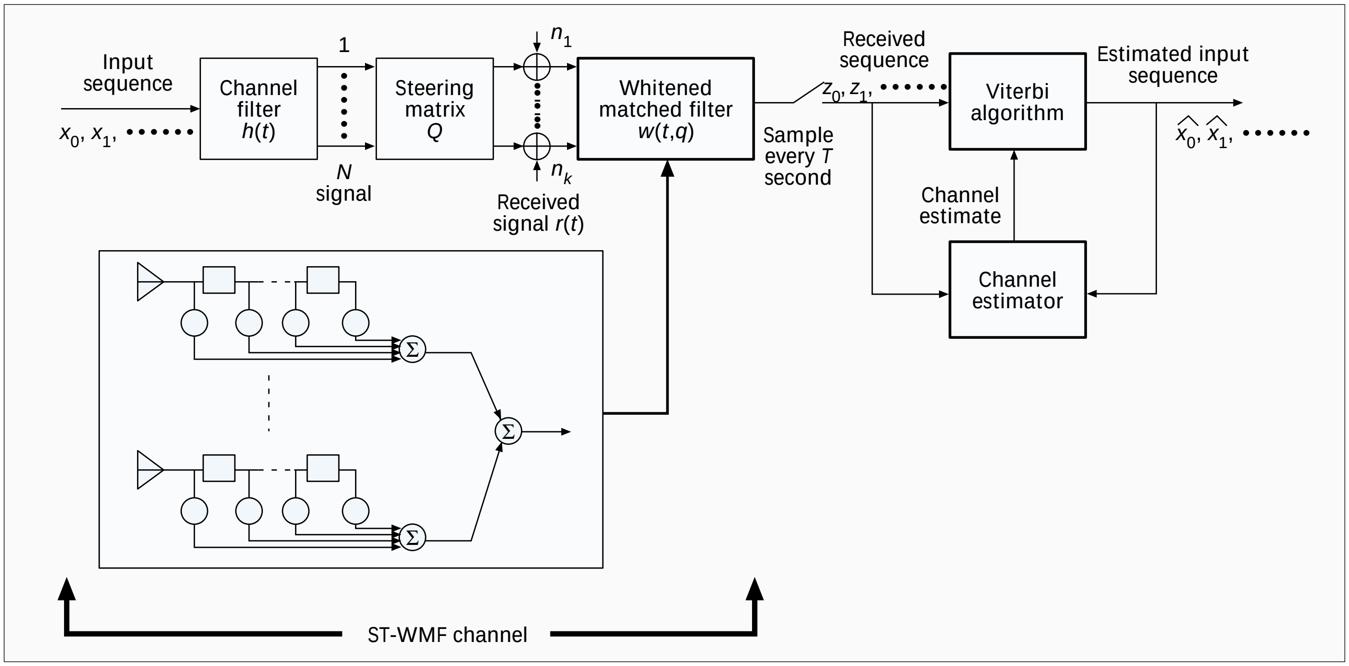
Adaptive antenna arrays, such as LMS, RLS, CMA, and Applebaum arrays, beamform to track the desired signal and to suppress interfering signals by nulls to maximize the array output signal-to-noise ratio (SNR) [17, 19, 20]. The Applebaum array is also useful when the DOA of the desired signal is known in advance. The LMS and RLS arrays do not require any knowledge of the DOA of the desired signal, as long as the reference signal correlated with the desired signal can be obtained. The array pattern will adaptively track the desired signal to maximize SNR. However, it is difficult to obtain a reliable reference signal in time-varying channels such as a mobile radio channel. The CMA array can update weights referring a constant envelope of modulated signals, but is available only for constant amplitude modulation in principle. In general, for these temporal updating algorithms, the weights take time to converge to optimum values.

These temporal updating algorithms originate from adaptive digital filters. On the other hand, several algorithms for controlling weights of antenna elements have been derived from the spatial spectrum of spatially sampled signals [22–26]. The DOA's can be estimated from spatial frequency spectrum, which can be obtained by DFT or MEM for spatially sampled signals. The weight coefficients are updated by the Wiener solution derived from the estimated spatial spectrum. Moreover, the MUSIC algorithm [24] estimates DOAs in noise subspace which is defined by eigen-vectors of a covariance matrix of spatially sampled signals, while DFT and MEM do it in signal subspace. MUSIC has better estimation performance than MEM if the noise subspace is larger for uncorrelated signals than signal subspace. These spatial spectral estimation algorithms can be used to obtain optimum or suboptimum weights by using spatial samples at one time instant (i.e., one snapshot). Therefore, if the processing speed is fast enough to track time variation of channels, these algorithms can be more attractive for a fast fading channel than the temporal updating algorithms.

To combat multipath fading, an adaptive equalizer based on a digital filter in the time domain and a diversity antenna in the space domain have been proposed and investigated in applications for a mobile radio channel with short and long time delay, respectively. In order to compensate for each other's disadvantages, combined structures between a temporal equalizer and a spatial diversity antenna have been proposed and investigated [4, 6–9, 40]. These are related to spatial and temporal equalization, but a diversity antenna is considered a diversity combiner in the space domain rather than a beamformer.

Spatial and Temporal Optimum Receiver

In the previous section, spatial and temporal equalization whose purpose is to reduce ISI due to multipath in a channel was discussed. Viterbi equalization, the purpose of which is to achieve maximum likelihood sequence estimation utilizing ISI, can also be generalized in spatial and temporal domains if an antenna array is employed [11, 12, 14, 43, 44].



