Distributed Cooperation and Diversity for Hybrid Wireless Networks

Yin Wang, Guevara Noubir, *Senior Member, IEEE*

Abstract—In this paper, we propose a new Distributed Cooperation and Diversity Combining framework. Our focus is on heterogeneous networks with devices equipped with two types of radio frequency (RF) interfaces: short-range high-rate interface (e.g., IEEE802.11), and a long-range low-rate interface (e.g., cellular) communicating over urban Rayleigh 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) technique, and a Post Soft-Demodulation Combining (PSDC) 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 software radio testbed. Our results also indicate that, under several communication scenarios, PMRC and PSDC can improve the throughput performance by over an order of magnitude.

Index Terms—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 antennas, have been proposed or adopted, nevertheless the cooperation gain on the mobile client side has not been exploited yet. 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. A short-range radio interface is used by the cooperating nodes to combine the long-range radio interface signals and boost its performance.

Currently, most smart-phones are equipped with a WiFi interface besides their cellular interface. The high speed local network makes the distributed cooperation with a small group of nearby users possible. 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.

RF-channel diversity is a general mechanisms to improve the robustness and efficiency of wireless communication systems and have been studied for many years [2], [3], [4]. 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 [5]. Further more, the existing diversity techniques introduced in the past (e.g., Maximum Ratio Combining, and Generalized Selective Combining [6], [2], [4]) were designed for antennas that are wired to a central combiner and not restricted by the local communication limitations.

Unlike traditional diversity paradigms, our approach combines the physical layer information from multiple distributed receivers in heterogeneous wireless network, as well as accounting for the constraints on the local network bandwidth, computation and energy consumption. It exploits both the antenna gain and the channel independence. We show that this type of cooperation can significantly improve the Signal to Noise Ratio (SNR), Bit Error Rate (BER) and throughput even with reasonably limited short range bandwidth. It leads to an improved coverage, capacity boost and reduction of interference. To the best of our knowledge, it is the first to consider a heterogeneous architecture to combine multiple long-range links at the physical layer for diversity purpose.

- *Y. Wang and G. Noubir are with the College of Computer and Information Science, Northeastern University, Boston MA, 02115.*
E-mail: {yin, noubir}@ccs.neu.edu

In Section 2.1, we first present our system model and the Hierarchical Priority Combining framework. In Section 2, we propose a strategy of Pre-Demodulation Combining – PMRC, and Post Soft-Demodulation Combining – PSDC. In Section 3, we present the evaluation model used in analysis. In Section 4, we present the performance evaluation results for PMRC and PSDC in terms of outage probability, Bit Error Rate, throughput, local bandwidth usage and delay. Finally, in Section 5 we present our prototype implementation of PSDC on using GNU Radio, and show the experimental results.

1.1 Contributions

We propose a distributed cooperation framework - Hierarchical Priority Combining strategy (HPC), which allows multiple levels of cooperation depending on the channel conditions and resource constraints. It consists of three levels of combining techniques: Pre-Demodulation Combining, Post Soft-Demodulation Combining, and Decode-and-Forward. We also propose an implementation of Pre-Demodulation Combining technique, called Priority Maximum Ratio Combining (PMRC), and an implementation of Post Soft-Demodulation Combining (PSDC) technique. We show that an order of magnitude improvement of the SNR, outage probability, BER and throughput can be achieved, even with a limited short-range bandwidth. We also show that most of the benefit of the traditional single device Maximum-Ratio Combining (MRC) can be exploited by PMRC or PSDC with the contribution from a small group of neighbouring nodes. In addition, we demonstrate the practicality of PSDC by implementing it on a USRP/GNU radio testbed and experimentally confirm substantial gains for channels with moderate fading.

1.2 Related work

While, cellular communications has 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 [7]. Most previous work on signal combining focussed on the centralized scenario of a smart antenna system with multiple elements [8]. Techniques such as Maximum Ratio Combining (MRC) and Generalized Selection Combining (GSC) were carefully analysed in [9], [10], [11]. The proposed PMRC technique is an extension of GSC where the master node signal is always included. The major difference between our work and previous work is that we consider a distributed cooperation setup where the local bandwidth is the main bottleneck. We compare PMRC with a proposed soft-combining variant (PSDC) that significantly reduces the local bandwidth requirement with only limited performance degradation. In addition to the analytical and simulation results, we also experimentally evaluate the proposed techniques.

