A Novel Receiver Diversity Combining Technique For Internet-Based 4G Wireless Communication

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Abstract: - Antenna diversity has been shown to improve mean signal strength and reduce signal level fluctuations in the fading channel. Combinational techniques such as Maximum Ratio Combination (MRC) or Equal Gain Combination (EGC) use the multiple signal branches that exist in the wireless channel advantageously by improving the antenna diversity and performance. MRC provides better performance than EGC, but the disadvantage of this technique, although optimal, is the complexity in its implementation since it requires SNR estimation algorithms. We introduce a novel combination technique termed Root-Mean-Square Gain Combination (RMSGC). We investigate the structure of this scheme using BPSK and its performance is quantified in terms of bit error rate (BER) and a novel metric termed signal-to-scattering noise ratio or SNR peakedness. We found that RMSGC is "near optimal" in the sense that it produced results superior to EGC and very close to MRC but with much less complexity at the receiver and without the need for channel amplitudes estimation. The results of this research are promising and can find applications in internet-based 4G wireless communication comprising small pico- and femto-cells.

Key-Words: - Bit error rate, equal gain combining, maximum ratio combining, root-mean-square gain combining, signal-to-scattering noise ratio, single-input multiple-output channels

1 Introduction

Multipath fading caused by scattering of the wireless signal is undoubtedly the major obstacle in wireless communication. Several classical techniques have been adopted to reduce the problem of fading in wireless channels. Most notably are the employment of frequency hopping spread spectrum (FHHS) modulation (as in GSM, DECT, Bluetooth …) and sectoring concepts within the cell (each cell has from 3 to 7 pie-shaped sectors) where omni-directional antennas are replaced by directional antennas that concentrate the radio signal in a narrow beam.

The *old perspective* was to treat multipath fading noise as a nuisance with the ultimate goal of combating the distortion it causes. In this context, modern cellular systems use adaptive equalization to reduce multipath by subtracting the reflected multipath signals from the received signal through the use of digital filters that dynamically change their characteristics in response to different situations [1]. Such techniques are expensive, computationally demanding, and suffer from increased latency which is undesirable in real-time transmission.

We treat the scattering phenomena from a *new perspective*: as a carrier of useful signal's envelope (and power) information. In our approach, we plan to make use of the fact that multipath fading is a function of the amplitude strength and spatial distribution of scatterers within the channel on a scale corresponding to the wavelength of the transmitted wave. Scattering noise is thus viewed as carrier of information about the envelope and power statistics of individual multipath waves within a channel. These characteristics are useful in average received power quantification.

In short, our goal is not to combat multipath per se, but rather to treat multipath propagation as representing multiple channels between transmitter and receiver and to use scattering statistical properties advantageously to enhance the received signal-to-sacettering-noise ratio (which is related to the *peakedness* of the SNR).

An emerging modern technique for multipath capacity gain is the multi-input multi-output (MIMO) scheme. MIMO systems use multiple antennas at both transmitter and receiver ends for communication [2-4]. Independent channel fading caused by multipath between different transmitting and receiving antenna pairs provides a significant capacity gain and link reliability over conventional single antenna systems. Independence of channels also means that the receiver will have more than one independent replica of the transmitted signal. MIMO systems can also be applied to provide a higher data rate and reliable communication. These have led to MIMO being regarded as one of the most promising emerging wireless DSP technologies [5].

Numerous MIMO systems using advanced wireless DSP have been proposed in [2-5]. In our work, we study a cost-efficient, yet effective, novel receiver *diversity gain processing* technique for single-input multiple-output (SIMO) systems (a sub-component of MIMO.

2 Receiver Diversity Gain Combining

Antenna diversity is a promising technique for overcoming multipath fading in a wireless channel. Diversity techniques are generally used to generate multiple signal branches between transmitter and receiver and have been shown to improve mean signal strength [2] and reduce signal level fluctuations in the fading channel.

Combinational techniques such as Maximum Ratio Combination (MRC) and Equal Gain Combination (EGC) use the multiple signal branches in the wireless channel advantageously by improving the antenna diversity and performance. MRC provides better performance than EGC, but the disadvantage of this technique is the complexity in its implementation since it requires SNR estimation. Another disadvantage of is that simultaneous demodulation of parallel channels is required.

