A Simple Transmit Diversity Technique for Wireless Communications

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***Abstract*— This paper presents a simple two-branch transmit diversity scheme. Using two transmit antennas and one receive antenna the scheme provides the same diversity order as maximal-ratio receiver combining (MRRC) with one transmit antenna, and two receive antennas. It is also shown that the scheme may easily be generalized to two transmit antennas and M receive antennas to provide a diversity order of $2M$. The new scheme does not require any bandwidth expansion any feedback from the receiver to the transmitter and its computation complexity is similar to MRRC.**

***Index Terms*—Antenna array processing, baseband processing, diversity, estimation and detection, fade mitigation, maximal-ratio combining, Rayleigh fading, smart antennas, space block coding, space–time coding, transmit diversity, wireless communications.**

I. Introduction

THE NEXT-generation wireless systems are required to have high voice quality as compared to current cellular mobile radio standards and provide high bit rate data services (up to 2 Mbits/s). At the same time, the remote units are supposed to be small lightweight pocket communicators. Furthermore, they are to operate reliably in different types of environments: macro, micro, and picocellular; urban, suburban, and rural; indoor and outdoor. In other words, the next generation systems are supposed to have better quality and coverage, be more power and bandwidth efficient, and be deployed in diverse environments. Yet the services must remain affordable for widespread market acceptance. Inevitably, the new pocket communicators must remain relatively simple. Fortunately, however, the economy of scale may allow more complex base stations. In fact, it appears that base station complexity may be the only plausible trade space for achieving the requirements of next generation wireless systems.

The fundamental phenomenon which makes reliable wireless transmission difficult is time-varying multipath fading [1]. It is this phenomenon which makes tetherless transmission a challenge when compared to fiber, coaxial cable, line-of-sight microwave or even satellite transmissions.

Increasing the quality or reducing the effective error rate in a multipath fading channel is extremely difficult. In additive white Gaussian noise (AWGN), using typical modulation and coding schemes, reducing the effective bit error rate (BER) from 10^{-2} to 10^{-3} may require only 1- or 2-dB higher signal-to-noise ratio (SNR). Achieving the same in a multipath fading environment, however, may require up to 10 dB improvement in SNR. The improvement in SNR may not be achieved by higher transmit power or additional bandwidth, as it is contrary to the requirements of next generation systems. It is therefore crucial to effectively combat or reduce the effect of fading at both the remote units and the base stations, without additional power or any sacrifice in bandwidth.

Theoretically, the most effective technique to mitigate multipath fading in a wireless channel is transmitter power control. If channel conditions as experienced by the receiver on one side of the link are known at the transmitter on the other side, the transmitter can predistort the signal in order to overcome the effect of the channel at the receiver. There are two fundamental problems with this approach. The major problem is the required transmitter dynamic range. For the transmitter to overcome a certain level of fading, it must increase its power by that same level, which in most cases is not practical because of radiation power limitations and the size and cost of the amplifiers. The second problem is that the transmitter does not have any knowledge of the channel experienced by the receiver except in systems where the uplink (remote to base) and downlink (base to remote) transmissions are carried over the same frequency. Hence, the channel information has to be fed back from the receiver to the transmitter, which results in throughput degradation and considerable added complexity to both the transmitter and the receiver. Moreover, in some applications there may not be a link to feed back the channel information.

Other effective techniques are time and frequency diversity. Time interleaving, together with error correction coding, can provide diversity improvement. The same holds for spread spectrum. However, time interleaving results in large delays when the channel is slowly varying. Equivalently, spread spectrum techniques are ineffective when the coherence bandwidth of the channel is larger than the spreading bandwidth or, equivalently, where there is relatively small delay spread in the channel.

In most scattering environments, antenna diversity is a practical, effective and, hence, a widely applied technique for reducing the effect of multipath fading [1]. The classical approach is to use multiple antennas at the receiver and perform combining or selection and switching in order to improve the quality of the received signal. The major problem with using the receive diversity approach is the cost, size, and power of the remote units. The use of multiple antennas and radio frequency (RF) chains (or selection and switching circuits) makes the remote units larger and more expensive. As a result, diversity techniques have almost exclusively been

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applied to base stations to improve their reception quality. A base station often serves hundreds to thousands of remote units. It is therefore more economical to add equipment to base stations rather than the remote units. For this reason, transmit diversity schemes are very attractive. For instance, one antenna and one transmit chain may be added to a base station to improve the reception quality of all the remote units in that base station's coverage area.[1] The alternative is to add more antennas and receivers to all the remote units. The first solution is definitely more economical.

