Distributed Cooperation and Diversity for Hybrid Wireless Networks

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Abstract. In this paper, we propose a new Distributed Cooperation and Diversity Combining framework. Our focus is heterogeneous networks with devices equipped with two types of radio frequency (RF) links: short-range high-rate interface (e.g., IEEE802.11), and a long-range low-rate interface (e.g., cellular) communicating in fading channels. Within this framework, we propose and evaluate a set of distributed cooperation techniques operating at different hierarchical levels with resource constraints such as short-range RF bandwidth. We propose a Priority Maximum-Ratio Combining (PMRC) for pre-demodulation combining, a post soft-demodulation combining, and a decode-and-forward technique. We show that the proposed techniques achieve significant improvements on Signal to Noise Ratio (SNR), Bit Error Rate (BER) and throughput through analysis, simulation, and experimentation on our platform prototype. Our results also indicate that, under several communication scenarios we are considering, PMRC can improve the throughput performance by over an order of magnitude.

Keywords: Diversity, Cooperation, Hybrid Wireless Networks

1 Introduction

Wireless communication networks are enabling an ever increasing set of applications. The service quality and scalability of these applications is limited by fundamental constraints. These include a scarce radio-frequency spectrum, signal propagation effects such as fading and shadowing resulting in areas with limited coverage, and the small form factor of mobile devices with limited energy capacity and antenna diversity. Recently due to the increasing demand of mobile services such as mobile cloud computing and video streaming, improving the robustness and throughput of cellular systems has become more critical. Many technologies including dynamic power control, adaptive coding and modulation, smart antenna, etc., have been proposed or adopted, nevertheless the cooperation gain has yet been exploited completely. To improve the spectrum efficiency, one of the solutions used by operators is to deploy additional base stations [1], but this strategy is ineffective and costly. In this paper, we propose to explore a new communication model, where multiple mobile nodes *cooperate with each other* and with the base stations. We will investigate communication strategies that exploit the channel diversity across a set of cooperating mobile nodes equipped with multiple radio interfaces.

Diversity and cooperation, as general mechanisms to improve the robustness and efficiency of wireless communication systems, have been studied for many years [2–4], but very little research has been done for distributed wireless systems with multiple types of air-interfaces and considering the unique characteristics of each interfaces. With the increased hardware integration, faster computation, and high users density, the cooperation between nearby devices is becoming possible and even necessary given the increased demand for bandwidth.

Unlike traditional diversity paradigms, our approach combines the physical layer information from multiple distributed receivers using the short-range high data-rate wireless network. It exploits both the antenna gain and the fading independence. This cooperation can significantly improve the Signal to Noise Ratio (SNR), Bit Error Rate (BER) and throughput. It leads to improved coverage, capacity boost and reduction of interference.

Contributions: We propose a distributed cooperation framework - Hierarchical Priority Combining, which allows multiple levels of cooperation depending on the channel conditions and resource constraints. It consists of three combining techniques: pre-demodulation combining, post soft-demodulation combining, and decode-and-forward. We also propose Priority Maximum Ratio Combining (PMRC) as an implementation of pre-demodulation combining, and show orders of magnitude improvement of the SNR, outage probability, BER and throughput even with limited short-range bandwidth. We also show that most of the benefit of the traditional single device Maximum-Ratio Combining (MRC) can be achieved by PMRC with the contribution from a small group of neighbouring nodes. In addition, we simulate its performance using a pilot-based channel estimator and show that a significant gain can be achieved. We also implemented the post soft-demodulation combining prototype on the USRP/GNU radio and revealed substantial gain for channels with moderate fading.

Related work: While, cellular have been benefiting from continuous improvements of the physical link-layer between a mobile station and one or multiple base stations (through various coding, modulation, and antenna technologies), it is only recently that distributed cooperation started to attract more interest from the wireless communications and networking research community [5]. Some studies have addressed specific cases such as diversity with *homogeneous* interfaces where the combining occurs over the air [6–8]. Several interesting approaches demonstrate the benefits of distributed cooperation in *ad hoc networks* with *homogeneous* wireless interfaces and challenged the community to investigate the full benefits of distributed cooperation [5,9,10]. Distributed MIMO in ad hoc network has also been theoretically studied in [11]. The use of cooperating *heterogeneous* air-interfaces was advocated in [12,13]. Cooperation of multi-radio access networks has also been researched in [14] to enhance the transmission robustness. More recently, several post soft-demodulation techniques were proposed [15,16].