Some studies have investigated specific cases of distributed cooperation such as diversity with *homogeneous* interfaces where the combining occurs over the air [5], [12], [13]. Other 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 [14], [15], [7]. A theory of distributed MIMO in ad hoc network has been studied in [16]. The use of cooperating *heterogeneous* air-interfaces was advocated in [17], [18]. A distinguishing feature of our work is that we aim at improving the performance of a long-range link (i.e., cellular) using cooperation over bandwidth constrained short-range links in heterogeneous wireless network. We propose several techniques, analyze their theoretical performance, and confirm their feasibility with a real world prototype. In our previous work [19], 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 and PSDC substantially superior combining techniques.

2 Approach

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. Our study is in the case where the long-range communication happens on quasi-orthogonal channels and is mainly limited by 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. 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.

In this paper, the proposed protocol and analysis are based on only single master node. Multiple master nodes are possible by allowing each node as the master node concurrently, but more advanced protocols need to be developed to handle the collision and delay.

2.1 Distributed Cooperation Framework

Consider the scenario depicted in Figure 1: there are a group of three nearby mobile users each with a cellular phone or mobile station (MS), and base stations or base transceiver stations (BTS). The base stations are controlled by the base station controller (BSC), which dictates the carrier frequencies, communication power and rate, etc. The base stations are also connected to

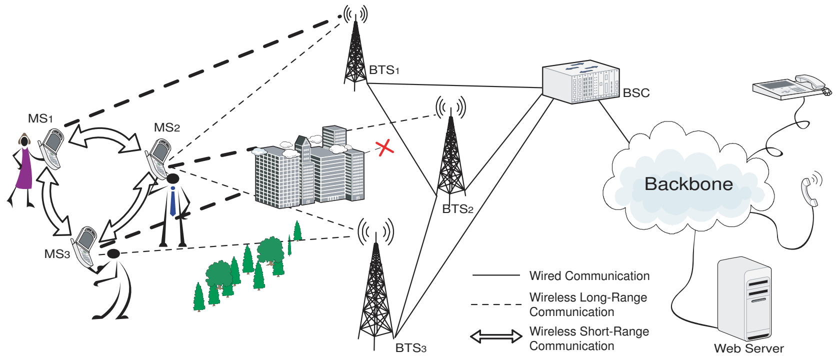


Fig. 1. Distributed diversity scenario.

the backbone which leads to the telephone network and the Internet. Communication between mobile stations and base stations is through long-range low data-rate links. Due to obstructing objects and the distance to the base station, they suffer from the typical channel fading and path loss (attenuation) that impair urban cellular communication. In contrast, mobile stations can also communicate with each other through short-range high data-rate links. Because of the short distance, their communications are fast and stable. Here we consider a simple topology with single hop communications. For example, a base station BTS_1 is communicating with a mobile station MS_1 and another mobile station MS_2 in the vicinity through long-range low data-rate links; the links from MS_1 to MS_2, from MS_2 to MS_3, and from MS_3 to MS_1 are short-range high data-rate links.

With cooperation, the long-range cellular signals are (1) independently received at each of the three nodes, (2) relayed through the high speed local wireless network, and (3) combined at the destination node. This cooperation can significantly improve the Signal to Noise Ratio (SNR), Bit Error Rate (BER) and throughput. It leads to improved coverage and a system capacity boost. Furthermore, it reduces interference as the base stations do not have to increase their transmission power to overcome the channel fading in order to reach mobile nodes.

For the proposed cooperation strategy to be used in practice, other mechanisms need to be developed to address the important issues of security, privacy, incentives mechanisms to encourage cooperation and enforce fairness. In this paper, we focus on evaluating the potential of distributed diversity mechanisms.

2.2 Hierarchical Priority Combining

In this part, 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 the performance analysis.