Recently, some interesting approaches for transmit diversity have been suggested. A delay diversity scheme was proposed by Wittneben [2], [3] for base station simulcasting and later, independently, a similar scheme was suggested by Seshadri and Winters [4], [5] for a single base station in which copies of the same symbol are transmitted through multiple antennas at different times, hence creating an artificial multipath distortion. A maximum likelihood sequence estimator (MLSE) or a minimum mean squared error (MMSE) equalizer is then used to resolve multipath distortion and obtain diversity gain. Another interesting approach is space–time trellis coding, introduced in [6], where symbols are encoded according to the antennas through which they are simultaneously transmitted and are decoded using a maximum likelihood decoder. This scheme is very effective, as it combines the benefits of forward error correction (FEC) coding and diversity transmission to provide considerable performance gains. The cost for this scheme is additional processing, which increases exponentially as a function of bandwidth efficiency (bits/s/Hz) and the required diversity order. Therefore, for some applications it may not be practical or cost-effective.

The technique proposed in this paper is a simple transmit diversity scheme which improves the signal quality at the receiver on one side of the link by simple processing across two transmit antennas on the opposite side. The obtained diversity order is equal to applying maximal-ratio receiver combining (MRRC) with two antennas at the receiver. The scheme may easily be generalized to two transmit antennas and M receive antennas to provide a diversity order of $2M$. This is done without any feedback from the receiver to the transmitter and with small computation complexity. The scheme requires no bandwidth expansion, as redundancy is applied in space across multiple antennas, not in time or frequency.

The new transmit diversity scheme can improve the error performance, data rate, or capacity of wireless communications systems. The decreased sensitivity to fading may allow the use of higher level modulation schemes to increase the effective data rate, or smaller reuse factors in a multicell environment to increase system capacity. The scheme may also be used to increase the range or the coverage area of wireless systems. In other words, the new scheme is effective in all of the applications where system capacity is limited by multipath fading and, hence, may be a simple and cost-effective way to address the market demands for quality and efficiency without a complete redesign of existing systems. Furthermore, the scheme seems to be a superb candidate for next-generation wireless systems, as it effectively reduces the effect of fading at the remote units using multiple transmit antennas at the base stations.

[1] In fact, many cellular base stations already have two receive antennas for receive diversity. The same antennas may be used for transmit diversity.

In Section II, the classical maximal ratio receive diversity combining is discussed and simple mathematical descriptions are given. In Section III, the new two-branch transmit diversity schemes with one and with two receive antennas are discussed. In Section IV, the bit-error performance of the new scheme with coherent binary phase-shift keying (BPSK) modulation is presented and is compared with MRRC. There are cost and performance differences between the practical implementations of the proposed scheme and the classical MRRC. These differences are discussed in detail in Section V.

II. Classical Maximal-Ratio Receive Combining (MRRC) Scheme

Fig. 1 shows the baseband representation of the classical two-branch MRRC.

At a given time, a signal $\mathbf{s}_0$ is sent from the transmitter. The channel including the effects of the transmit chain, the airlink, and the receive chain may be modeled by a complex multiplicative distortion composed of a magnitude response and a phase response. The channel between the transmit antenna and the receive antenna zero is denoted by $\boldsymbol{h_0}$ and between the transmit antenna and the receive antenna one is denoted by $\boldsymbol{h_1}$ where

$$\begin{aligned}\boldsymbol{h_0} &= \alpha_0 e^{j\theta_0}\\ \boldsymbol{h_1} &= \alpha_1 e^{j\theta_1}.\end{aligned} \tag{1}$$

Noise and interference are added at the two receivers. The resulting received baseband signals are

$$\begin{aligned}\boldsymbol{r_0} &= \boldsymbol{h_0 s_0} + \boldsymbol{n_0}\\ \boldsymbol{r_1} &= \boldsymbol{h_1 s_0} + \boldsymbol{n_1}\end{aligned} \tag{2}$$

where $\boldsymbol{n_0}$ and $\boldsymbol{n_1}$ represent complex noise and interference.

Assuming $\boldsymbol{n_0}$ and $\boldsymbol{n_1}$ are Gaussian distributed, the maximum likelihood decision rule at the receiver for these received signals is to choose signal $\boldsymbol{s_i}$ if and only if (iff)

$$\begin{aligned}d^2(\boldsymbol{r_0}, \boldsymbol{h_0 s_i}) + d^2(\boldsymbol{r_1}, \boldsymbol{h_1 s_i}) &\le d^2(\boldsymbol{r_0}, \boldsymbol{h_0 s_k})\\ &+ d^2(\boldsymbol{r_1}, \boldsymbol{h_1 s_k}), \qquad \forall \boldsymbol{i} \ne \boldsymbol{k}\end{aligned} \tag{3}$$

where $d^2(\mathbf{x}, \mathbf{y})$ is the squared Euclidean distance between signals $\boldsymbol{x}$ and $\boldsymbol{y}$ calculated by the following expression:

$$d^2(\boldsymbol{x}, \boldsymbol{y}) = (\boldsymbol{x} - \boldsymbol{y})(\boldsymbol{x}^* - \boldsymbol{y}^*). \tag{4}$$