In our previous work [17], we have introduced Threshold Maximum-Ratio Combining and studied its performance. In this paper, we significantly extend our previously proposed distributed cross-layer diversity framework to hierarchical combining (HPC) and introduce PMRC a substantially superior combining technique.

2 System Model

We consider a hybrid network where the mobile nodes are equipped with two radio interfaces: a long-range, low data-rate cellular interface, and a short-range, high data-rate interface. The performance of long-range cellular links is limited by the shadowing and channel fading caused by multipath propagation and mobility. These are critical problems in cellular communication as they result in dead-signal areas and localized poor system performance. *RF-channel diversity* is a typical approach to overcome them through independent transmission paths. Many existing technologies, such as MIMO, require multiple antennas to be co-located at the same device. Due to the minimum spatial separation (0.4λ [4]) and high cost of RF front ends, however, it is impractical to implement these schemes on a single small form factor device such as a cell phone [6]. Our cooperation strategy intends to make use of the RF front ends of a group of geographically separated devices. This cooperation operates at the physical-link layer, and it is transparent to applications. Therefore the existing applications would have an improved performance without requiring any awareness or modifications.

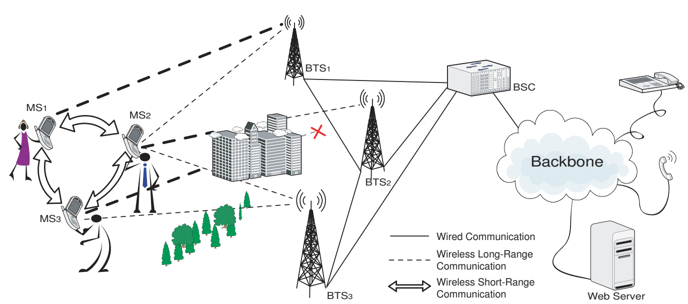


Fig. 1: Example of setup for distributed cross-layer diversity.

Currently, most smart-phones are equipped with a WiFi interface besides their cellular interface. The high speed local network makes the distributed co-operation with a small group of nearby users possible. For example, consider the scenario depicted in Figure 1. Three mobile users, each with a cellular phone, suffer from the typical channel fading and shadowing, that impairs urban cellular communication, and also from path loss (attenuation) due to the distance to the base station. In this scenario, the long-range cellular signals are (1) independently received at each node, (2) relayed through the high speed local wireless network, and (3) combined at the destination node.

The existing techniques introduced in the past (e.g., Maximum Ratio Combining, and Generalized Selective Combining [2,4,18]) were designed for antennas that are wired to a central combiner and not restricted by the local communication limitations. The proposed cooperation strategy allows the nodes to forward information to other nodes through a local wireless network. This raises interesting questions on how to maximize the system performance with the constraints on the local network bandwidth, computation and energy consumption. We propose a novel cooperation framework that improve the long-range communication performance while accounting for the local bandwidth constraint.

For the proposed cooperation to be used in practice, other mechanisms need to be developed to address the issues regarding security, privacy and fairness. They will be in our future work. In this paper, we mainly focus on the performance analysis, protocol design and evaluation.

3 Hierarchical Priority Combining

In this section, we introduce a distributed cooperation framework - Hierarchical Priority Combining (HPC). It incorporates three levels of combining: *decode-and-forward*, *post soft-demodulation*, and *pre-demodulation*. We first outline the three combining techniques used in HPC; then describe the proposed HPC protocol; followed by performance analysis, and simulation and experiment results.

Decode-and-forward: if at least one of the assisting nodes can demodulate the packet and verify its integrity, then the decoded packet can be relayed to the master node through the local network. This level of combining uses the minimum local bandwidth, but can only be used when the overall signal strength is high while the mobile nodes are experiencing strong uneven fading or shadowing. This could be the case of a group of moving people in a car, bus, or train.