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 its short-range link. This level of combining uses the minimum local bandwidth, but can only be used when the overall signal strength is high, and the mobile nodes are experiencing strong uneven fading or shadowing. This could be the case when a group of people are in motion, e.g., inside a car, a bus, or a train. A similar idea has been discussed in [20]. The main difference in our research is that we are considering to relay the packet through a different interface rather than re-injecting it back to the same channel with a different coding scheme. This approach, in our opinion, is more realistic from system's perspective, however it requires a different analysis.

Post Soft-Demodulation Combining: At this level, the signal received by each of the assisting nodes has incorrectable errors. However, it is already strong enough for demodulation. 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 for bit-level combining (Refer Section 2.4 for more detail of soft-decision values). Cooperation at this level can be very efficient at correcting errors when the signal strength is relatively high. This is still a sub-optimal diversity combining technique but has the advantage of requiring only a moderate short-range communication bandwidth.

Pre-Demodulation Combining: At this level, *some* of the assisting nodes transmit the sampled down-converted RF-signal to the master node. We introduce *Priority Maximum Ratio Combining* (PMRC) as the potential candidates for Pre-Demodulation Combining. In PMRC, only the assisting nodes with the strongest SNR relay their received signals to the master. The master then combines its received signal with other gathered signals. Signal combining at this level gives the best error correction capability, but communicating the digitized waveform information requires a large local bandwidth. Therefore, it is more appropriate for the scenarios where the long-range radio signal is extremely weak and experiences strong fading, but the local short-range links is fast and stable.

The HPC protocol dynamically decides which of the above three combining techniques to use at the time of the reception of the packet. Intuitively, Pre-Demodulation Combining takes all the information of the originally received signals among the cooperative nodes, so it should perform the best in error correction, but it also requires a huge amount of local bandwidth. Decode-and-Forward Combining and Post Soft-Demodulation Combining can be taken as the light-weight version of Pre-Demodulation Combining as it either sends the complete demodulated data or partially demodulated data with soft-decision values. The advantage of Decode-and-Forward Combining is that it uses a minimal amount of local bandwidth, but requires a node to have a strong signal reception in order to independently and successfully decode the packet. Post Soft-Demodulation Combining, on the other hand, performs better due to the freedom of using soft-decision values from multiple sources compared to Decode-and-Forward Combining. To achieve the best performance while still minimizing the local bandwidth usage, our HPC strategy uses the received signal quality to decide which combining technique to adopt for each packet. There are many possible ways to cooperate, but the proposed HPC strategy has the benefit of being effective and easy to implement due to its simplicity and hierarchical structure.

The HPC cooperation protocol runs in two phases. *Phase I* is a very short period, within which the nodes exchange information with each other about the quality of received signal. In *Phase II*, each node decides if and what level of combining information it will send to the master. In the following, we provide a high-level description of the protocol.

Let M be the total number of nodes involved in the cooperation, and N be 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 distributed assisting nodes that relay their signals to the master node.

Phase I: The master node broadcasts a cooperation request beacon if it is unable to decode the packet. Upon receipt of the cooperation-request beacon, the assisting nodes measure the SNR of the received signal (denoted by γ) from their long-range air interface and compare it with a predefined threshold γ_{D}. (γ_{D} is the threshold above which demodulating the packet is feasible.) If $\gamma < \gamma_{D}$, the assisting nodes broadcast the SNR to others. Otherwise, they will try to demodulate the packet independently and verify its integrity using a CRC-like checksum. Finally, the assisting nodes broadcast both the SNR and the CRC verification result. Each node is assigned a particular time slot during the phase I to avoid collision.

Phase II: In this phase each node makes a decision after hearing the report of signal quality from other assisting nodes. If at least one assisting node can demodulate the long-range RF signal and pass the CRC check, one of them with the highest ID will relay the decoded packet to the master, that is the Decode-and-Forward case. 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 $N_{\text{soft}}-1$ nodes with the strongest SNR transmit (in the order of their ID) their soft-decision values to the master for Post Soft-Demodulation Combining. N_{soft} is a pre-set system parameter, and the transmission size $N_{\text{soft}}-1$ is limited by the local bandwidth. In the end, if none of the above cases happens, then the assisting nodes, send the sampled long-range radio waveform to the master node for Pre-Demodulation Combining.