The receiver combining scheme for two-branch MRRC is as follows:

$$\begin{aligned}\tilde{s}_0 &= \boldsymbol{h}_0^* \boldsymbol{r_0} + \boldsymbol{h}_1^* \boldsymbol{r_1}\\ &= \boldsymbol{h}_0^*(\boldsymbol{h_0 s_0} + \boldsymbol{n_0}) + \boldsymbol{h}_1^*(\boldsymbol{h_1 s_0} + \boldsymbol{n_1})\\ &= (\alpha_0^2 + \alpha_1^2)\boldsymbol{s_0} + \boldsymbol{h}_0^* \boldsymbol{n_0} + \boldsymbol{h}_1^* \boldsymbol{n_1}.\end{aligned} \tag{5}$$

Expanding (3) and using (4) and (5) we get

choose $\boldsymbol{s_i}$ iff

$$\begin{aligned}&(\alpha_0^2 + \alpha_1^2)|\boldsymbol{s_i}|^2 - \tilde{s}_0 \boldsymbol{s}_i^* - \tilde{s}_0^* \boldsymbol{s_i}\\ &\quad \le (\alpha_0^2 + \alpha_1^2)|\boldsymbol{s_k}|^2 - \tilde{s}_0 \boldsymbol{s}_k^* - \tilde{s}_0^* \boldsymbol{s_k}, \qquad \forall \boldsymbol{i} \ne \boldsymbol{k}\end{aligned} \tag{6}$$

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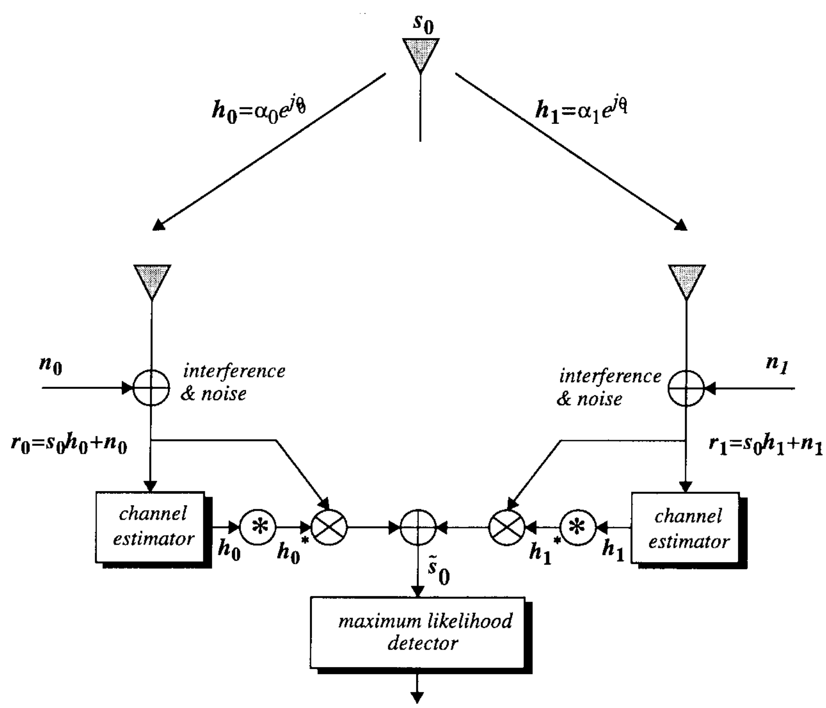

Fig. 1. Two-branch MRRC.

or equivalently

choose s_i iff

$$(\alpha_0^2+\alpha_1^2-1)|s_i|^2+d^2(\tilde{s}_0, s_i) \le (\alpha_0^2+\alpha_1^2-1)|s_k|^2+d^2(\tilde{s}_0, s_k), \qquad \forall i \ne k. \quad (7)$$

For PSK signals (equal energy constellations)

$$|s_i|^2=|s_k|^2=E_s, \qquad \forall i, k \quad (8)$$

where E_s is the energy of the signal. Therefore, for PSK signals, the decision rule in (7) may be simplified to

choose s_i iff

$$d^2(\tilde{s}_0, s_i) \le d^2(\tilde{s}_0, s_k), \qquad \forall i \ne k. \quad (9)$$

The maximal-ratio combiner may then construct the signal $\tilde{s}_0$, as shown in Fig. 1, so that the maximum likelihood detector may produce $\hat{s}_0$, which is a maximum likelihood estimate of s_0.

III. The New Transmit Diversity Scheme

A. Two-Branch Transmit Diversity with One Receiver

Fig. 2 shows the baseband representation of the new two-branch transmit diversity scheme.