■ **Figure 4.** *Spatial and temporal optimum receiver.*

In the presence of ISI and additive white Gaussian noise (AWGN), the tandem structure of a whitened matched filter (WMF) and a maximum likelihood sequence estimator (MLSE), or Viterbi detector (VD), is traditionally considered to be an optimum receiver [41, 42]. The optimum receiver is generalized into space and time domains in this section [34, 45].

Spatial and Temporal Whitened Matched Filter

First, the spatially and temporally whitened matched filter (ST-WMF) is derived using a TDL antenna array. The SNR at the TDL antenna array output is represented using the delay operator D as

$$SNR = \frac{\sigma_s^2 \left| \mathbf{w}^T(D,\Theta) \sum_{k=1}^{K} h_k(D) \mathbf{q}(\theta_k) \right|^2}{\sigma^2 \left| \mathbf{w}(D,\Theta) \right|^2}, \tag{8}$$

where $h_k(D)$, $W(D, \Theta)$, $\mathbf{q}(\theta_k)$, σ_s^2, and σ^2 denote the impulse response of the kth path, the N-dimensional impulse response or weight vector of the array at the arrival angle set Θ, the steering vector for DOA θ_k of the kth path, the variance of the input sequence $x(D)$, and the noise power, respectively. From Schwarz's inequality, the optimal weight vector $W(D, \Theta)$ (N-dimensional) for maximizing the SNR at the TDL antenna array output is given by the time inversion $h_k(D^{-1})D^{K_0}$ (k = 1,2,…,K) of the impulse response and the directivity information Θ as

$$\mathbf{w}(D,\Theta) = \sum_{k=1}^{K} h_k\left(D^{-1}\right) D^{K_0} \mathbf{q}(\theta_k), \tag{9}$$

where $\mathbf{q}^*$ means the complex conjugate of $\mathbf{q}$.

$$\mathbf{q}(\theta_k) = [1 e^{-j\pi\sin\theta_k} \ldots e^{-j(N-1)\pi\sin\theta_k}]. \tag{10}$$

where K_0 satisfies $\max_{k=1,2,\ldots,K}\{I_k\} \leq K_0$ for the delay spread of the kth path I_k.

If a multipath channel is represented by a single time impulse response because an antenna does not distinguish DOA as does an omnidirectional antenna, then the time inversion of the channel's impulse response denotes a temporal WMF (T-WMF). If a uniform linear array is used instead of TDL array (M = 1), then a spatial WMF (S-WMF) for the kth path is realized by the complex conjugated operation of received phase difference $\exp(jn\pi\sin\theta_k)$ due to DOA θ_k (n = 1, 2, …, N). An S-WMF's weight is represented by $W(\Theta) = [w_1, w_2,\ldots,w_N]^T$, where w_n in the nth antenna element is

$$w_n = \sum_{k=1}^{K} \exp\left(jn\pi \sin\theta_k\right). \tag{11}$$

where interelement spacing in array is assumed $\lambda/2$. Therefore, the above $\mathbf{W}(D, \Theta)$ is the generalization of the WMF in both the spatial and temporal domains.

Spatial and Temporal Optimum Receiver

Figure 4 shows a VD connected to an ST-WMF which is constructed by a TDL antenna array. We call this a spatial and temporal optimum receiver. As a special case, a receiver with an S-WMF and a VD and one with a T-WMF and a VD are included. The detection algorithm in the proposed receiver is described as follows:

- Each antenna element receives signals.
- The received signals in each antenna element are filtered by an ST-WMF, which is matched to the transmission channel impulse response.
- The maximum likelihood sequence is estimated from the ST-WMF output.

The symbol error probability $P(e)$ of the proposed optimal receiver in the spatial and temporal domains is bounded from above by

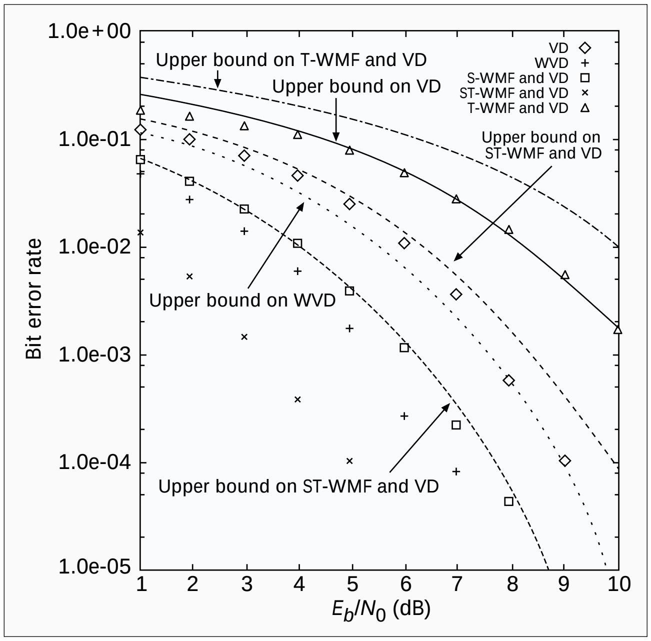
$$P(e) \leq \alpha Q_{\text{error}}(d_{\min}/2\sigma), \tag{12}$$

where $d_{\min}$ is the minimum Euclidean distance, α is a small constant, and $Q_{\text{error}}(\cdot)$ is the error function.

