A Cooperative MIMO Mobile Multihop Relay for Cellular Networks

Jong-Moon Chung[1], Hyung-Weon Cho[2], Ki-Yong Jin[1], Min-Hee Cho[1], Ho Kim[2]

[1] School of Electrical & Electronic Engineering
Yonsei University
Seoul 120-749, Republic of Korea
http://www.yonsei.ac.kr/jmc

[2] Samsung Thales, Co. Ltd.
Yongin-City, Gyeonggi-Do, 449-712, Republic of Korea

Abstract: In this paper, we present an analysis of mobile multihop relay (MMR) technology using cooperative multiple-input-multiple-output (MIMO) transmission. New wireless broadband protocols, such as WiMAX, and 3G-LTE apply MIMO technology, and mobile communication protocols under standardization are investigating MMR as a future technology to use. These two technologies are expected to be among the most important techniques in the near future. However conventional MIMO technology can not be applied directly in some applications. Therefore, we investigate a novel MMR scheme to which a cooperative MIMO transmission scheme can be applied. Since MMR is conducted normally for far outreaching users, one of the main factors that influence a MMR transmission scheme is the interference, which comprises of inner and outer co-channel interference (CCI). Therefore, this paper focuses on the performance analysis of the MMR scheme where the analysis is based on the signal to interference power ratio (SIR) outage probability. The results of this paper show that the CCI controlled MMR scheme can provide a performance improvement compared to the conventional MMR scheme in cellular mobile communications.

Key-Words: Mobile Multihop Relay, Cooperative MIMO, Cellular Networks

1 Introduction

In recent years, wireless asymmetric data services have been requested heavily and are expected to be even more popular in the future considering the trend of the growing multimedia mobile communication market. One of the solutions to asymmetric traffic rate support over wide services areas is multihop relay techniques, which take advantage of dynamic traffic dispersion [1]. The authors of [1] show that a number of ad hoc relaying stations can overcome traffic congestion by balancing the load among different cells in a cost-effective way. Furthermore, there are many investigations that show the great advantages of MMR technology, such as, low power consumption, more cost efficient system capacity enhancement, and higher service coverage [2], [3]. However, the extra relay overhead, more complex resource allocation schemes are required for relaying, and increments in the implementation complexity are drawbacks of multihop relay technology.

For MIMO systems, one of the most important features is its ability to transmit data at higher data rates than that of single-input single output (SISO) systems using the same transmission power. This means, in turn, that we can transmit a fixed amount of data with less power if we use MIMO systems. In cellular communication, the fact that we are able to transmit data with less power is important, because the impact of interference depends on the level of the transmission power, and also the battery lifeline can be extended. Therefore MIMO systems have an advantage in being used in cellular mobile communications due to the effect of resulting in less interference.

In some cases, however, MIMO technology can not be applied to an application directly due to system requirements. For example, in wireless sensor networks MIMO technology can not be used due to the node size being too small to have multiple antennas. In addition, the hardware and software complexity and the system energy consumption of MIMO systems are higher than SISO systems. However, if we let multiple nodes operate cooperatively we can solve this problem. That is, after a node broadcasts information to other local nodes, each local node can be programmed to operate like one of the antennas of a MIMO system, and can relay the signal to (or towards) the destination node [4], [5]. Using a cooperative MIMO scheme, MMR can provide enhanced advantages of energy efficiency, reliability, high data rate, and end-to-end guaranteed QoS for shadowed areas. Furthermore, taking advantage of the higher throughput the drawback of MMR systems requiring extra relay overhead can be partially solved using cooperative MIMO technology.

The remainder of the paper is organized as follows. Section 2 presents the system model. In Section 3, the derivation of the signal to interference power ratio is presented. The experimental results are presented in Section 4, and finally, Section 5 concludes the paper.

2 System Model

2.1 Cellular Structure

We assume a multihop cellular structure, which consists of a hexagonal pattern, as illustrated in Fig. 1. There is one base station (BS), several multihop relay stations (RSs), and a number of mobile stations (MSs) in each cell. MSs are assumed to be uniformly distributed. In this model, the frequency reuse factor is 7 and the interference is comprised of inner and outer interference. Inner interference is due to the multihop relay, and the outer interference results from co-channel interference, which is caused by cells using the same frequency.