The scheme uses two transmit antennas and one receive antenna and may be defined by the following three functions:

- the encoding and transmission sequence of information symbols at the transmitter;
- the combining scheme at the receiver;
- the decision rule for maximum likelihood detection.

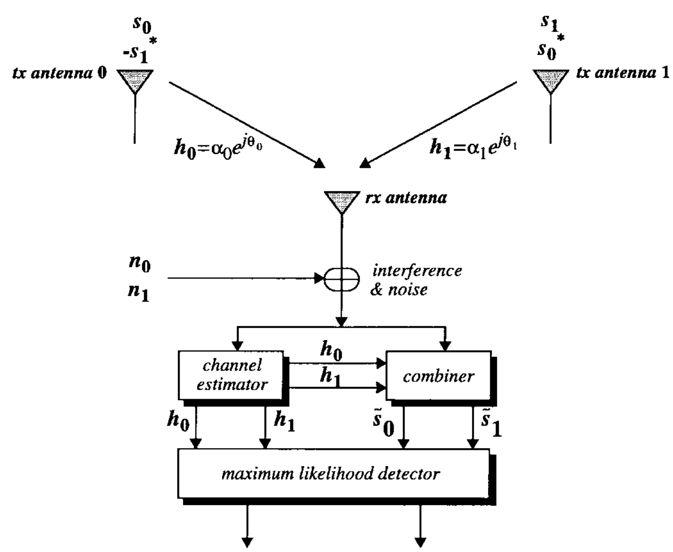

Fig. 2. The new two-branch transmit diversity scheme with one receiver.

1) The Encoding and Transmission Sequence: At a given symbol period, two signals are simultaneously transmitted from the two antennas. The signal transmitted from antenna zero is denoted by s_0 and from antenna one by s_1. During the next symbol period signal $(-s_1^*)$ is transmitted from antenna zero, and signal s_0^* is transmitted from antenna one where $*$ is the complex conjugate operation. This sequence is shown in Table I.

In Table I, the encoding is done in space and time (space–time coding). The encoding, however, may also be done in space and frequency. Instead of two adjacent symbol periods, two adjacent carriers may be used (space–frequency coding).

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TABLE I
THE ENCODING AND TRANSMISSION SEQUENCE FOR THE TWO-BRANCH TRANSMIT DIVERSITY SCHEME

	antenna 0	antenna 1
time t	s_0	s_1
time $t+T$	$-s_1^*$	s_0^*

The channel at time t may be modeled by a complex multiplicative distortion $h_0(t)$ for transmit antenna zero and $h_1(t)$ for transmit antenna one. Assuming that fading is constant across two consecutive symbols, we can write

$$\begin{aligned} h_0(t) &= h_0(t+T) = h_0 = \alpha_0 e^{j\theta_0} \\ h_1(t) &= h_1(t+T) = h_1 = \alpha_1 e^{j\theta_1} \end{aligned} \tag{10}$$

where T is the symbol duration. The received signals can then be expressed as

$$\begin{aligned} r_0 &= r(t) = h_0 s_0 + h_1 s_1 + n_0 \\ r_1 &= r(t+T) = -h_0 s_1^* + h_1 s_0^* + n_1 \end{aligned} \tag{11}$$

where r_0 and r_1 are the received signals at time t and $t+T$ and n_0 and n_1 are complex random variables representing receiver noise and interference.

2) The Combining Scheme: The combiner shown in Fig. 2 builds the following two combined signals that are sent to the maximum likelihood detector:

$$\begin{aligned} \tilde{s}_0 &= h_0^* r_0 + h_1 r_1^* \\ \tilde{s}_1 &= h_1^* r_0 - h_0 r_1^*. \end{aligned} \tag{12}$$

It is important to note that this combining scheme is different from the MRRC in (5). Substituting (10) and (11) into (12) we get

$$\begin{aligned} \tilde{s}_0 &= (\alpha_0^2 + \alpha_1^2) s_0 + h_0^* n_0 + h_1 n_1^* \\ \tilde{s}_1 &= (\alpha_0^2 + \alpha_1^2) s_1 - h_0 n_1^* + h *_1 n_0. \end{aligned} \tag{13}$$

3) The Maximum Likelihood Decision Rule: These combined signals are then sent to the maximum likelihood detector which, for each of the signals s_0 and s_1, uses the decision rule expressed in (7) or (9) for PSK signals.

The resulting combined signals in (13) are equivalent to that obtained from two-branch MRRC in (5). The only difference is phase rotations on the noise components which do not degrade the effective SNR. Therefore, the resulting diversity order from the new two-branch transmit diversity scheme with one receiver is equal to that of two-branch MRRC.

B. Two-Branch Transmit Diversity with M Receivers

There may be applications where a higher order of diversity is needed and multiple receive antennas at the remote units are feasible. In such cases, it is possible to provide a diversity order of $2M$ with two transmit and M receive antennas. For illustration, we discuss the special case of two transmit and two receive antennas in detail. The generalization to M receive antennas is trivial.