2.3 Priority Maximum-Ratio Combining

We introduce Priority Maximum-Ratio Combining (PMRC) as an implementation of pre-demodulation combining scheme. PMRC is based on *Maximum Ratio Combining* (MRC) [2], but optimized for distributed cooperation and accounts for the local bandwidth usage. 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. The Algorithm 2 can be modified slightly to avoid the hidden node problem. In this case, if an assisting node fails to hear all other nodes' broadcast messages in Phase I, it should exclude itself from cooperation for that around.

MRC is a linear combining technique to combine multiple independent signal branches. Let n be the total number of signal branches for combining. The signal received from the i^{th} branch is $r_i e^{j\theta_i} s(t)$, where r_i is signal amplitude and θ_i is the signal phase. In MRC, a weight $\alpha_i = a_i e^{-j\theta_i} s(t)$ is applied at the i^{th} signal branch. If the fading channels are independent and identically distributed (i.i.d), by choosing a proper weight to be the square root of the SNR for each branch (i.e., $a_i = \sqrt{r_i^2/N_0}$), the SNR of MRC scales linearly with the number of independently signal branches, that is $\gamma_\Sigma = \sum \gamma_i$ [6].

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 MRC. 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. Since the master's signal does not need to be transmitted, there is no bandwidth consumption for it. To assist our analysis we consider