For single-input-multiple-output (SIMO) systems with L antennas at the receiver, diversity receivers extract multiple signal branches or copies of the same signal received from different channels and apply gain combining schemes to enhance the signal-to-fading-noise ratio and improve the system's performance.

Although we consider (1 x L) SIMO systems in our analysis, the results can be extended to (M x L) MIMO systems using simple *spatial cycling* techniques [6]. Under such techniques, MIMO systems are implemented by using only one transmitter at a time and by cycling over the M transmitters periodically, effectively employing a SIMO structure at every transmission period.

2.1 Root-Mean-Square Gain Combining

In this section, we introduce our receiver diversity gain combining scheme, termed root-mean-square gain combining (RMSGC) and illustrated in Fig. 1. In the RMSGC technique, diversity signal paths arrive at the L receiver antennas, where each signal is squared using a square law device. Depending on the polarity of the original arriving signal, the squared signal is inverted (if originally negative), which is achieved by a signum filter. Then all the signals are summed and the composite diversity signal is processed using a square-root (of the absolute value) device before being sent to a detector. If the polarity of the composite signal is negative, the square-rooted signal is inverted using a signum gain.

The envelope β of the RMSGC signal is

$$\beta \approx \sqrt{\sum_{i=1}^{L} \gamma_{i,r}^{2}}, \text{ for } \overline{\rho} >> \qquad (1)$$

where $\gamma_{i.r}$ is the received diffuse envelope of the ith diversity signal path, L is the number of antennas, and $\overline{\rho}$ is the average SNR per bit. The phases are assumed corrected.

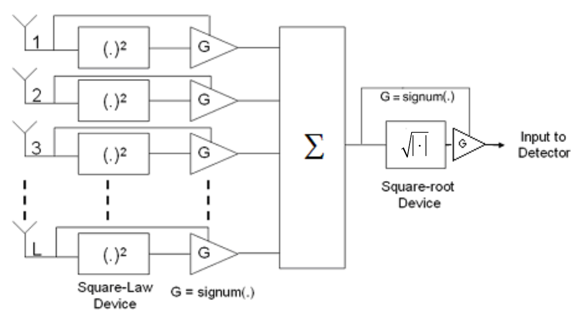

Fig. 1 Novel RMSGC diversity combining scheme

The fading power statistic β^2 (for $\overline{\rho} >>$) is consistent with that of a Gamma law with shaping parameter L and scaling parameter P_{dif} (or chi-square with 2L degrees of freedom) and is denoted by $\beta^2 \sim$ Gamma(L, P_{dif}^{-1}). As a result, the envelope β is Nakagami-m (with $m = L$) distributed. These statistics arise from the independence of diversity signal branches.

For comparative statistical analysis, we consider the practical and widely used EGC scheme where the received diversity signal branches are simply coherently summed. We do not consider MRC for comparative theoretical analysis (an experimental comparison is conducted in Section 3.3) because it requires SNR estimation over an L-branch communication system, thus rendering theoretical

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derivations of the fading statistics complicated by the presence of estimation errors (which is not the purpose of this paper).

3 Performance Analysis

In this section, we study the performance of RMSGC and compare it to that of EGC in terms of a novel metric.

3.1 Signal-to-Scattering Noise Ratio and Signal-to-Noise Ratio Peakedness

The next natural step would be to devise a measure to study the statistical gain of diversity processing techniques. We introduce a new performance metric that captures the "amount" or "degree" of fading. This measure relates directly to the more severe multiplicative fading noise and is a good measure of performance in noise- and interference-limited environments, as opposed to other measures such as the signal-to-interference noise ratio (SINR), which relates to the additive background noise and co-channel interference (CCI). Our approach is based on the fundamental principles of statistical optics and radar imaging where the underlying random physical phenomena is similar to wireless multipath channels and the surface scattering speckle noise model is statistically identical to multipath fading [7, 8]. In fact, RMSGC, in terms of fading power, emulates multi-look speckle processing in SAR images and can be conceived as "EGC" of the diversity signals' fading powers.