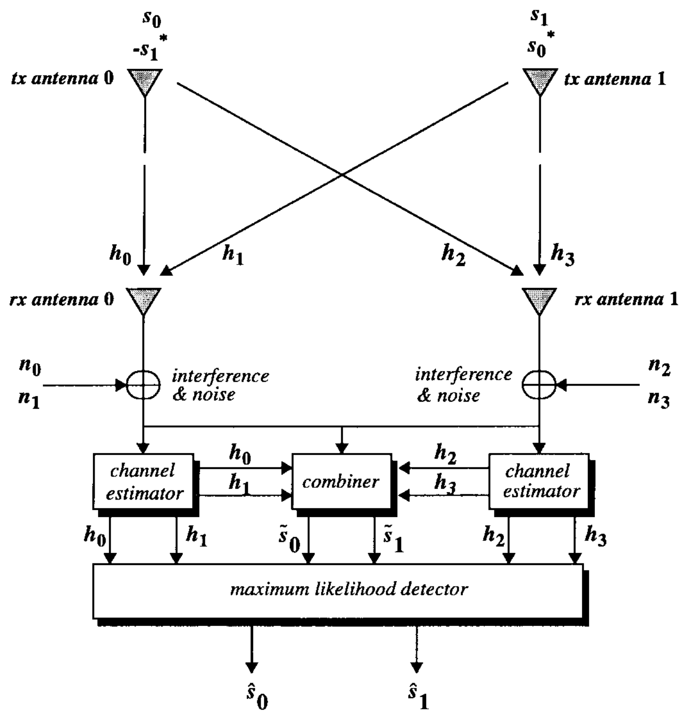

Fig. 3. The new two-branch transmit diversity scheme with two receivers.

TABLE II
THE DEFINITION OF CHANNELS BETWEEN THE TRANSMIT AND RECEIVE ANTENNAS

	rx antenna 0	rx antenna 1
tx antenna 0	h_0	h_2
tx antenna 1	h_1	h_3

TABLE III
THE NOTATION FOR THE RECEIVED SIGNALS AT THE TWO RECEIVE ANTENNAS

	rx antenna 0	rx antenna 1
time t	r_0	r_2
time $t+T$	r_1	r_3

Fig. 3 shows the baseband representation of the new scheme with two transmit and two receive antennas.

The encoding and transmission sequence of the information symbols for this configuration is identical to the case of a single receiver, shown in Table I. Table II defines the channels between the transmit and receive antennas, and Table III defines the notation for the received signal at the two receive antennas.

Where

$$\begin{aligned} r_0 &= h_0 s_0 + h_1 s_1 + n_0 \\ r_1 &= -h_0 s_1^* + h_1 s_0^* + n_1 \\ r_2 &= h_2 s_0 + h_3 s_1 + n_2 \\ r_3 &= -h_2 s_1^* + h_3 s_0^* + n_3 \end{aligned} \tag{14}$$

n_0, n_1, n_2, and n_3 are complex random variables representing receiver thermal noise and interference. The combiner in Fig. 3 builds the following two signals that are sent to the maximum

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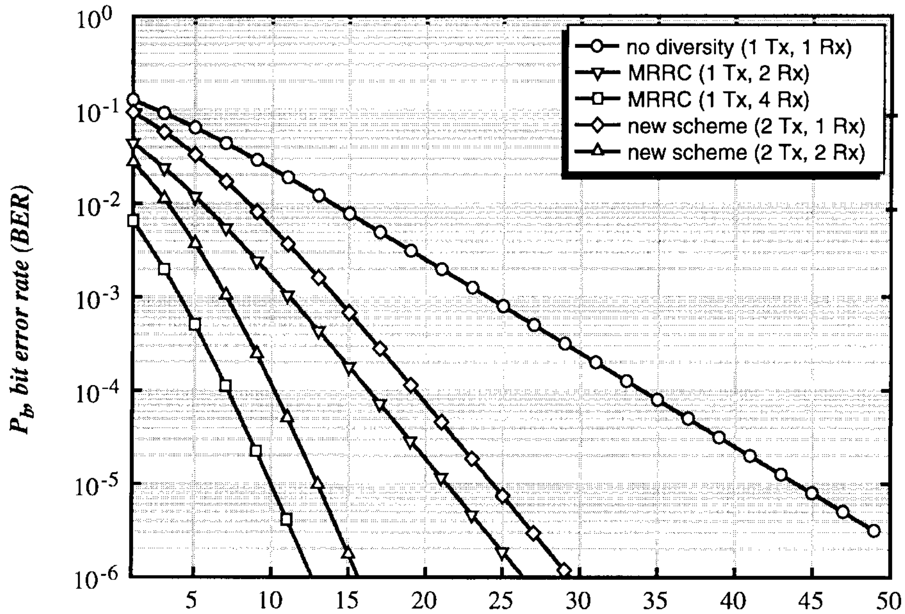