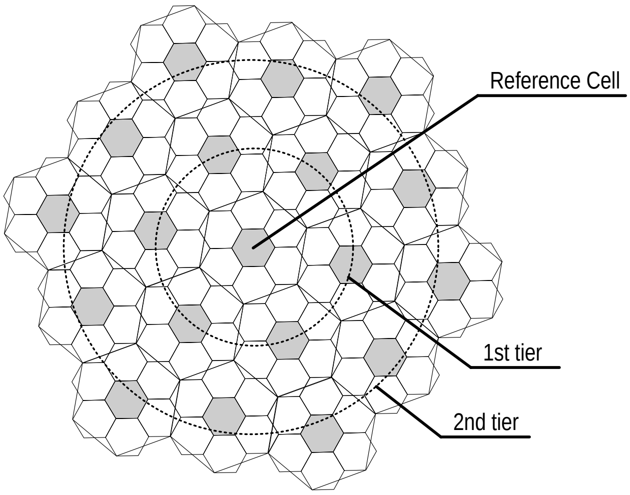

Fig. 1. Cellular Structure

2.2 Cellular Structure

The radio model is based on the path-loss power for radio propagation [6] and the added transmission probability. According to this model, signal power will depend on the local mean power and shadowing effects in propagation [7] which can be described as,

$$P_r = \mu + \varsigma \tag{1}$$

$$\mu = P_r + G_t + G_r + 10\log_{10}(q_t) - 10n\log_{10}(R) \tag{2}$$

$$\varsigma = N(0,\sigma^2) \tag{3}$$

where P_r is the mean value of the received signal power at the reference cell, μ is the local mean power as described in (2), and ς is the shadowing parameter as represented in (3). P_t is the transmitter power, G_t and G_r are the transmitter and receiver antenna gains respectively, q_t is the transmission probability, n is the path loss exponent, R is the distance between Tx and Rx, and σ is the standard deviation.

2.3 MIMO Systems

According to the link budget relationship [8], we can calculate the transmit power P_t as

$$P_t = E_b R_b \times \frac{(4\pi d)^2}{G_t G_r \lambda^2} M_l N_f \tag{4}$$

where E_b is the required energy per bit at the receiver for a given bit error rate (BER) requirement, R_b is the bit rate, d is the transmission distance, G_t is the transmitter antenna gain, G_r is the receiver antenna gain, λ is the carrier wavelength, M_l is the link margin, N_f is the receiver noise figure defined as $N_f = (N_r/N_0)$ with N_0 = -171dBm/Hz which is the single-sided thermal noise power spectral density (PSD) and N_r is the PSD of the total effective noise at the receiver input [4]. For MIMO systems based on the Alamouti schemes with BPSK modulation in Rayleigh-fading channels, we can assume the instantaneous received SNR (γ) and the average BER (P_b) are given by [4], [9]

$$\gamma = \frac{\|\mathbf{H}\|_F^2}{M_t} \frac{E_b}{N_0},\ M_t = 1,2 \tag{5}$$

$$P_b = \varepsilon_H \left\{ Q\left(\sqrt{2\gamma}\right) \right\} \tag{6}$$

where **H** is a scalar fading matrix.

2.4 Multihop Cooperative MIMO

The system architecture of the multihop cooperative MIMO scheme is shown in Fig. 2. The information that is to be sent to the MS is broadcasted to a neighboring RS around the BS first. Then the RS encodes according to the Alamouti code and transmits the data bits to the MS in the next hop (Fig. 2. (a)). For the case of uplink (Fig. 2. (b)), the procedure is the same with that of the downlink. We assume the Rayleigh fading channel and the path loss is modeled as a power falloff proportional to the distance squared. In a cell, it is also assumed that the transmission power of the BS is restricted under which a given average BER is guaranteed.

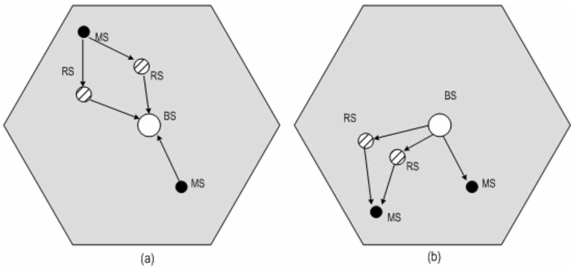

Fig. 2. Multihop Cooperative MIMO

2.5 Interference Model

The interference scenarios that will be discussed in this paper are the interference caused by MSs and RSs in the uplink. System degradation in the downlink cycle at the reference cell is less sensitive than that in the uplink cycle. This stems from the fact that the propagation from BS to BS suffers less attenuation than that from a MS to BS or RS to BS. Therefore, system performance evaluation in the uplink cycle is reasonable. Fig. 5 shows interfering cells that use the same frequency and interfering entities observed from the reference cell.