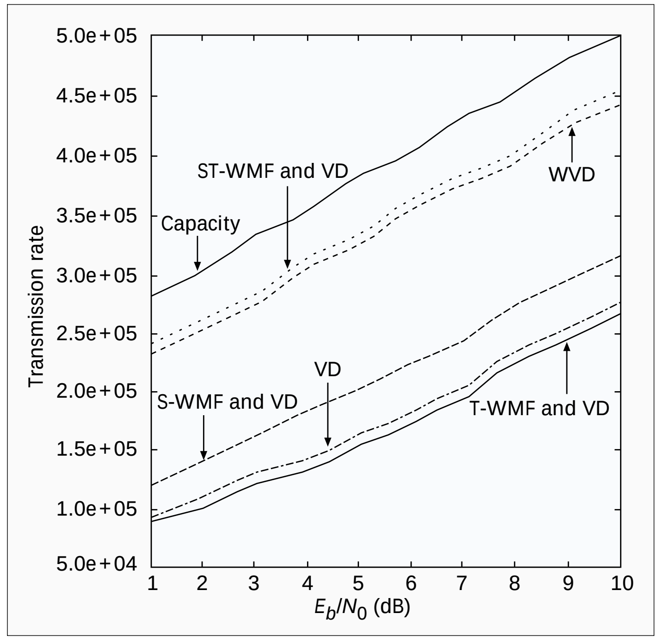
Since ISI is taken into account, the transmission rate R_{st} is derived as

$$R_{st} = W \log \frac{\sigma_s^2 \sum_{k=0}^{2K-1} |g_k|^2 + \sigma^2}{\sigma^2}, \tag{13}$$

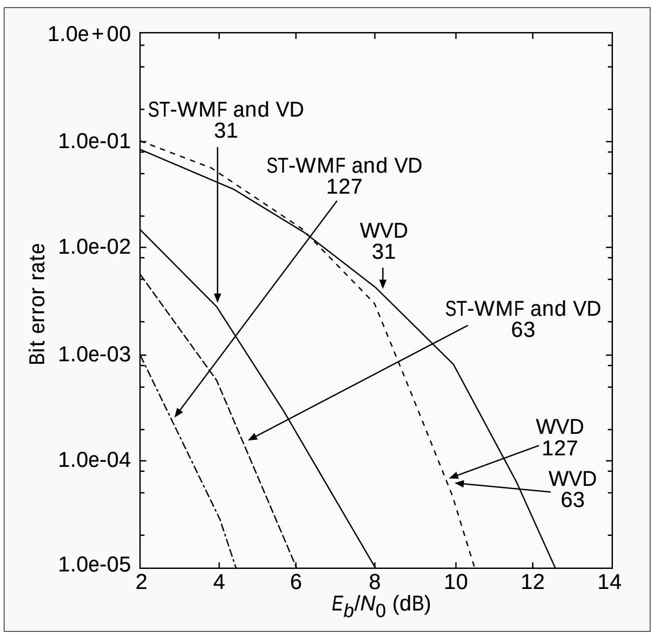
where W and g_k is the signal bandwidth and the delay part of the discrete channel impulse response of the kth path, respectively. Figures 5 and 6 show the BER and the transmission rate of the proposed ST-WMF and VD receiver in comparison with other receivers. These numerical results are derived



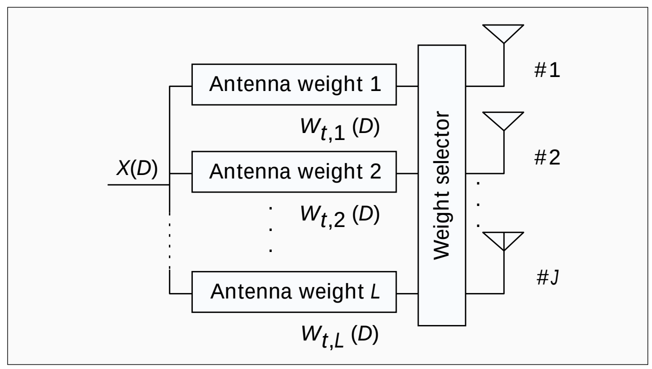
■ **Figure 5.** *BER of optimum receivers in spatial and/or temporal domains.*



■ **Figure 6.** *Achievable transmission rate of optimum receivers comparing with Shannon capacity.*



■ **Figure 7.** *The BER of an optimum CDMA multi-user receiver in spatial and temporal domains according to different processing gains (three users).*



■ **Figure 8.** *Structure of transmitting TDL antenna array (*J *elements and* L *sets of antenna weights.)*

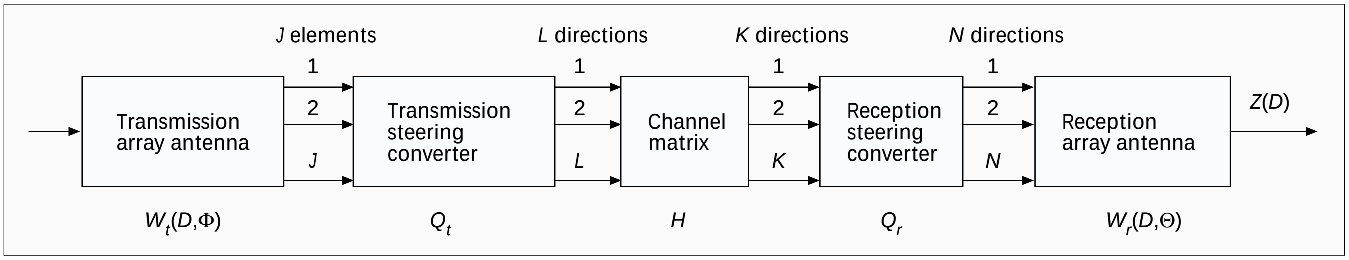
in the following case. The number of element antennas and that of taps in each element are $N = 3$ and $M = 3$, respectively. Two incoming signals are assumed, for example, $h_1(D) = 1.0 + 0.5D$ and $h_2 = 0.7 + 0.2D$ for DOA's $\theta_1 = 30$(deg) and $\theta_2 = 60$(deg), respectively.