Fig. 4. The BER performance comparison of coherent BPSK with MRRC and two-branch transmit diversity in Rayleigh fading.

likelihood detector:

$$\begin{aligned}\tilde{s}_0 &= h_0^* r_0 + h_1 r_1^* + h_2^* r_2 + h_3 r_3^* \\ \tilde{s}_1 &= h_1^* r_0 - h_0 r_1^* + h_3^* r_2 - h_2 r_3^*.\end{aligned} \tag{15}$$

Substituting the appropriate equations we have

$$\begin{aligned}\tilde{s}_0 &= (\alpha_0^2 + \alpha_1^2 + \alpha_2^2 + \alpha_3^2) s_0 + h_0^* n_0 + h_1 n_1^* \\ &\quad + h_2^* n_2 + h_3 n_3^* \\ \tilde{s}_1 &= (\alpha_0^2 + \alpha_1^2 + \alpha_2^2 + \alpha_3^2) s_1 - h_0 n_1^* + h_1^* n_0 \\ &\quad - h_2 n_3^* + h_3^* n_2.\end{aligned} \tag{16}$$

These combined signals are then sent to the maximum likelihood decoder which for signal s_0 uses the decision criteria expressed in (17) or (18) for PSK signals.

Choose s_i iff

$$\begin{aligned}&(\alpha_0^2 + \alpha_1^2 + \alpha_2^2 + \alpha_3^2 - 1)|s_i|^2 + d^2(\tilde{s}_0, s_i) \\ &\quad \le (\alpha_0^2 + \alpha_1^2 + \alpha_2^2 + \alpha_3^2 - 1|s_k|^2 + d^2(\tilde{s}_0, s_k).\end{aligned} \tag{17}$$

Choose s_i iff

$$d^2(\tilde{s}_0, s_i) \le d^2(\tilde{s}_0, s_k), \qquad \forall i \neq k. \tag{18}$$

Similarly, for s_1, using the decision rule is to choose signal s_i iff

$$\begin{aligned}&(\alpha_0^2 + \alpha_1^2 + \alpha_2^2 + \alpha_3^2 - 1)|s_i|^2 + d^2(\tilde{s}_1, s_i) \\ &\quad \le (\alpha_0^2 + \alpha_1^2 + \alpha_2^2 + \alpha_3^2 - 1)|s_k|^2 + d^2(\tilde{s}_1, s_k)\end{aligned} \tag{19}$$

or, for PSK signals,

choose s_i iff

$$d^2(\tilde{s}_1, s_i) \le d^2(\tilde{s}_1, s_k), \qquad \forall i \neq k. \tag{20}$$

The combined signals in (16) are equivalent to that of four-branch MRRC, not shown in the paper. Therefore, the resulting diversity order from the new two-branch transmit diversity scheme with two receivers is equal to that of the four-branch MRRC scheme.

It is interesting to note that the combined signals from the two receive antennas are the simple addition of the combined signals from each receive antenna, i.e., the combining scheme is identical to the case with a single receive antenna. We may hence conclude that, using two transmit and M receive antennas, we can use the combiner for each receive antenna and then simply add the combined signals from all the receive antennas to obtain the same diversity order as $2M$-branch MRRC. In other words, using two antennas at the transmitter, the scheme doubles the diversity order of systems with one transmit and multiple receive antennas.

An interesting configuration may be to employ two antennas at each side of the link, with a transmitter and receiver chain connected to each antenna to obtain a diversity order of four at both sides of the link.

IV. Error Performance Simulations

The diversity gain is a function of many parameters, including the modulation scheme and FEC coding. Fig. 4 shows the BER performance of uncoded coherent BPSK for MRRC and the new transmit diversity scheme in Rayleigh fading.

It is assumed that the total transmit power from the two antennas for the new scheme is the same as the transmit power from the single transmit antenna for MRRC. It is also assumed that the amplitudes of fading from each transmit antenna to each receive antenna are mutually uncorrelated Rayleigh distributed and that the average signal powers at each receive antenna from each transmit antenna are the same. Further, we assume that the receiver has perfect knowledge of the channel.

Although the assumptions in the simulations may seem highly unrealistic, they provide reference performance curves for comparison with known techniques. An important issue is

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whether the new scheme is any more sensitive to real-world sources of degradation. This issue is addressed in Section V.