Post soft-demodulation combining: at this level, the signal received by the assisting nodes is already strong enough for demodulation but still has a significant number of errors. In this case, *some* of the assisting nodes, with the strongest received signals, send the soft-decision output of the demodulator to the master node. Combining at this level can be very efficient at correcting errors when the signal strength is relatively high and has the advantage of requiring only a moderate local communication bandwidth.

Pre-demodulation combining: at this level, *some* of the assisting nodes with the strongest SNR transmit the sampled down-converted RF-signal to the master node to combine with the master's signal. Combining at this level delivers the best error correction result, but transmitting the sampled waveform requires a large local bandwidth. Therefore, it is more appropriate in the scenarios where the long-range radio signal is weak and experiences strong fading. We introduce *Priority Maximum Ratio Combining* as an implementation candidate for pre-demodulation combining.

HPC protocol decides which level of combining to use based on the received signal quality at each node. It runs in two phases. In Phase I, the nodes exchange information with each other about the quality of the received signals. In phase

II, each node decides if and what level of combining to operate. The high-level description of the protocol is provided below. M is the total number of nodes involved in the cooperation. N is the number of signal sources involved in combining. Note that since the cooperation always includes the master node, $N-1$ is the actual number of remote assisting nodes.

Phase I: The master node broadcasts a cooperation request beacon if it is unable to decode the packet. Upon recipience of the cooperation-request beacon, the assisting node measures the SNR of the received signal (denoted by γ) from the long-range air interface and compares it with a predefined value γ_D, the threshold above which demodulating the packet is feasible.) If $\gamma < \gamma_D$ the assisting node just broadcasts the SNR to others. If $\gamma > \gamma_D$, it will try to demodulate the packet and verify its integrity using a CRC-like checksum. Finally, the assisting node will broadcast both the SNR and the CRC verification result. Each node is assigned to a time slot during this phase to avoid collisions.

Phase II: In this phase each node makes a decision after hearing other assisting nodes' report of signal quality. If at least one assisting node can demodulate the long-range RF signal and also pass the CRC check, one of them with the highest ID will relay the decoded packet to the master. If no one passes the CRC check and the total number of assisting nodes with $\gamma > \gamma_D$ is more than a predefined value, the top $N_{soft}-1$ nodes with the strongest SNR transmit their soft decision values to the master, in the order of their IDs, for post soft-demodulation combining, and the value $N_{soft}-1$ is limited by the local bandwidth. Last, if none of the above cases happen, the top $N_{pre}-1$ nodes with strongest SNR send the sampled waveform to the master for pre-demodulation combining. N_{pre} is also limited by the local bandwidth. N_{soft} and N_{pre} are usually different, depending on system parameters. For simplicity of notation, in the following discussion we may use N to represent either.

3.1 Priority Maximum-Ratio Combining

We introduce Priority Maximum-Ratio Combining (PMRC) as an implementation of pre-demodulation combining scheme. In PMRC, a subset of the assisting nodes with strongest SNR relay their signals to the master to combine with the signal received at the master node. The complete protocol is described in Algorithm 1 and 2. As the master's signal does not need to be transmitted, there is no bandwidth consumption for it. Therefore, we first introduce SPMRC, which is a special case of PMRC, where the signals are combined without the master's contribution. Then we will use SPMRC to derive PMRC.

Consider a system of M mobile nodes in cooperation. For each packet (or time slot) PMRC first identifies the $N-1$ strongest signals out of the $M-1$ cooperating neighbours and then combines their sampled signals with the signal received by the master node (destination) before demodulation. The selected signals are combined by *Maximum Ratio Combining* (MRC) [2]. In the following we denote by (M, N)-PMRC a scheme where the master's signal is combined with the signal from $N-1$ remote cooperating nodes. $(M, 1)$-PMRC is the non-cooperative case. (M, M)-PMRC is the traditional MRC with M branches. We will show that $(M, N < M)$-PMRC (e.g. $M = 5, N = 3$) are the most interesting schemes that benefit from distributed diversity at low bandwidth/energy cost. We first study the distribution of the combined SNR. This allows us to compute the outage probability, BER, frame error rate (FER) as well as throughput. Our analysis of PMRC is in two steps. First, we derive the SNR distribution of the combined signal from only the $N-1$ strongest remote assisting nodes ((M, N)-SPMRC), and then compute the actual SNR distribution at the master node where it is also combined with the master's own signal.