We define the signal-to-scattering-noise ratio

$$SSNR = \frac{E\left(\beta^2\right)}{\sigma_{\beta^2}} \qquad (2)$$

which corresponds to the reciprocal of speckle contrast in active radar imagery [7 - 8]. Since the SNR contains the random multiplicative fading power term β^2 and the constant AWGN power spectral density term N_0, an equivalent metric to the SSNR is the signal-to-noise ratio peakedness *SNRF* = $E(\rho)/\sigma_\rho$, where ρ is the random SNR. This metric measures the "amount" or "degree" of randomness of the SNR and is, in our view, more significant than the average SNR, especially in shadow fading environment where there will be significant fluctuations of the SNR around an underlying mean value.

Similarly, a large *SSNR* metric signifies that the signal's power level fluctuations are small relative to the mean signal's power strength, indicating "reliable" communication. According to Eq. (2), this metric is invariant to a constant gain. This is consistent with the fact that direct constant gain amplification at the receiver's antennas is ineffective in a fading environment since a linear amplifier of constant gain C will amplify the faded power at every received symbol by C while also amplifying the variance of the power by C^2. The mean relative to the standard deviation remains unchanged (unity), thus rendering the amplifiers *statistically transparent* to the system.

We define the diversity combining statistical gain

$$\begin{aligned} G &= SSNR_{SIMO} / SSNR_{SISO} \\ &= SSNF_{SIMO} / SSNF_{SISO}. \end{aligned} \qquad (3)$$

For a single-input-single-output (SISO) system, the *SSNR* is unity (or asymptotically one) under various fading conditions (except for Rician and shadowed multipath fading). It can be readily shown that in the case of RMSGC, the *SSNR* is enhanced by $\sqrt{L}$ (e.g., the RMSGC statistical gain of 4 antennas is 100%). A notable exception is RMSGC of diversity signal branches over shadow-fading, where the multipath branches are Gamma distributed with a *random mean* power (the shadow), which in turn is driven by an underlying Gamma process. In this doubly stochastic fading model, *SSNR* = $\sqrt{Lp/(L+p+1)}$ and G = $\sqrt{L(p+2)/(L+p+1)}$, where p is the Gamma distribution shaping parameter.

Another notable exception is RMSGC in shadow-fading with exponential fading power driven by an underlying exponential shadow process. A practical application where such fading statistics arise is the mobile station of cellular systems in a macro-cell with hills or micro-cell with scattering automobiles [5]. In this environment, RMSGC significantly improves the system's performance since the *SSNR* of a SISO system in such a fading environment is at a very low value of $1/\sqrt{3}$ (by comparison, the *SSNR* of a SISO system over a Rayleigh channel is 1).

For Rician statistics, RMSGC has a diminishing statistical gain for very large Rician factors. This usually happens in fading environments where the power of the line of sight (specular component) is much larger than the average diffuse power (eg. land mobile satellite or LMS).

3.2 *SSNR*-based Comparison

For EGC, the *SSNR* is obtained by generating the 2nd and 4th moments of the envelope β_{EGC} from the MGF

$$M_{\beta_{EGC}}(s) = \exp\left(0.125LP_{dif}s^2\right)\left[D_{-2}\left(-s\sqrt{0.5P_{dif}}\right)\right]^L \quad ,(4)$$

where $D_{-\eta}(.)$ is the parabolic cylinder function.

The *SSNR* of RMSGC is always larger than that of EGC regardless of the distribution of the fading envelopes $\{\gamma_{i,,r}\}$. This follows from the Lagrange identity

$$\left(\sum_{i=1}^{L}\gamma_{i,r}\right)^2 = L\sum_{i=1}^{L}\gamma_{i,r}^2 - \sum_{1\le i<j\le L}\left(\gamma_{i,r}-\gamma_{j,r}\right)^2 \quad (5)$$

and from the Cauchy-Schwarz-Buniakowski inequality

$$\beta_{EGC}^2 = \left(\sum_{i=1}^{L}\gamma_{i,r}\right)^2 \le L\sum_{j=1}^{L}\gamma_{j,r}^2 = L\beta_{EMSGC}^2 \quad (6)$$

with equality if and only if $\gamma_{i,r}=\gamma_{j,r}\ \forall i,j$ (with $P(\gamma_{i,r}=\gamma_{j,r})=0$). Applying the expectation operator to Eq.(6) results in $SSNR_{\mathrm{EGC}} \le SSNR_{\mathrm{RMSGC}}$.