Algorithm 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 γ from all branches;
      Δ[1...M] ← collect δ 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: 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
```

SPMRC, a special case of PMRC. In (M,N)-SPMRC, the signals are combined at the master without the master's contribution. Instead, the master only combines the signal from the $N-1$ strongest remote assisting nodes. In our analysis, Section 3.2, we will first derive the SNR distribution of SPMRC, and then derive the SNR distribution of PMRC. This allows us to compute the outage probability, BER, frame error rate (FER) as well as throughput.

2.4 Post Soft-Demodulation Combining

For Pre-Demodulation Combining techniques such as PMRC, the signal is first down-converted to the intermediate frequency and then sampled using an *analog-to-digital converter* (ADC). However, this sampled signal can be substantially large. Therefore, directly transmitting the sampled signal is not very efficient and should be avoided if possible.

A more efficient solution is to use the soft-decision values from the demodulator instead of the hard values. A soft-decision value SV is a real number in $[-1,1]$. In the case of binary, if $SV<0$ it represents 0, otherwise 1. It means the confidence or how close of being 0 or 1. Due to the extra information they provide, they can have a better error correction ability in comparison with the hard values. In our analysis, we assume that SV directly maps to a probability. Soft-decision values can be encoded in very few bits. In Section 5, we will show each value can be compressed to as few as 3 bits with a small performance compromise. Therefore, transmitting them would require much lighter local bandwidth usage than transmitting the sampled signal.

Upon receiving a set of soft-decision values from the assisting nodes, the master node needs a method to combine those values and the value from itself, and output the most likely initially transmitted value. One simple solution is to take the value which has the highest confidence. Another simple solution is to take a majority vote or the sum of all the soft values. However, these are suboptimal combining techniques. We introduce Maximum Likelihood Soft Combining algorithm to combine the soft values from multiple signal sources. We will show that the Maximum Likelihood Soft Combining algorithm produces the value with the lowest error probability.

2.4.1 Maximum Likelihood Soft Combining

First, we need to transform the soft-decision values into a form that can be used by the combiner. For a given soft-decision value SV (float), in the case of binary it is 1 if $SV\geq 0$ and 0 if $SV<0$. We map each SV into a pair (y,Pe), where y is the hard decision value and Pe is the error probability. Inspired by the Maximum-Likelihood receiver [2], our combining technique - Maximum-Likelihood Soft Combining is as follows:

Let y_i be the decoded hard decision value (0 or 1 for the binary case) from the i^{th} signal source. $\vec{Y}=(y_1,...,y_n)$ represents a vector of hard decision values from the n signal sources. Let Pe_i be the error probability for value y_i, and $\vec{Pe}=(Pe_1,...,Pe_n)$ represents a vector of error probabilities for the vector $\vec{Y}$. We also assume that all the branches are independent, which is a common assumption in fading environments where the receivers are well separated. As a result, the errors from different nodes are independent. $\vec{\varepsilon}=(\varepsilon_1,...,\varepsilon_n)$ represents a vector of errors, where $\varepsilon_i=1$ means that

y_i is incorrectly decoded, which occurs with probability Pe_i. The probability of this error vector is:

$$Pr(\vec{\varepsilon}) = Pr(\varepsilon_1) \times ... \times Pr(\varepsilon_n) \quad (1)$$

For a u-ary system, the Maximum-Likelihood Soft Combining decoder combines the n signal sources to produce an outcome that is the most probable (Equation 2). Therefore, it minimizes the bit error rate.

$$\hat{x} = \underset{0 \le x < u}{\arg\max}\ Pr(X = x | \vec{Y} = (y_1, ..., y_n)) \quad (2)$$