Algorithm 1: **Protocol 1.** PMRC - master node protocol

```
Initialize the cooperative network with M nodes
Broadcast the cooperation control packet -CCINFO
/* CCINFO contains the info. such as frequency, modulation, GSM time slot allocation, and parameters (M, N) for the PMRC
   cooperation scheme.                                                                                                  */
begin
    while until the session ends do
        buf[0] ←receive signal at the next expected time slot from the long-range interface;
        Γ[0] ← the SNR γ of the received signal;
        Δ[0] ← 1 if γ > γ_D . and CRC correct;
        if Δ[0] = 1 then
            Broadcast to cancel cooperation;
            out ← decode(buf[0]); return;
        Broadcast the Phase I beacon to all nodes through the short-range interface;
          Γ[1...M] ← collect γs from all branches;
          Δ[1...M] ← collect δs from all branches;
        if sum(Δ[1...M]) > 1 then
            out←Received data at Phase II; return.
        if num(γ' > γ_D ) ≥ S,γ' ∈ Γ[1...M] then
            out← soft decision decode on the aggregated data from N strongest neighboring nodes;
            return;
        buf[1...N − 1] ← collect the sampled signals with the top (N − 1) SNRs from assisting nodes;
        out←decode(MRC(buf,γ));
        /* out is the output data                                                                        */
end
```

Algorithm 2: **Protocol 2.** PMRC - assisting nodes protocol

```
Receive the cooperation control packet - CCINFO.
begin
    while until the session ends do
        buf←receive signal at the next master's time slot from the long-range interface;
        γ ← the SNR of the received signal;
        δ ← the result from CRC check if γ > γ_D ;
        Wait for the Phase I beacon from the master;
          Receive the Γ[1...M] and Δ[1...M] from all other assisting nodes;
          Broadcast γ and δ at its dedicated time slot;
        Wait for the Phase II beacon from the master;
        if it's the highest ID with δ = 1 then
            Send the decoded packet to master; return;
        if other nodes pass the CRC check then return;
        if γ > γ_D and num(γ' > γ_D ) ≥ S,γ' ∈ Γ[] and γ is among the N strongest signal branches then
            send soft decision decoding values to the master
            return;
        if γ is within N^th strongest SNR of all assisting nodes then
            transmit buf to the master in the i^th time slot through the short-range interface.
end
```

3.2 Channel Model

We consider a typical channel propagation model for cellular communications-Rayleigh channel [4]. We assume that frame can be delayed and aligned at the destination node for constructive combining. In this model, the distribution function of the signal to noise ratio (SNR denoted by γ) is as a function of the long run average SNR (denoted by $\bar{\gamma}$).

$$p(\gamma \le t) = \int_0^t \frac{1}{\bar{\gamma}} e^{-\frac{\gamma}{\bar{\gamma}}}\, d\gamma = 1 - e^{-\frac{t}{\bar{\gamma}}}$$

In practice the average SNR might not be the same for each node, e.g. shadowing, but to demonstrate the potential gain our analysis assumes equal average SNR for each node with the noise power spectral density $\mathcal{N}_0/2$. Due to the spatial separation, the fading channel for each node is independent. The probability that the signals received by all nodes have an SNR less than t is:

$$p(\gamma_1 \le t, \cdots, \gamma_M \le t) = p(\gamma_1 \le t) \cdots p(\gamma_M \le t) = (1 - e^{-\frac{t}{\bar{\gamma}}})^M$$