Spatial and Temporal Optimum Multi-User Receiver for CDMA

A direct-sequence CDMA(DS/CDMA) mobile radio communication channel is modeled as a channel with both ISI due to multipath and co-channel interference (CCI) due to the correlation between spreading sequences of multiple access users. The optimum multi-user receiver for DS/CDMA detects every user's data in a sense of MLSE by utilizing CCI as redundant information that multiple access users share. By using an adaptive TDL antenna array, we derive a spatial and temporal optimum multi-user receiver such that MLSE for every user's data can be achieved with both CCI and ISI present [46]. From a different viewpoint, it is considered that conventional multi-user receivers are designed only in a time domain [47, 48], but it can be generalized into a spatially and temporally optimized multiuser receiver.

The receiver has an extended structure in Fig. 4 so that correlators for every user are located in front of the ST-WMF, and the ST-WMF is modified to be a multiple input/output structure with cross-coupling and is followed by multiple VDs. The detection algorithm in the proposed receiver is described as follows:

- Each antenna element receives signals.
- Received signals in each element are filtered by each user's correlator.
- Each user's correlator output vector is filtered by each user's ST-WMF, which is matched to each user's CIR.
- Each user's maximum likelihood sequence is estimated for each user's ST-WMF output, where the path metric is calculated taking into consideration the influence of CCI.



■ **Figure 9.** *A channel including a transmitter and a receiver.*

Figure 7 shows the BER of the ST optimum multi-user receiver according to different processing gains or spreading ratios of 31, 63, and 127 (typed in the figures) in the case of three users; the first user, $h_{1,1} = 0.8 + 0.7D$ for $\theta_{1,1}$ = 20(deg), $h_{1,2} = 0.5D^2$ for $\theta_{1,2}$ = –45(deg), the second user, $h_{2,1}$ = 3.50.7D for $\theta_{2,1}$ = 15(deg),$h_{2,2} = 7.0 + 2.8D^2$ for $\theta_{2,2}$ = –60(deg), the third user, $h_{3,1} = 7.0 + 5.6D$ for $\theta_{3,1}$ = 25(deg), $h_{3,2} = 4.2D^2$ for $\theta_{3,2}$ = 10(deg).

A Spatial and Temporal Joint Equalizer in the Transmitter and Receiver

Spatial and Temporal Partial Response Signaling

In the previous sections, we have discussed equalization and detection in a receiver which is useful for unknown or time-varying channels because channel characteristics can be adaptively estimated in a receiver. Equalization in a partial response signaling (PRS) transmitter, or precoding, is also possible in a two-way interactive communication such as time- or frequency-division duplex(TDD or FDD), because the channel characteristics estimated by received signals can be employed for PRS. If transmitting TDL antenna arrays are prepared in a transmitter, the spatial and temporal PRS can be carried out [33].

Figure 8 shows the transmitting TDL antenna array which consists of J element antennas and M taps in each element. The number of antenna weight sets is L, and these antenna weight sets are used for signal transmission in L directions. The transmitting TDL antenna array in a time domain is characterized by the matrix of finite impulse response $W_{t,l}(D)$ (l = 1,2,…,L) (J x M-dimensional), where TDL with M taps are used as a precoder or pre-equalizer in a time domain. Although L sets of transmitting TDL antenna arrays are required in order to precode data signals for L directions of transmission (DOTs), for the sake of reducing hardware complexity a set of J element antennas can be used by periodically switching L sets of antenna weights as shown in Fig. 8. The procedure in the proposed precoder is described as follows:
- Signals are precoded by temporal PRS for each DOT.
- The precoder outputs are appropriately weighted for each DOT.
- The weighted signals are transmitted from every element.

Transmitted signals with the DOT ϕ_l, (l = 1, 2, …, L) are propagated through a multipath channel and received with DOA θ_k, (k = 1,2,…,K). The channel can be represented as an L inputs and K outputs multidimensional channel with cross-coupling. The channel model is represented by Fig. 9.

If the channel characteristics are known in a transmitter, the precoder can equalize the channel distortion. However, since the channel has unknown, nonlinear, time-varying factors, a receiving antenna array is required to compensate for the residual distortion.

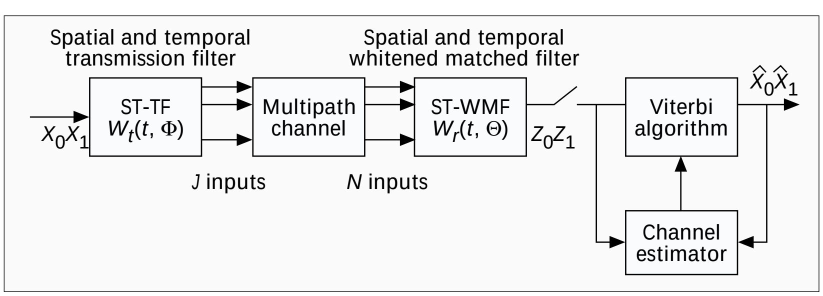
A Spatial and Temporal Joint Transmitter-Receiver System

If transmitting and receiving TDL antenna arrays are used, they should be jointly optimized with a certain criterion (e.g., MLSE) [49].