In the case of a binary channel ($u = 2$), the Maximum-Likelihood Soft Combining algorithm works as follows: For a given input $\vec{Y}$ and $\vec{Pe}$, the decoder runs the decision function (Equation 3), and outputs its result.

The decision function is defined as

$$\begin{aligned} MLSC(\vec{Y}, \vec{Pe}) &= MLSC((y_1, ..., y_n), (Pe_1, ..., Pe_n)) \\ &= \begin{cases} 0, & \prod_{k=1}^{n} (\frac{Pe_k}{1-Pe_k})^{(-1^{y_k})} \le 1 \\ 1, & \text{otherwise} \end{cases} \end{aligned} \quad (3)$$

Theorem 1. *Let us assume that the source sends 0s and 1s with the same probability, $Pr(X = 0) = Pr(X = 1) = \frac{1}{2}$ (if not the data can be compressed). Given the received bit vector $\vec{Y} = (y_1, ..., y_n)$ and error probability vector $\vec{Pe} = (Pe_1, ..., Pe_n)$ from the n signal branches, the Maximum-Likelihood Soft Combining produces the most probable value.*

Proof: Let X be the random variable for the output resulting from the MLSC function. Here we calculate $Pr(X|\vec{Y})$. Without loss of generality, we can first compute the probability of $X = 0$, given a vector of $\vec{Y}$ and an associated error probability vector $\vec{Pe}$. We then compute the probability of $X = 1$ under the same condition. Finally, we compare of those two values to verify the theorem.

The probability of $X = 0$ is:

$$\begin{aligned} & Pr(X = 0 | \vec{Y} = (y_1, ..., y_n)) \\ =& \frac{Pr(X = 0, \vec{Y} = (y_1, ..., y_n))}{Pr(\vec{Y} = (y_1, ..., y_n))} \\ =& \frac{Pr(X = 0, \vec{X} + \vec{\varepsilon} = (y_1, ..., y_n))}{Pr(\vec{X} + \vec{\varepsilon} = (y_1, ..., y_n))} \\ =& \frac{Pr(X = 0, \vec{\varepsilon} = (y_1, ..., y_n))}{\sum_{x=0}^{1} Pr(\vec{X} + \vec{\varepsilon} = (y_1, ..., y_n) | X = x) Pr(X = x)} \\ =& \frac{Pr(X = 0, \vec{\varepsilon} = (y_1, ..., y_n))}{\sum_{x=0}^{1} Pr(\vec{X} + \vec{\varepsilon} = (y_1, ..., y_n), X = x)} \\ =& \frac{Pr(X = 0, \vec{\varepsilon} = (y_1, ..., y_n))}{Pr(\vec{\varepsilon} = (y_1, ..., y_n), X = 0) + Pr(\vec{1} + \vec{\varepsilon} = (y_1, ..., y_n), X = 1)} \\ =& (1 + \frac{Pr(\vec{1} + \vec{\varepsilon} = (y_1, ..., y_n), X = 1)}{Pr(\vec{\varepsilon} = (y_1, ..., y_n), X = 0)})^{-1} \end{aligned} \quad (4)$$

$$= (1 + \prod_{k=1}^{n} (\frac{Pe_k}{1 - Pe_k})^{(-1^{y_k})})^{-1} \quad (5)$$

The probability of $X = 1$ can be calculated as

$$Pr(X = 1 | \vec{Y}) = 1 - Pr(X = 0 | \vec{Y}) \quad (6)$$

According to the Maximum-Likelihood Soft Combining algorithm (Equation 3), if $Pr(X = 0|\vec{Y}) \ge Pr(X = 1|\vec{Y})$, its outcome is 0, otherwise 1. We have

$$\begin{aligned} & Pr(X = 0 | \vec{Y}) \ge Pr(X = 1 | \vec{Y}) \\ \Leftrightarrow & \\ & Pr(X = 0 | \vec{Y}) \ge 1 - Pr(X = 0 | \vec{Y}) \\ \Leftrightarrow & \\ & Pr(X = 0 | \vec{Y}) \ge \frac{1}{2} \\ \Leftrightarrow & \\ & \prod_{k=1}^{n} (\frac{Pe_k}{1 - Pe_k})^{(-1^{y_k})} \le 1 \end{aligned} \quad (7)$$

□

3 Evaluation Model

3.1 Channel Model

In wireless communications various types of fading cause the signal power to fluctuate over time and space due to multipath propagation and shadowing. This is the case of urban cellular communications, where the signal travels through multiple paths due to the reflection from objects such as buildings and trees. The signals from these paths might add up or cancel each other and result in weak signals. In our analysis, we consider a typical channel propagation model for cellular communications, the Rayleigh channel [4], where there is no dominant propagation path between the transmitter and the receiver, and multiple delayed signals from different paths add up at the receiver. It is usually the case where there is no line-of-sight (LOS). If there is LOS, the fading can be modelled as Rician channel. In this paper, we mainly consider the case of Rayleigh channel. The analysis of Rician and other fading channels can be completed in the similar manner. We assume the channel coherence time to be larger than the packet length. This is usually characterized as slow fading, which is in contrast to fast fading, in which the channel condition rapidly changes within a symbol duration. This assumption can be loosened by fragmenting the packets into smaller packets. Under the common assumption that the in-phase and quadrature components of the received signal are both zero-mean Gaussian random variables, and the received signal envelope r is Rayleigh distributed [3]. The probability density function for r is given by