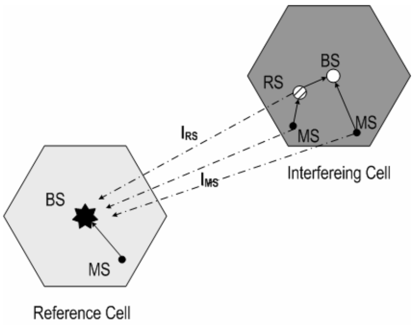

Fig. 3. Interference model

3 SIR Performance Derivations

3.1 Desired Signal Power Calculation

Desired signal power can be calculated using (1) for omni-directional antennas and normalized antenna gain in local mean power at the reference cell [6]. Thus, the desired signal power is represented as

$$P_s = \mu_{MB} + \varsigma_{MB} \tag{7}$$

where $\mu_{MB} = -10 n_{MB} \log_{10}(R_d)$, $\varsigma_{MB} = N(0, \sigma_{MB}^2)$, and the path loss exponent between the MS and BS is 4. Then, the probability density function of the desired signal power is expressed as a Gaussian random variable *X*.

$$f_{P_S}(\gamma) = N(\mu_{MB}, \sigma_{MB}^2) \equiv X_{MB}^1(\gamma) \tag{8}$$

3.2 Aggregate Interference Calculation

The aggregate interference P_I in dB consists of all interference scenarios

$$P_I = 10\log_{10}\left(\sum_{i=0}^{\alpha} p_i\right) = 10\log_{10}\left(\sum_{i=0}^{\alpha}\left(p_i^{MS} + p_i^{BS} + p_i^{RS}\right)\right) \tag{9}$$

where p_i^{MS} is the transmission power from the MS at the neighboring cell c_i, P_i^{BS} is transmission power from the BS in the neighboring cell c_i, P_i^{RS} is the transmission power from the RS in the neighboring cell c_i, and α is the number of neighboring cells. Each transmission power from different entities is given in (10)-(12), and is expressed as the sum of co-channel interference from within the same cell and neighboring cells. A neighboring cell is defined as a cell in the 1st and 2nd tires, and uses the same frequency as the reference cell. Next we obtain,

$$10\log_{10}\left(\sum_{i=1}^{\alpha}\left(p_i^{MS}\right)\right) \equiv X_{MS}^{\alpha} = N\left(\mu_{MS}^{\alpha}, \sigma_{MS}^{\alpha}\right),\ P_0^{MS} = 0 \tag{10}$$

$$10\log_{10}\left(\sum_{i=1}^{\alpha}\left(p_i^{BS}\right)\right) \equiv X_{BS}^{\alpha} = N\left(\mu_{BS}^{\alpha}, \sigma_{BS}^{\alpha}\right),\ P_0^{BS} = 0 \tag{11}$$

$$10\log_{10}\left(\sum_{i=0}^{\alpha}\left(p_i^{RS}\right)\right) \equiv X_{RS}^{\alpha+1} = N\left(\mu_{RS}^{\alpha+1}, \sigma_{RS}^{\alpha+1}\right),\ P_0^{RS} \neq 0 \tag{12}$$

where P_0^{Entity} is the transmission power in the reference cell, and therefore, $P_0^{MS} = P_0^{BS} = 0$ and $P_0^{RS} \neq 0$. The standard deviation of the random variables σ_{MS}, σ_{BS}, and σ_{RS} are set respectively to 6, 8, 6 dB [9]. The probability density function of the aggregated interference can be represented as

$$f_{P_I}(\gamma) = 10\log_{10}\left(\sum_{i=0}^{\alpha} p_i\right) = 10\log_{10}\left(\sum_{i=0}^{\alpha}\left(p_i^{MS} + p_i^{RS}\right)\right)$$
$$= X_{MS}^{\alpha}(\gamma) + X_{RS}^{\alpha+1}(\gamma). \tag{13}$$

3.3 SIR Outage Probability

The signal to interference power ratio (SIR) outage probability used in this paper is defined as

$$P\{Outage\} = P\{SIR\langle\tau\} = \int_{-\infty}^{\tau} f_{SIR}(\gamma)\, d\gamma \tag{14}$$

where the outage probability is defined as the probability when the SIR is lower than a threshold value τ and the probability density function (*pdf*) of the SIR can be represented as a convolution of the *pdf* of the signal power and the *pdf* of the interference power.

$$f_{SIR} = f_{P_S}(\gamma) \otimes f_{P_I}(-\gamma) \tag{15}$$

4 Experimental Results

The multihop cellular network performance was evaluated using the *pdf* of interference and the outage probability of the signal to interference power ratio. The system performance was evaluated in 3 different environments: (1) without multihop relaying, (2) multihop relaying in a part of the frame, and (3) multihop relaying using cooperative MIMO. Moreover different multihop relay rates are considered in the performance evaluation.

The parameters used in the simulation are defined as follows. The number of uplink time slots is 33, up to 3 multihop relays exist in each cell, and the number of time slots for multihop relay is defined as *H*. The multihop relay rate is defined by the percentage of *H* over *N* and its values γ_R have been set as 0.1, 0.2, 0.3, 0.4, 0.5, and 0.6 in the performance analysis.