Even though square law combining (SLC) [6, 9] is not studied in this paper, we mention that

$$SSNR_{SLC} = \sqrt{L(L+1)/(2(2L+3))} \quad (7)$$

for independent Rayleigh fading paths. This is yet an additional proof to the superiority of the RMSGC technique since $SSNR_{SLC} < SSNR_{RMSGC} = \sqrt{L}\ \forall L$ and asymptotically $SSNR_{SLC} \underset{L\to\infty}{\to} 0.5\, SSNR_{RMSGC}$.

3.3 BER-based Comparison

Wireless systems present a uniquely different challenge in the sense that, in addition to the hostile fading environment (multiplicative noise), they are also *noise*- and *interference-limited* (additive white or colour noise), unlike wire-line systems which are only noise-limited (additive white Gaussian noise or AWGN). As a mobile receiver moves in a multipath channel, fading causes the signal power to fluctuate in space along with interfering noise, resulting in a *random* SNR.

We now consider BPSK over independent Rayleigh fading (slow and non frequency selective) diversity channels with AWGN. The average reference SNR $\overline{\rho} = E_b P_{dif}/N_0$, E_b is the energy per bit, P_{dif} is the mean diffuse power, and $N_0/2$ is the AWGN power spectral density [5]. In a SIMO channel with RMSGC, the SNR ρ_{RMSGC} obeys the same statistics as the RMSGC fading power, that is, ρ_{RMSGC} ~ Gamma(L, $\overline{\rho}$). Considering the case where the BER is evaluated at the average operating condition, Jensen's inequality yields a BER upper bound:

$$\sup\left(BER_{RMSGC}\right) = 0.5\left(1-\sqrt{L\overline{\rho}/(1+L\overline{\rho})}\right) \quad (8)$$

We now consider the exact error probability in which the BER is averaged over the possible operating conditions by keeping the operating conditions random and thus capturing their statistical fluctuations. Rigorous mathematical analysis yields the expression

$$\overline{BER} = \frac{1}{2(L-1)!}\left([L-1]_{L-1} - \sqrt{\frac{\overline{\rho}}{\pi}}\left(1+\overline{\rho}\right)^{\frac{1}{2}-L} \sum_{l=0}^{L-1}[L-1]_l\,\Gamma\left(L-l-\frac{1}{2}\right)\left(1+\overline{\rho}\right)^l\right) \quad (9)$$

where $[N]_M$ is the reverse-Pochhammer symbol and $\Gamma(.)$ is the gamma function.

For EGC, the BER upper limit is

$$\sup\left(BER_{EGC}\right) = 0.5\left(1-\sqrt{L\overline{\rho}[1+(L-1)\pi/4]/(1+L\overline{\rho}[1+(L-1)\pi/4])}\right). \quad (10)$$

The exact mean BER of the EGC fading envelope is given in the form of a single finite-range integral and an integrand composed of tabulated transcendental functions involving Hermite polynomials [6]. Since such form is not analytically tractable, we approximate its mean BER using the Delta method:

$$\begin{aligned} BER_{EGC} &= E\left(Q\left(\sqrt{2\rho_{EGC}}\right)\right) \\ &\approx Q\left(\sqrt{2E\left(\rho_{EGC}\right)}\right) + 0.5\sigma_{\rho}^2 Q''\left(\sqrt{2x}\right)\Big|_{x=E(\rho_{EGC})}, \\ E\left(\rho_{EGC}\right) &= E_b M''_{\beta_{EGC}}(0)/N_0, \\ \sigma_{\rho_{EGC}}^2 &= E_b^2 M_{\beta_{EGC}}^{(4)}(0)/N_0^2 - E^2\left(\rho_{EGC}\right), \end{aligned} \quad (11)$$

where the moment generating function $M(.)$ was given in Eq.(4) and the second derivative of the Q-function is $Q''\left(\sqrt{2x}\right) = 0.5\exp(-x)(1+x^{-1})/\sqrt{\pi x}$.