$$p(r) = \frac{r}{\sigma^2} \exp\left(-\frac{r^2}{2\sigma^2}\right), \quad r \ge 0, \quad (8)$$

where σ^2 is the variance, and represents the AC power in the signal envelope.

Let $\mathcal{N}_0/2$ be the noise *power spectral density* (PSD). The SNR (signal to noise ratio) $\gamma = r^2(t)/\mathcal{N}_0$ is exponentially distributed. We assume that the long-range communication is over a licensed band and does not suffer from external interference. Interference from devices and base stations internal to the system is thus controlled by the cellular protocols. Therefore, the probability distribution of the SNR can be modelled as

$$p(\gamma) = \begin{cases} \frac{1}{\bar{\gamma}} e^{-\frac{\gamma}{\bar{\gamma}}}, & \gamma \geq 0 \\ 0, & \text{otherwise} \end{cases} \tag{9}$$

where $\bar{\gamma}$ denotes the long run average SNR. The cumulative distribution function is

$$p(\gamma \leq t) = \int_0^t \frac{1}{\bar{\gamma}} e^{-\frac{\gamma}{\bar{\gamma}}} \, d\gamma = 1 - e^{-\frac{t}{\bar{\gamma}}} \tag{10}$$

In practice the average SNR might not be the same for each node, e.g. due to shadowing, but as a first step 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:

$$\begin{aligned} p(\gamma_1 \leq t, \cdots, \gamma_M \leq t) =& p(\gamma_1 \leq t) \cdots p(\gamma_M \leq t) \\ =& (1 - e^{-\frac{t}{\bar{\gamma}}})^M \end{aligned} \tag{11}$$

3.2 SNR Distribution for PMRC ($N = 2, 3, 4$)

To compute the SNR distribution for PMRC, we first consider a simplified case SPMRC. In SPMRC, 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].

$$p_X(x) = \frac{M}{\bar{\gamma}} e^{-\frac{x}{\bar{\gamma}}} (1 - e^{-\frac{x}{\bar{\gamma}}})^{M-1} \tag{12}$$

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:

$$p_{X,Y}(x, y) = \begin{cases} \frac{M}{\bar{\gamma}} e^{-\frac{x}{\bar{\gamma}}} \frac{(M-1)}{\bar{\gamma}} e^{-\frac{y}{\bar{\gamma}}} \times & \\ (1 - e^{-\frac{y}{\bar{\gamma}}})^{M-2}, & x \geq y \\ 0, & \text{otherwise} \end{cases} \tag{13}$$

Applying MRC to the two strongest signals X and Y gives, $\gamma_\Sigma = X + Y$[6]:

$$\begin{aligned} p_{\gamma_\Sigma}(\gamma) =& \int_0^\gamma p_{X,Y}(\gamma - y, y) \, dy \\ =& \frac{M(M-1) e^{-\frac{\gamma}{\bar{\gamma}}}}{\bar{\gamma}} \times \\ & \left(\frac{\gamma}{2\bar{\gamma}} + \sum_{i=1}^{M-2} \frac{(-1)^i}{i} \binom{M-2}{i} (1 - e^{-\frac{i\gamma}{2\bar{\gamma}}}) \right) \end{aligned} \tag{14}$$

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

$$p_{X,Y,Z}(x, y, z) = \begin{cases} \frac{M}{\bar{\gamma}} e^{-\frac{x}{\bar{\gamma}}} \frac{(M-1)}{\bar{\gamma}} e^{-\frac{y}{\bar{\gamma}}} \frac{(M-2)}{\bar{\gamma}} & e^{-\frac{z}{\bar{\gamma}}} \times \\ (1 - e^{-\frac{z}{\bar{\gamma}}})^{M-3}, & x \geq y \geq z \\ 0, & \text{otherwise} \end{cases} \tag{15}$$

$$\begin{aligned} p_{\gamma_\Sigma}(\gamma) =& \iint_{D_{y,z}} p_{X,Y,Z}(\gamma - y - z, y, z) \, dy \, dz \\ =& \frac{1}{2} M(M-1)(M-2) (\frac{1}{\bar{\gamma}})^3 e^{-\frac{\gamma}{\bar{\gamma}}} \times \\ & \left(\frac{\gamma^2}{6} + \sum_{i=1}^{M-3} \frac{(-1)^i}{i} \binom{M-3}{i} \times \right. \\ & \left. \left((1 - e^{-\frac{i\gamma}{3\bar{\gamma}}})(\bar{\gamma}\gamma - \frac{3\bar{\gamma}^2}{i}) + \bar{\gamma}\gamma e^{-\frac{i\gamma}{3\bar{\gamma}}} \right) \right) \end{aligned} \tag{16}$$

In PMRC, the master node always combines its own received signal with the $N - 1$ strongest signals from the assisting nodes. Using its own signal does not incur any local bandwidth usage or energy consumption and always improves the combined SNR.

Let $\gamma_{\Sigma'}$ denote the random variable of the PMRC signal's SNR at the master node, γ_Σ be the random variable of the the combined signal SNR from $N - 1$ assisting nodes, and γ be the random variable of the signal SNR of the master node. Because the master combines the signal from assisting nodes and the signals from itself using MRC, we have