As shown in Fig. 4, the performance of the new scheme with two transmitters and a single receiver is 3 dB worse than two-branch MRRC. As explained in more detail later in Section V-A, the 3-dB penalty is incurred because the simulations assume that each transmit antenna radiates half the energy in order to ensure the same total radiated power as with one transmit antenna. If each transmit antenna in the new scheme was to radiate the same energy as the single transmit antenna for MRRC, however, the performance would be identical. In other words, if the BER was drawn against the average SNR per transmit antenna, then the performance curves for the new scheme would shift 3 dB to the left and overlap with the MRRC curves. Nevertheless, even with the equal total radiated power assumption, the diversity gain for the new scheme with one receive antenna at a BER of 10^{-4} is about 15 dB. Similarly, assuming equal total radiated power, the diversity gain of the new scheme with two receive antennas at a BER of 10^{-4} is about 24 dB, which is 3 dB worse than MRRC with one transmit antenna and four receive antennas.

As stated before, these performance curves are simple reference illustrations. The important conclusion is that the new scheme provides similar performance to MRRC, regardless of the employed coding and modulation schemes. Many publications have reported the performance of various coding and modulation schemes with MRRC. The results from these publications may be used to predict the performance of the new scheme with these coding and modulation techniques.

V. Implementation Issues

So far in this report, we have shown, mathematically, that the new transmit diversity scheme with two transmit and M receive antennas is equivalent to MRRC with one transmit antenna and $2M$ receive antennas. From practical implementation aspects, however, the two systems may differ. This section discusses some of the observed difference between the two schemes.

A. Power Requirements

The new scheme requires the simultaneous transmission of two different symbols out of two antennas. If the system is radiation power limited, in order to have the same total radiated power from two transmit antennas the energy allocated to each symbol should be halved. This results in a 3-dB penalty in the error performance. However, the 3-dB reduction of power in each transmit chain translates to cheaper, smaller, or less linear power amplifiers. A 3-dB reduction in amplifiers power handling is very significant and may be desirable in some cases. It is often less expensive (or more desirable from intermodulation distortion effects) to employ two half-power amplifiers rather than a single full power amplifier. Moreover, if the limitation is only due to RF power handling (amplifier sizing, linearity, etc.), then the total radiated power may be doubled and no performance penalty is incurred.

B. Sensitivity to Channel Estimation Errors

Throughout this paper, it is assumed that the receiver has perfect knowledge of the channel. The channel information may be derived by pilot symbol insertion and extraction [7], [8]. Known symbols are transmitted periodically from the transmitter to the receiver. The receiver extracts the samples and interpolates them to construct an estimate of the channel for every data symbol transmitted.

There are many factors that may degrade the performance of pilot insertion and extraction techniques, such as mismatched interpolation coefficients and quantization effects. The dominant source of estimation errors for narrowband systems, however, is time variance of the channel. The channel estimation error is minimized when the pilot insertion frequency is greater or equal to the channel Nyquist sampling rate, which is two times the maximum Doppler frequency. Therefore, as long as the channel is sampled at a sufficient rate, there is little degradation due to channel estimation errors. For receive diversity combining schemes with M antennas, at a given time, M independent samples of the M channels are available. With M transmitters and a single receiver, however, the estimates of the M channels must be derived from a single received signal. The channel estimation task is therefore different. To estimate the channel from one transmit antenna to the receive antenna the pilot symbols must be transmitted only from the corresponding transmit antenna. To estimate all the channels, the pilots must alternate between the antennas (or orthogonal pilot symbols have to be transmitted from the antennas). In either case, M times as many pilots are needed. This means that for the two-branch transmit diversity schemes discussed in this report, twice as many pilots as in the two-branch receiver combining scheme are needed.

C. The Delay Effects

With N branch transmit diversity, if the transformed copies of the signals are transmitted at N distinct intervals from all the antennas, the decoding delay is N symbol periods. That is, for the two-branch diversity scheme, the delay is two symbol periods. For a multicarrier system, however, if the copies are sent at the same time and on different carrier frequencies, then the decoding delay is only one symbol period.

D. Antenna Configurations

For all practical purposes, the primary requirement for diversity improvement is that the signals transmitted from the different antennas be sufficiently uncorrelated (less than 0.7 correlation) and that they have almost equal average power (less than 3-dB difference). Since the wireless medium is reciprocal, the guidelines for transmit antenna configurations are the same as receive antenna configurations. For instance, there have been many measurements and experimental results indicating that if two receive antennas are used to provide diversity at the base station receiver, they must be on the order of ten wavelengths apart to provide sufficient decorrelation. Similarly, measurements show that to get the same diversity improvement at the remote units it is sufficient to separate the

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antennas at the remote station by about three wavelengths.[2] This is due to the difference in the nature of the scattering environment in the proximity of the remote and base stations. The remote stations are usually surrounded by nearby scatterers, while the base station is often placed at a higher altitude, with no nearby scatterers.