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Equation (11) is obtained by a one step Taylor approximation of $Q\left(\sqrt{2\rho_{EGC}}\right)$ about the mean $E\left(\rho_{EGC}\right)$. The approximation is good if $\overline{\rho}$ has a high probability of being close to its mean (i.e. *SSNR* is large).

The simulated BER curves are plotted as a function of the average SNR $\overline{\rho}$ (dB) for 8 antennas in Fig. 2. The simulated results show that the performance of RMSGC is superior to that of EGC and that the BER decreases monotonically with an increase in the average SNR. The performance of RMSGC is very close to that of MRC and almost identical for SNR above 16 dB. While MRC is the theoretical *optimal* scheme, we conclude that RMSGC is *near-optimal*.

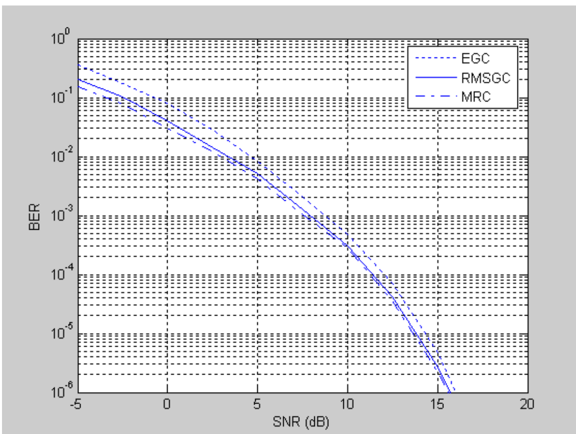

Fig. 2 BER for RMSGC, MRC, and EGC combining techniques using 8 antennas

In Fig. 3, the BER decreases with an increase in the number of antennas. However, this improvement is diminished and is negligible above 8 antennas.

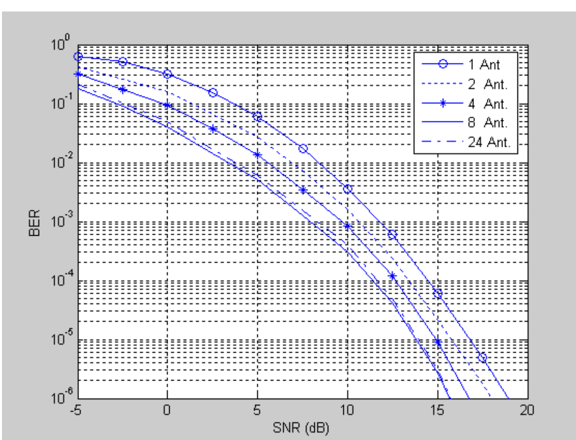

Fig. 3 BER for RMSGC using different antenna numbers

4 Conclusions and Future Work

In this paper, we devised a novel diversity gain combining technique termed RMSGC. The performance of this scheme was characterized in terms of a new SSNR metric which captures the degree of fading randomness, and in terms of the average BER. The performance of RMSGC was then compared to the widely used EGC and the theoretically optimal MRC. RMSGC enhanced the SSNR gain by $\sqrt{L}$ and proved to be near optimal in the sense that the BER results were lower than EGC, very similar to MRC and almost identical for SNR over 16 dB. In addition, we found that the BER of RMSGC decreased as the number of antennas increased, but the improvement was gradually diminished and negligible after 8 antennas.

RMSGC is a promising new technique because it is relatively simple and, unlike MRC, does not require SNR estimation. We are currently improving the RMSGC scheme by investigating denoising techniques and implementing RMSGC, being a non linear system, using FPGA [10 - 14].

The results of this research are promising and can find applications in internet-based 4G wireless communication comprising small pico- and femto-cells.

As future work, we propose to study the CCI resulting from the correlation between the receiver antennas. There exist a critical number of antennas for which the CCI noise becomes very limiting and causes the system's performance to deteriorate. CCI can be resolved using OFDM. Since SIMO is a sub-component of MIMO, this work can also be extended to MIMO systems.

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