3.3 SPMRC: SNR Distribution for N=1, 2, 3

Let (M, N)-SPMRC, be the combined signal of the N strongest assisting nodes excluding the master node. Let X, Y, Z denote the random variable for the highest, second highest and third highest SNR among all M neighbors. In the case of $(M, 1)$-SPMRC, this is traditionally known as *Selective Combining* [4].

$$p_X(x) = \frac{M}{\bar{\gamma}} e^{-\frac{x}{\bar{\gamma}}} (1 - e^{-\frac{x}{\bar{\gamma}}})^{M-1}$$

In the case of $(M, 2)$-SPMRC, the master collects the two strongest signals from the M neighboring nodes. The joint probability density function (PDF) is:

$$p_{X,Y}(x, y) = \begin{cases} \frac{M}{\bar{\gamma}} e^{-\frac{x}{\bar{\gamma}}} \frac{(M-1)}{\bar{\gamma}} e^{-\frac{y}{\bar{\gamma}}} \times (1 - e^{-\frac{y}{\bar{\gamma}}})^{M-2}, & x \ge y \\ 0, & \text{else} \end{cases}$$

Applying MRC to the two strongest signals X and Y gives, $\gamma_\Sigma = X + Y$ [18]:

$$\begin{aligned} p_{\gamma_\Sigma}(\gamma) &= \int_0^\gamma p_{X,Y}(\gamma - y, y)\, dy \\ &= \frac{M(M-1)e^{-\frac{\gamma}{\bar{\gamma}}}}{\bar{\gamma}} \times \left(\frac{\gamma}{2\bar{\gamma}} + \sum_{i=1}^{M-2} \frac{(-1)^i}{i} \binom{M-2}{i} (1 - e^{-\frac{i\gamma}{2\bar{\gamma}}}) \right) \end{aligned}$$

Similarly for $(M, 3)$-SPMRC:

$$p_{X,Y,Z}(x, y, z) = \begin{cases} \frac{M}{\bar{\gamma}} e^{-\frac{x}{\bar{\gamma}}} \frac{(M-1)}{\bar{\gamma}} e^{-\frac{y}{\bar{\gamma}}} \frac{(M-2)}{\bar{\gamma}} e^{-\frac{z}{\bar{\gamma}}} \times (1 - e^{-\frac{z}{\bar{\gamma}}})^{M-3}, & x \ge y \ge z \\ 0, & \text{else} \end{cases}$$

$$\begin{aligned} p_{\gamma_\Sigma}(\gamma) &= \iint_{D_{y,z}} p_{X,Y,Z}(\gamma - y - z, y, z)\, dy\, dz \\ &= \frac{1}{2} M(M-1)(M-2)(\frac{1}{\bar{\gamma}})^3 e^{-\frac{\gamma}{\bar{\gamma}}} \times \\ &\left(\frac{\gamma^2}{6} + \sum_{i=1}^{M-3} \frac{(-1)^i}{i} \binom{M-3}{i} \left((1 - e^{-\frac{i\gamma}{3\bar{\gamma}}})(\bar{\gamma}\gamma - \frac{3\bar{\gamma}^2}{i}) + \bar{\gamma}\gamma e^{-\frac{i\gamma}{3\bar{\gamma}}} \right) \right) \end{aligned}$$

3.4 PMRC: SNR Distribution for N=2, 3, 4

In PMRC, the master's signal does not need to transmit, so the master always combines its own received signal with the $N-1$ strongest signals from the remote nodes. Let $\gamma_{\Sigma'}$ denote the SNR of PMRC at the master node: $\gamma_{\Sigma'} = \gamma_{\Sigma} + \gamma$.

The distribution of the sum of two independent random variables is the convolution of these two random variables' distributions. Therefore, for $N = 2, 3, 4$ of PMRC we have $p_{\gamma_{\Sigma'}}(\gamma) = \int_0^{\gamma} p_{\gamma_{\Sigma}}(\tau) \cdot p(\gamma - \tau)\, d\tau$, where $p_{\gamma_{\Sigma}}$ was derived in the previous section. Computing the SNR distribution for higher values of N is hard to obtain analytically in a closed form formula. However, we will show that small values of N are sufficient to obtain most of the diversity gain.