Figure 10 shows a spatial and temporal joint transmitter-receiver system which consists of an ST transmission filter (ST-TF) based on a transmitting TDL array, an ST-WMF based on a receiving TDL array, and a VD for MLSE. The detection algorithm for the received sequence is described as follows:
- Each antenna element receives signals.
- Received signals in each antenna element are filtered by an ST-WMF.
- The maximum likelihood sequence is estimated for the ST-WMF output by the VD.

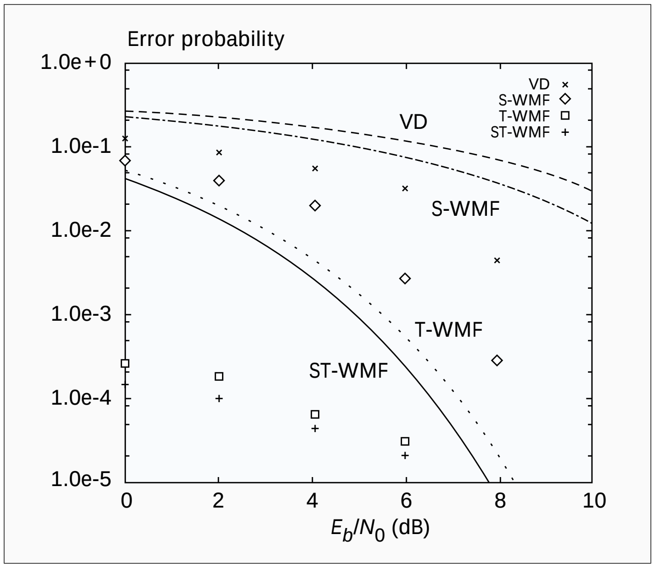
ST-TF is optimized such that minimum Euclidean distance in a trellis diagram of a VD can be maximized. The ST-WMF is matched to the impulse response of both the ST-TF and the multipath channel.

The symbol error probability $PTR(e)$ and the achievable transmission rate R_{st-TR} of the proposed joint transmitter-receiver system in the spatial and temporal domains are derived in a similar manner to an ST optimum receiver, and are illustrated in Figs. 11 and 12, respectively. These numerical results are derived in the following case. The number of element antennas and that of taps in each element are $J = N$ = 3 and M = 3, respectively. Two DOTs and two DOAs are assumed, for example, for the first DOT ϕ_1 = 10(deg), $h_1(D)$ = 1.0 + 0.5D and h_2 = 0.7 + 0.2D for DOAs θ_1 = 30(deg) and θ_2 = 60(deg), respectively. For the second DOT ϕ_1 = 50(deg), $h_1(D)$=0.1 – 0.2D and h_2=–0.3 + 0.4D for DOAs θ_1 = 30(deg) and θ_2 = 60(deg), respectively.

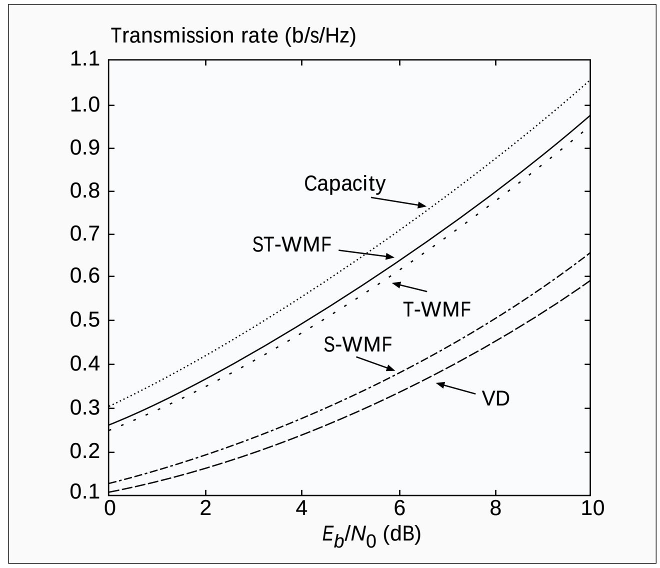


■ **Figure 10.** *A spatial and temporal joint transmitter-receiver system.*

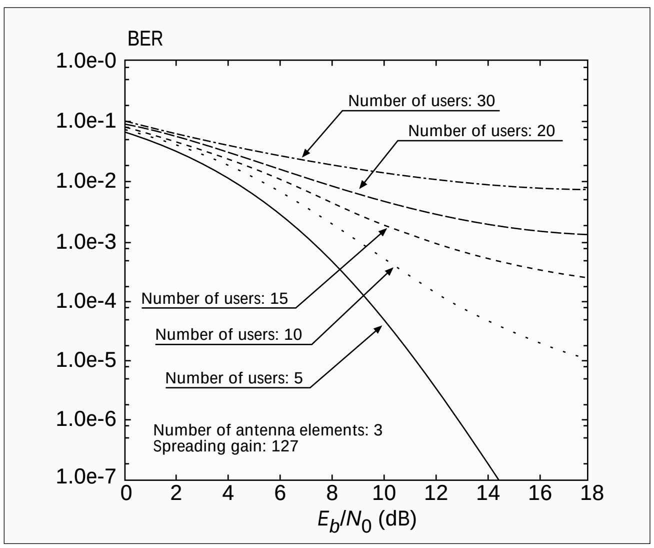
Optimum solution of combination between transmitting and receiving TDL antenna arrays, $\mathbf{W}_t$ and $\mathbf{W}_r$, is not unique in a sense of minimum BER at the whole output, but there are several combinations in a spatial and temporal joint transmitter-receiver system of Fig. 10. If balance of hardware complexity between transmitter and receiver is considered, the complexity of receiving and transmitting antennas in a mobile station (MS) can be minimized by installing a complex transmitting and receiving antenna arrays in a base station (BS) for