Now assume that two transmit antennas are used at the base station to provide diversity at the remote station on the other side of the link. The important question is how far apart should the transmit antennas be to provide diversity at the remote receiver. The answer is that the separation requirements for receive diversity on one side of the link are identical to the requirements for transmit diversity on the other side of link. This is because the propagation medium between the transmitter and receiver in either direction are identical. In other words, to provide sufficient decorrelation between the signals transmitted from the two transmit antennas at the base station, we must have on the order of ten wavelengths of separation between the two transmit antennas. Equivalently, the transmit antennas at the remote units must be separated by about three wavelengths to provide diversity at the base station.

It is worth noting that this property allows the use of existing receive diversity antennas at the base stations for transmit diversity. Also, where possible, two antennas may be used for both transmit and receive at the base and the remote units, to provide a diversity order of four at both sides of the link.

E. Soft Failure

One of the advantages of receive diversity combining schemes is the added reliability due to multiple receive chains. Should one of the receive chains fail, and the other receive chain is operational, then the performance loss is on the order of the diversity gain. In other words, the signal may still be detected, but with inferior quality. This is commonly referred to as soft failure. Fortunately, the new transmit diversity scheme provides the same soft failure. To illustrate this, we can assume that the transmit chain for antenna one in Fig. 2 is disabled, i.e., $\boldsymbol{h}_1 = 0$. Therefore, the received signals may be described as [see (11)]

$$\begin{aligned} \boldsymbol{r}_0 &= \boldsymbol{h}_0 \boldsymbol{s}_0 + \boldsymbol{n}_0 \\ \boldsymbol{r}_1 &= -\boldsymbol{h}_0 \boldsymbol{s}_1^* + \boldsymbol{n}_1. \end{aligned} \tag{21}$$

The combiner shown in Fig. 2 builds the following two combined signals according to (12):

$$\begin{aligned} \tilde{\boldsymbol{s}}_0 &= \boldsymbol{h}_0^* \boldsymbol{r}_0 = \boldsymbol{h}_0^*(\boldsymbol{h}_0 \boldsymbol{s}_0 + \boldsymbol{n}_0) = \alpha_0^2 \boldsymbol{s}_0 + \boldsymbol{h}_0^* \boldsymbol{n}_0 \\ \tilde{\boldsymbol{s}}_1 &= -\boldsymbol{h}_0 \boldsymbol{r}_1^* = -\boldsymbol{h}_0(-\boldsymbol{h}_0^* \boldsymbol{s}_1 + \boldsymbol{n}_1^*) = \alpha_0^2 \boldsymbol{s}_1 - \boldsymbol{h}_0 \boldsymbol{n}_1^*. \end{aligned} \tag{22}$$

These combined signals are the same as if there was no diversity. Therefore, the diversity gain is lost but the signal may still be detected. For the scheme with two transmit and two receive antennas, both the transmit and receive chains are protected by this redundancy scheme.

[2] The separation required depends on many factors such as antenna heights and the scattering environment. The figures given apply mostly to macrocell urban and suburban environments with relatively large base station antenna heights.

F. Impact on Interference

The new scheme requires the simultaneous transmission of signals from two antennas. Although half the power is transmitted from each antenna, it appears that the number of potential interferers is doubled, i.e., we have twice the number of interferers, each with half the interference power. It is often assumed that in the presence of many interferers, the overall interference is Gaussian distributed. Depending on the application, if this assumption holds, the new scheme results in the same distribution and power of interference within the system. If interference has properties where interference cancellation schemes (array processing techniques) may be effectively used, however, the scheme may have impact on the system design. It is not clear whether the impact is positive or negative. The use of transmit diversity schemes (for fade mitigation) in conjunction with array processing techniques for interference mitigation has been studied for space-time trellis codes [9]. Similar efforts are under way to extend these techniques to the new transmit diversity scheme.

VI. Conclusions and Discussions

A new transmit diversity scheme has been presented. It is shown that, using two transmit antennas and one receive antenna, the new scheme provides the same diversity order as MRRC with one transmit and two receive antennas. It is further shown that the scheme may easily be generalized to two transmit antennas and M receive antennas to provide a diversity order of $2M$. An obvious application of the scheme is to provide diversity improvement at all the remote units in a wireless system, using two transmit antennas at the base stations instead of two receive antennas at all the remote terminals. The scheme does not require any feedback from the receiver to the transmitter and its computation complexity is similar to MRRC. When compared with MRRC, if the total radiated power is to remain the same, the transmit diversity scheme has a 3-dB disadvantage because of the simultaneous transmission of two distinct symbols from two antennas. Otherwise, if the total radiated power is doubled, then its performance is identical to MRRC. Moreover, assuming equal radiated power, the scheme requires two half-power amplifiers compared to one full power amplifier for MRRC, which may be advantageous for system implementation. The new scheme also requires twice the number of pilot symbols for channel estimation when pilot insertion and extraction is used.

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