3.5 Outage Probability

Outage probability can effectively measure the performance of communication systems. Assume that γ_0 is the minimum SNR that can be tolerated by the decoding scheme. Outage probability is defined as $P_{out}(\bar{\gamma}) = p_{\gamma_{\Sigma'}}(\gamma \leq \gamma_0)$, where $\bar{\gamma}$ is the average SNR. Figure 2, shows the performance of $(5, N)$ PMRC for $N = 2, 3, 4$ and compares it with the non-cooperative scheme and the traditional MRC. For example, for a target $P_{out} = 10^{-2}$, in $(5, 2)$-PMRC the average transmission energy can be reduced by more than $17dB$ comparing to non-cooperative scheme, which is 50 times low energy. From this graph we conclude that most of the benefit of the diversity gain can be acquired by requesting the contribution from only a few neighbors with strong signals.

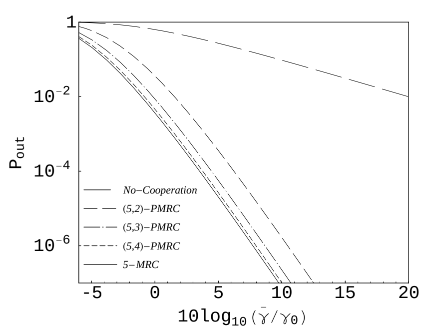


Fig. 2: Outage probability of PMRC vs. MRC and Non-Cooperation.

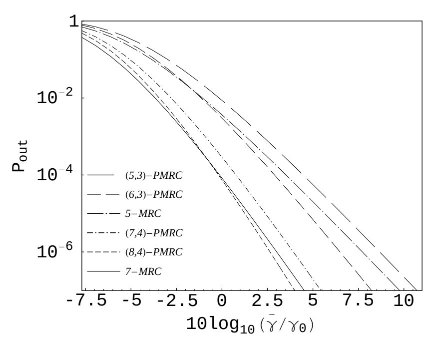


Fig. 3: Impact of M on the performance of PMRC.

We also studied the impact of the number of cooperating nodes on the outage probability. Figure 3, shows that increasing M significantly reduces the outage probability. For example, although 5-MRC outperforms $(5, 3)$-PMRC, increasing M by 1 gives $(6, 3)$-PMRC which not only outperforms 5-PMRC (by 2dB at $P_{out} = 10^{-7}$) but also requires only 2 cooperating nodes to send their contributions instead of totally 4 nodes in the case of 5-MRC. Therefore 5-MRC requires 100% more bandwidth for lesser performance than $(6, 3)$-PMRC. We observe that when the average SNR increases, $(M', 1)$ will eventually outperform M-MRC (or any $(M, N) - PMRC$)) as long as $M' > M$. Note that M-MRC (i.e., MRC with M branches) is identical to (M, M)-PMRC.

3.6 Bit Error Rate and Throughput

Bit Error Rate (BER) is another important measure of the performance of communication systems. We consider the coherent Minimum-Shift Keying (MSK) modulation, which is similar to GMSK used in GSM system, with uncoded communication. To compute BER, We assume a pulse shaping transmission with bit duration equal to $1/W$ such as raised cosine pulses (similar to $sinc()$, but it is widely used in practice [2].) with $\beta = 1$ (where W is the used frequency bandwidth). Therefore $E_b/\mathcal{N}_0 = \gamma$ and the $BER = Q(\sqrt{\frac{2E_b}{\mathcal{N}_0}}) = Q(\sqrt{2\gamma})$.

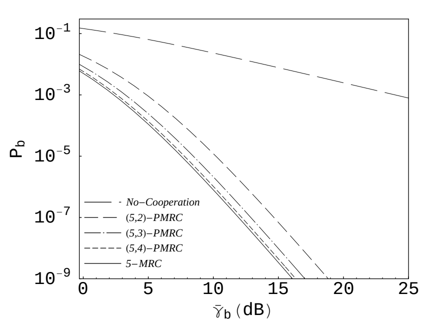


Fig. 4: BER of MSK demodulator under PMRC vs. MRC and Non-Cooperation.