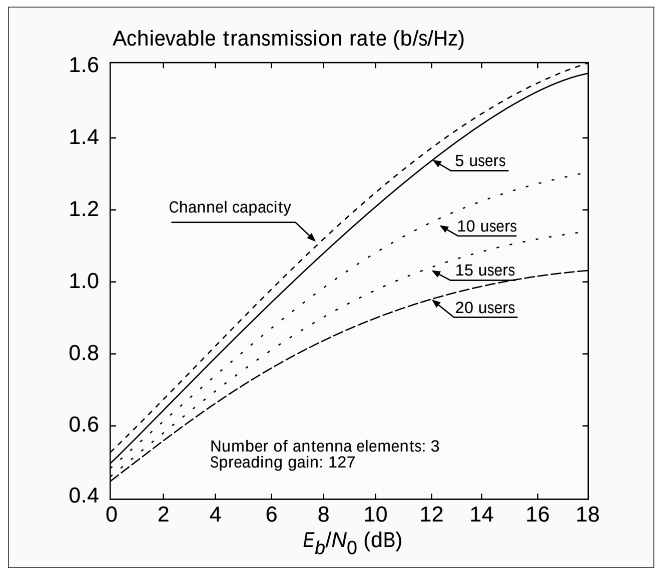
■ **Figure 11.** *BER of spatial and/or temporal joint transmitter-receiver systems.*



■ **Figure 12.** *Achievable transmission rate of spatial and/or temporal joint transmitter-receiver systems.*



■ **Figure 13.** *BER according to the number of users in a spatial and temporal joint transmitter-receiver system for CDMA.*



■ **Figure 14.** *Achievable transmission rate according to the number of users in a spatial and temporal joint transmitter-receiver system for CDMA.*

downlink (from MS to BS) and uplink (from BS to MS), respectively, in a cellular mobile communication system.

Spatial and Temporal Joint Multi-User Transmitter-Receiver System for CDMA

The spatial and temporal joint transmitter-receiver system can be extended to the multi-user environment in CDMA in the same manner as the spatial and temporal optimum receiver [50]. Figure 13 illustrates that the BER depends on the number of users. For the limit of pages, specification in this calculation is omitted. The number of element antennas and that of taps in each element are $J = N = 3$ and $M = 3$, respectively, for all users. Figure 14 illustrates that the achievable transmission rate of the proposed system can be close to the channel capacity when the number of users is small.

Although hardware complexity increases according to the number of accessing users, these figures theoretically prove that the spatial and temporal joint optimization of transmitting and receiving antenna arrays can drastically improve user capacity of CDMA. At the BS in a cellular CDMA system, the single adaptive TDL antenna array can be shared for all users' detection if correlators for the users are installed at each element antenna in parallel. Schemes for reducing complexity while maintaining capacity improvement should be further studied.

Concluding Remarks

The feasibility of implementing an adaptive antenna array is increasing in higher frequency bands such as the millimeter-wave band [31, 32]. When an adaptive array antenna is available in practice, the spatial and temporal communication theory will become more important for achieving high-speed and highly reliable radio communications. Moreover, since an adaptive antenna array can be such a mighty antenna that any antenna pattern can be designed with software, it will be a vital tool to carry out a software radio transceiver.

Some ideal conditions have been assumed in channel modeling, and a physical structure of an adaptive antenna array such that readers can easily understand the concept of the spatial and temporal communication theory based on an adaptive antenna array has been used. Analysis and optimization of the systems should be achieved for more practical mobile radio channels.

An adaptive antenna array brings us a new researching paradigm. Not only the introduced theory but also further research subjects, such as spatial and temporal coding [51], modulation, and an adaptive algorithm for a time-varying channel, should be also taken into account.

References

[1] D. L. Schilling, "Wireless Communications Going Into the 21st Century," *IEEE Trans. Vehic. Tech.*, vol. 43, no. 3, pp. 645–52, Aug. 1994.

[2] R. Kohno, R. Meidan, and L. B. Milstein, "Spread Spectrum Access Methods for Wireless Communications," *IEEE Commun. Mag.*, vol. 33, no. 1, Jan. 1995, pp. 57–67.

[3] S. U. H. Qureshi, "Adaptive Equalization,'' *Proc. IEEE*, vol. 73, no. 9, Sept. 1985.

[4] P. Monsen, "MMSE Equalization of Interference on Fading Diversity Channels," *IEEE Trans. Commun*., Jan. 1984, pp. 5–12.

[5] J. H. Winters, "Signal Acquisition and Tracking with Adaptive Arrays in Digital Mobile Radio System IS-54 with Flat Fading," *IEEE Trans. Vehic. Tech.*, July 1993, pp. 377–84.