Fig. 4 shows the *pdf* of the aggregated interference using the MIMO scheme under the circumstance of no MMR. Fig. 5 shows that the *pdf* of the aggregated interference when MMR is applied (with $\gamma_R = 0.4$).

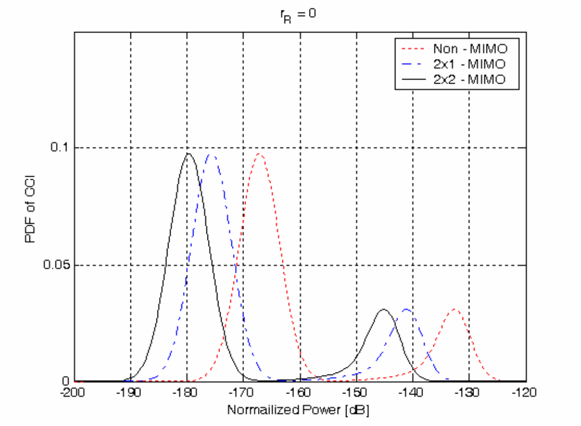

Fig. 4. PDF of the aggregated interference, *r* = 0.

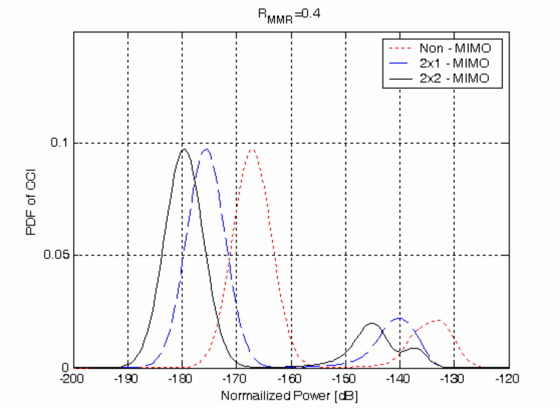

Fig. 5 PDF of the aggregated interference, *r* = 0.4.

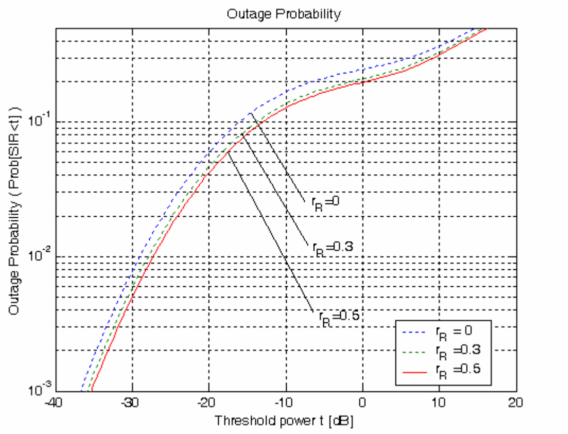

Fig. 6. Outage probability of the SIR.

Comparing these two graphs, we can observe that interference can be reduced if we use the MIMO scheme to transmit data. This is due to the nature of the low power consumption of the MIMO scheme. Fig. 6 shows the outage probability of the SIR adopting multihop relaying.

Interference from the BS, I_{BS}, is dominant when $\gamma_R = 0$, but when γ_R increases, the interference due to the RSs becomes more significant and heavily effect the system. In other words, when adopting multihop relay, I_{RS} becomes the dominant interference factor and the system performance is severely degraded by I_{RS}.

4 Conclusion

In this paper a cooperative MIMO MMR scheme is presented and its performance has been analyzed. The MMR scheme provides several technical advantages. However, as the results demonstrate, as the multihop relay rate increases, the co-channel interference level increases, and there needs to be a scheme to control (i.e., manage) the interference, or the advantages of using MMR technology will disappear. To solve this problem, this paper proposes a cooperative MIMO scheme combined with MMR technology.

In this combined model, the base station broadcasts data to the relay station first, and then the relay station encodes the data and transmits it to the destination node. Through this procedure, the relay stations are operated as a single antenna of the MIMO transmitter, and the advantages of MIMO systems can be obtained. Using the mathematical analysis provided, we can see that the aggregated interference can be reduced by adopting the cooperative MIMO scheme. This is due to the fact that the MIMO scheme consumes less transmission energy when transmitting the same amount of data. However, as the rate of using MMR increases, the outage probability also increases. Therefore, the multihop relay rate should be chosen carefully not to cancel out the gain which is obtained by using cooperative MIMO. The analysis and results of this paper provide a method to accurately estimate the performance influencing factors of cooperative MIMO in mobile multihop applications, such that future broadband mobile communication techniques can be developed with an improved overall system performance and wider service range through MMR technology.

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