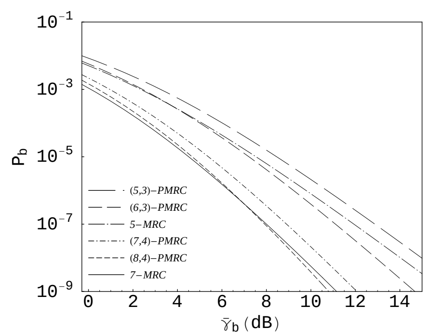
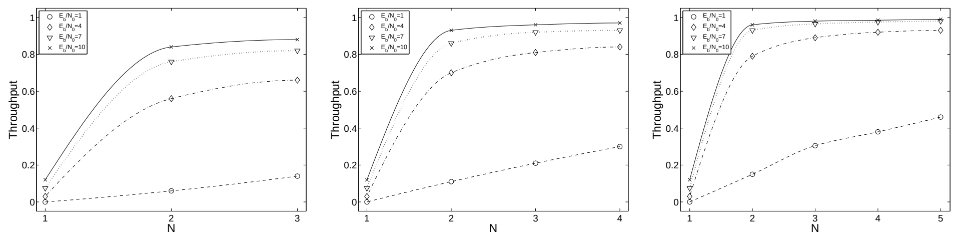


Fig. 5: Impact of M on the performance of PMRC in terms of BER.

We compare the performance of PMRC to the non-cooperative mode and the traditional MRC. The BER performance of PMRC is consistent with the outage probability. Figure 4 shows that for a target BER of 10^{-3}, $(5, 2)$-PMRC requires 20dB (100 times) less power and with the contribution from only one cooperating neighbor. Higher gains are achievable when the target BER is lower. Most of the gain of MRC is obtained using the 2 to 3 strongest signals from neighboring nodes. Figure 5, shows the impact of increasing M. Similarly, to the outage probability, increasing the number of cooperating nodes outperforms the benefit by increasing N, the number of nodes who are effectively sending their contributions.

To measure the throughput of PMRC, we only consider the overhead of 32 bits CRC necessary for error detection. To compare the various PMRC schemes with fairness, the packet size is normalized to maximizes throughput. Figure 6 shows that the throughput of the master node can be significantly increased (over an order of magnitude) by signal combining with a limited number of cooperation nodes. We also find that PMRC gives comparable performance of MRC by using fewer active branches. For example of $N = 3$ and $M = 5$, besides the master's branch it uses only two active branches out of the four external diversity branches, but it achieves more than 90% the performance given by MRC with a fairly low $E_b/\mathcal{N}_0$ (4 or above) while it uses only half of the bandwidth required by MRC. For a very low $E_b/\mathcal{N}_0$ at value 1,it still maintains at least 65% throughput.

$$Throughput = \frac{(L - OH)(1 - BER)^L}{L}, OH \text{ is the CRC length, } L \text{ is the frame length}$$



(a) $M = 3$ (b) $M = 4$ (c) $M = 5$

Fig. 6: Throughput in different cooperation scenarios and $E_b/\mathcal{N}_0$(dB)

3.7 Local Bandwidth Consumption

To compute the local bandwidth consumption, we consider a 2-level HPC strategy which consists of only decode-and-forward and pre-demodulation combining. The local bandwidth can be computed by considering three cases. 1)The master can correctly decode the frame/packet (with probability $1 - FER$). 2)The master fails to decode the packet but at least one of the $M - 1$ assisting nodes is capable of decoding it (with probability $FER \times (1 - FER^{M-1})$). 3)None of the nodes can correctly decode the packet, so nodes execute $PMRC$ combining. The N assisting nodes with the strongest signals send their sampled signals to the master (with probability FER^M). The average local traffic is:

$$Avg - Throughput_{local} = L \times FER \times (1 - FER^{M-1}) + N \times L \times R \times FER^M$$

where L denotes the frame size and R denotes the average number of bits used to represent each sampled signal. R can be 8 bits in the case of a non-coherent decoding, and as high as 96 bits for coherent decoding (4 over-sampling factor, 12 bits quantization for I and Q).