[6] J. W. Mondestino and V. M. Eyuboglu, "Integrated Multielement Receiver Structures for Spatially Distributed Interference Channels," *IEEE Trans. IT*, Mar. 1986, pp. 195–219.

[7] R. Kohno et al., "Combination of an Adaptive Array Antenna and a Canceller of Interference for Direct-Sequence Spread-Spectrum Mutliple-Acess System,'' *IEEE JSAC*, vol. 8, May 1990, pp. 675–82.

[8] N. Kuroiwa, R. Kohno, and H. Imai, "Design of a Directional Diversity Receiver Using an Adaptive Array Antenna," *Trans. IEICE Japan*, vol. J73-B-II, no. 11, Nov. 1990, pp. 755–63.

[9] R. Kohno, H. Wang, and H. Imai, "Adaptive Array Antenna Combined with Tapped Delay Line Using Processing Gain for Spread-Spectrum CDMA Systems," *Proc. PIMRC '92*, Boston, MA, 1992.

[10] R. Kohno, "Spatial and Temporal Filtering for Co-Channel Interference in CDMA," Ch. 3, *Code Division Multiple Access Communications*, S. G. Glisic and P. A. Leppanen, Eds., Kluwer, 1995.

[11] G. E. Bottomley and K. Jamal, "Adaptive Arrays and MLSE Equalization," *Proc. VTC*, July 1995, pp. 50–54.

[12] Y. Doi, T. Ohgane, and E. Ogawa, "ISI and CCI Canceller Combining the Adaptive Array Antennas and the Viterbi Equalizer in a Digital Mobile Radio," *Proc. VTC*, Apr. 1996, pp. 81–85.

[13] B. C. Ng, J. T. Chen, and A. Paulraj, "Space-Time Processing for Fast Fading Channels with Co-Channel Interference," *Proc. VTC*, Apr. 1996, pp. 1491–95.

[14] S. N. Diggavi and A. Paulraj, "Performance of Multisensor Adaptive MLSE in Fading Channels," *Proc. VTC*, May 1997, pp. 2148–52.

[15] S. Haykin and A. Steinhardt, Eds., *Adaptive Radar Detection and Estimation*, Wiley, 1992.

[16] R. A. Monzingo and W. T. Miller, *Introduction to Adaptive Arrays*, Wiley, 1980.

[17] R. T. Compton, Jr., *Adaptive Antennas: Concepts and Performance*, Prentice Hall, 1988.

[18] B. D. V. Veen and K. M. Buckley, "Beamforming: A Versatile Approach to Spatial Filtering," *IEEE ASSP Mag.*, Apr. 1988, pp. 4–24.

[19] D. H. Johnson and D. E. Dudgeon, *Array Signal Processing: Concepts and Techniques*, Prentice Hall, 1993.

[20] J. Litva and T. K-Y. Lo, *Digital Beamforming in Wireless Communications*, Artech, 1996.

[21] J. S. Thompson, P. M. Grant, and B. Mulgrew, "Smart Antenna Arrays for CDMA Systems," *IEEE Pers. Commun*., vol. 3, no. 5, Oct. 1996, pp. 16–25.

[22] R. Kohno, C. Yim, and H. Imai, "Array Antenna Beamforming Based on Estimation on Arrival Angles Using DFT on Spatial Domain," *Proc. PIMRC '91*, London, U.K., Sept. 1991, pp. 38–43.

[23] M. Nagatsuka *et al.*, "Array Antenna Based on Spatial Spectrum Estimation Using Maximum Entropy Method," *IEICE Trans. Commun.*, vol. E77-B, no. 5, May 1994, pp. 624–33

[24] R. O. Schmidt, "Multiple Emitter Location and Signal Parameter Estimation," *IEEE Trans. Antennas and Propagation*, vol. AP-34, no. 3, Mar. 1986, pp. 276–80.

[25] R. Roy and T. Kailath, "ESPRIT-Estimation of Signal Parameters via Rotational Invariance Techniques," *IEEE Trans. Acoustics, Speech, and Signal Processing*, vol. ASSP-37, July 1989, pp. 984–95.

[26] M. Haardt, "Efficient One-, Two-, and Multidimensional High-Resolution Array Signal Processing," doctoral thesis, Tech. Univ. of Munich, Aachen, Shaker Verlag, 1997.

[27] J. Mitola, "The Software Radio Architecture," *IEEE Commun. Mag.*, vol. 33, no. 5, May 1995, pp. 26–38.

[28] J. Kennedy and M. C. Sulivan, "Direction Finding and "Smart Antennas" Using Software Radio Architectures," *IEEE Commun. Mag.*, vol. 33, no. 5, May 1995, pp. 62–68.

[29] R. Miura *et al.*, "Beamforming Experiment with a DBF Multibeam Antenna in a Mobile Satellite Environment," *IEEE Trans. Antennas Prop.*, vol. AP-45, no. 4, Apr. 1997, pp. 707–14.

[30] T. Tanaka, R. Miura and Y. Karasawa, "Implementation of a Digital Signal Processor in a DBF Self-Beam-Steering Array Antenna," *IEICE Trans. Commun.*, vol. E80-B, no. 1, Aug. 1995, pp. 1166–75.

[31] Y. Karasawa and H. Inomata, "Research on Digital and Optical Beamforming Antennas in Japan," *Proc. JINA '96*, Nov. 1996, pp. 159–68.

[32] P. E. Mogensen *et al.*, "A Hardware Testbed for Evaluation of Adaptive Antennas in GSM/UMTS," *Proc. IEEE PIMRC '96*, Oct. 1996, pp. 540–44.