4 Simulation and Experiment Results

4.1 PMRC with Imperfect Channel Knowledge

In Section 3.6, we show that PMRC can significantly reduce the BER. Like many other combining techniques, it assumes perfect phase synchronization among the signal branches. However, in practical it is well known to be a challenging task. To solve this problem, we use a pilot-based technique for estimating the channel condition and adjusting the phase of each signals. We consider a long range communication link using the Gaussian Minimum Shift Keying modulation (such as used in the GSM cellular communication standard) with a 200 KHz frequency band, and a symbol rate of 250 Kbps. For channel estimation, we supplement the data signals with a pilot tone (i.e., non modulated sin wave) separated by 200KHz from the center of the communication band. Similar technique is commonly used in many communication systems such as IEEE802.11a (4 pilots for 48 carriers), and WiMax (8 pilots for 256 carriers). Note that a single pilot tone can be shared by multiple frequency bands. On the receiver side, the pilot tone is filtered and used to estimate the channel to resynchronize the master and assisting nodes signals before combining. We use an over-sampling rate of 4 samples per bit. Figure 7, summarizes the performance of PMRC when simulated with the Matlab Simulink environment for $M = 5$. The simulation results confirm that significant gains can be achieved by combining the master data with the two strongest assisting nodes. A gain of 10 dB (order of magnitude reduction in energy cost) is reachable. We also note that due to the imperfection of the phase synchronization technique a full MRC has poorer results than (5, 4)-PMRC, so it is preferable to only combine the strongest signals.

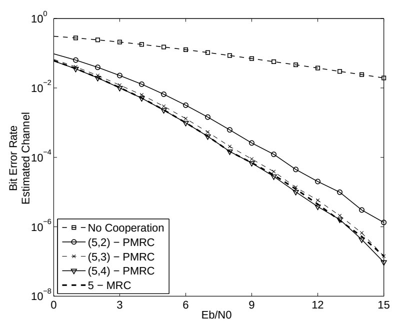


Fig. 7: BER performance of PMRC with pilot-based channel estimation.

TX Amp	Bit errors non-coop	Bit errors PMRC2	Bit errors PMRC3	Bit errors PMRC4
2000	1145	109	89	46
3000	289	3	8	18
4000	92	0	0	8
5000	70	0	0	0

Table 1: Experimental results for post soft-demodulation combining. Note that the signal synchronization imperfections, can in some cases, lead to a (5, 4)-PMRC performance lower then the (5, 2)-PMRC.

4.2 Post Soft Decoding on Prototype

We have implemented a testbed prototype based on USRP/GNU Radio [19], and measured the performance of the post soft-demodulation combining on this platform. We use a GMSK modulation at 500 Kbps on the 915MHz ISM band. The GMSK demodulator is modified to extract the soft decision values and combine the master bits with the N strongest signals from the assisting nodes. We conducted experiments with various transmission power levels where the cooperating nodes are fairly distant from the transmitter and located in a different office (around 50 feet away) allowing for significant multi-path fading effects. Table 1 summarizes the results for four transmission power levels (values are normalized to 2, 3, 4, 5). Each shows the number of bits in error of 1 megabit data. The experiment results demonstrate the number of bits in error can be significantly reduced by combining the soft decision values obtained from two assisting nodes with strongest signals.

5 Conclusions

In this paper, we introduced a framework for distributed cooperation and diversity. We proposed and studied several combining techniques that can be used in multiple levels of decoding process. We proposed and analysed PMRC in terms of SNR gain, outage probability, bit error rate, and throughput. Our results from the simulation for PMRC with a pilot-based channel estimation, as well as experiments for a post soft-demodulation combining, reveal that the cooperation between devices with a combination of cellular and short-range air-interfaces is a promising approach to increase network capacity and mitigate the effects of channel fading and shadowing. Still, our results are only a first step towards understanding the potential of distributed cooperation and diversity. Future work will consider complete trade-offs in terms of local communications and overall performance improvement, and more realistic channels and node distributions.

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