[33] R. Kohno, "Information Theoretical Aspect of Adaptive Array Antenna Systems," *1995 IEEE Int'l. Wksp. Info. Theory*, June 1995.

[34] R. Kohno, "Spatial and Temporal Precoding and Equalization Using Adaptive Array Antenna for Mobile Radio Communications," *1995 Allerton Conf. Commun., Control, and Comp., Proc.*, Oct. 1995, pp. 776–85.

[35] N. Ishii, "Signal Design and Detection Theory Based on an Adaptive Array Antenna in Spatial and Temporal Domains," doctoral thesis, Yokohama Nat'l. Univ., Dec. 1996.

[36] R. Kohno, "Spatial and Temporal Communication Theory Based on Adaptive Array Antenna for Mobile Radio Communications," Pt. 3,*Wireless Communications, TDMA versus CDMA*, S .G. Glisic and P. A. Leppanen, Eds., Kluwer, 1997, pp. 293–321.

[37] P. C. Eggers, "TSUNAMI: Spatial Radio Spreading as Seen by Directive Antennas," COST 231 TD(94)119, Darmstadt, Germany, 1994.

[38] J. J. Blanz, P. Jung, and P. W. Baier, "A Flexibly Configurable Statistical Channel Model for Mobile Radio Systems with Directional Diversity," *AGARD SPP Symp.*, Athens, Greece, pp. 38-1–11, 1995.

[39] N. Ishii and R. Kohno, "Spatial and Temporal Equalization Based on an Adaptive Tapped Delay Line Array Antenna," *IEICE Trans. Commun.*, vol. E78-B, no. 8, pp. 1162–69, Aug. 1995.

[40] S. Y. Miller and S. C. Schwartz, "Integrated Spatial-Temporal Detectors for Asynchronous Gaussian Multiple-Access Channels," *IEEE Trans. Commun*., vol. 43, Feb./Mar./Apr. 1995, pp. 396–411.

[41] G. D. Forney, Jr., "Maximum-likelihood Sequence Estimation of Digital Sequences in the Presence of Intersymbol Interference,'' *IEEE Trans. Info. Theory*, vol. IT-18, May 1972, pp. 363–78.

[42] F. R. Magee, Jr. and J. G. Proakis, "Adaptive Maximum-Likelihood Sequence Estimation for Digital Signaling in the Presence of Intersymbol Interference," *IEEE Trans. IT*, vol. IT-19, Jan. 1973, pp. 120–24.

[43] R. Krenz and K. Wesolowski, "Comparison of Several Space Diversity Techniques for MLSE Receivers in Mobile Communications," *IEEE PIMRC '94*, vol. II, Sept. 1994, pp. 740–44.

[44] N. Ishii and R. Kohno, "Tap Selectable Viterbi Equalizer Combined with Diversity Antenna," *IEICE Trans. Commun.*, vol. E78-B, no.11, Nov. 1995, pp. 1498–1506.

[45] M. Nagatsuka, R. Kohno, and H. Imai, "Optimal Receiver in Spatial and Temporal Domains Using Array Antenna," *Proc. ISITA 1994*, Nov. 1994, pp. 893–98.

[46] M. Nagatsuka and R. Kohno, "A Spatially and Temporally Optimal Multi-user Receiver Using an Array Antenna for DS/CDMA," *IEICE Trans. Commun.*, vol. E78-B, no. 11, Nov. 1995, pp. 1489–97.

[47] R. Kohno, H. Imai, and M. Hatori, "Cancellation Techniques of Co-Channel Interference in Asynchronous Spread Spectrum Multiple Access Systems,'' *Trans. IEICE*, vol. J66-A, no. 5, May 1983, pp. 416–23.

[48] S. Verdu, "Minimum probability of error for asynchronous Gaussian multiple access channels,'' *IEEE Trans. I. T.*, vol. IT-32, Jan. 1986, pp. 85–96.

[49] N. Ishii and R. Kohno, "Spatial and Temporal Joint Transmitter-Receiver Using an Adaptive Array Antenna," *IEICE Trans. Commun.*, vol. E79-B, no. 3, Mar. 1996, pp. 361–67.

[50] N. Ishii and R. Kohno, "Joint Optimization of Spatial and Temporal Multiuser Equalization in Both Transmitter and Receiver Using an Adaptive Array Antennas for DS/CDMA," *IEEE GLOBECOM '96, Commun. Theory Mini-Conf.,* pp. 137–41, Nov. 1996.

[51] A. Saifuddin, R. Kohno and H. Imai, "Integrated Receiver Structure of Staged Decoder and CCI Canceller for CDMA with Multilevel Coded Modulation,'' *Euro. Trans. Telecommun. and Related Tech.*, vol. 6, no. 1, pp. 9–19, Jan.-Feb., 1995.

Biography

RYUJI KOHNO (kohno@kohnolab.dnj.ynu.ac.jp) received B.E. and M.E. degrees in computer engineering from Yokohama National University in 1979 and 1981, respectively, and a Ph.D. degree in electrical engineering from the University of Tokyo in 1984. He joined the Department of Electrical Engineering, Toyko University in 1984 and became an associate professor in 1986. In 1988 he joined the Division of Electrical and Computer Engineering, Yokohama National University, and since 1998 he has been a professor. During 1984–1985 he was a visiting scientist in the Department of Electrical Engineering, University of Toronto.