$$\gamma_{\Sigma'} = \gamma_\Sigma + \gamma \tag{17}$$

Since the probability distribution of the sum of two independent random variables is the convolution of the two random variables, we obtain the probability distribution of $\gamma_{\Sigma'}$ is

$$p_{\gamma_{\Sigma'}}(\gamma) = \int_0^\gamma p_{\gamma_\Sigma}(\tau) \cdot p_\gamma(\gamma - \tau) \, d\tau \tag{18}$$

Computing the SNR probability distribution for higher values of N can be done in the same way. However, we will show that small values of N are sufficient to obtain most of the diversity gain.

3.3 SNR Distribution for Priority Signal Source

The proposed Post Soft-Demodulation Combining(PSDC) uses the soft-decision values from the master and a subset of assisting nodes with the strongest signals among all assisting nodes. Let M be the total number of nodes in cooperation including the master node. For each packet, $N-1$ assisting nodes with the strongest signals transmit their soft-decision values to the master node for combining. We also consider Rayleigh fading as our channel model (See Section 3.1).

Let A be the random variable for the SNR at the master node, and let X, Y, Z be the random variables for the highest, the second highest and the third highest SNR among the $M-1$ nodes. a, x, y, z are the parameters of the probability distribution functions.

In the case of $N = 2$, the joint probability of the master node and the assisting node with the highest SNR is:

$$p_{A,X}(a,x) = \frac{1}{\bar{\gamma}} e^{-\frac{a}{\bar{\gamma}}} \cdot \frac{(M-1)}{\bar{\gamma}} e^{-\frac{x}{\bar{\gamma}}} (1 - e^{-\frac{x}{\bar{\gamma}}})^{M-2} \tag{19}$$

In the case of $N = 3$, the joint probability distribution $p_{A,X,Y}$ of the master node and the two assisting nodes with the highest SNR can be shown to be:

$$p_{A,X,Y}(a,x,y) = \begin{cases} \frac{1}{\bar{\gamma}} e^{-\frac{a}{\bar{\gamma}}} \cdot \frac{M-1}{\bar{\gamma}} e^{-\frac{x}{\bar{\gamma}}} \frac{(M-2)}{\bar{\gamma}} & e^{-\frac{y}{\bar{\gamma}}} \times \\ (1 - e^{-\frac{y}{\bar{\gamma}}})^{M-3}, & x \geq y \\ 0, & \text{otherwise} \end{cases} \tag{20}$$

In the case of $N = 4$, the joint probability of the master node and three assisting nodes with the highest SNR is:

$$p_{A,X,Y,Z}(a,x,y,z) = \begin{cases} \frac{(M-1)(M-2)(M-3)}{\bar{\gamma}^4} & e^{-\frac{a+x+y+z}{\bar{\gamma}}} \times \\ (1 - e^{-\frac{z}{\bar{\gamma}}})^{M-4}, & x \geq y \geq z \\ 0, & \text{otherwise} \end{cases} \tag{21}$$

A generalized form can be derived as follows. Let $\vec{\Gamma}$ be a vector of the random variables of the received signal SNR. Let γ_i be the random variable for the $(i-1)^{th}$ highest SNR among the $M-1$ assisting nodes ($i \geq 2$). The joint probability of i nodes (the master node and $i-1$ assisting nodes with the highest SNR) is

$$Pr(\vec{\Gamma}) = Pr(\gamma_1, ..., \gamma_i) = \begin{cases} \frac{\prod_{k=1}^{i-1}(M-k)}{\bar{\gamma}^i} e^{-\frac{\sum_{k=1}^{n}\gamma_k}{\bar{\gamma}}} \times \\ (1 - e^{-\frac{\gamma_i}{\bar{\gamma}}})^{M-i}, \; \gamma_2 \geq ... \geq \gamma_i \\ 0, \qquad \text{otherwise} \end{cases} \tag{22}$$

4 Evaluation Results

In this section, we will present the evaluation results in terms of *outage probability*, *bit error rate (BER)*, *throughput*, *local bandwidth usage*, and impact of short-range link delay and bandwidth; compare the performance of our proposed techniques with existing techniques; and compare the performance between PMRC and PSDC.

4.1 Outage Probability

Outage probability is a common and effective metric to evaluate 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. Since PMRC operates at signal level, we are able to compute the outage probability for PMRC. 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 less 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.

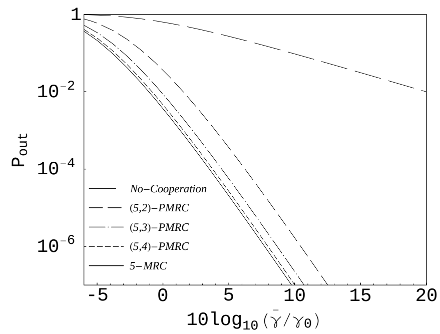


Fig. 2. Outage probability of PMRC vs. MRC and Non-Cooperation.

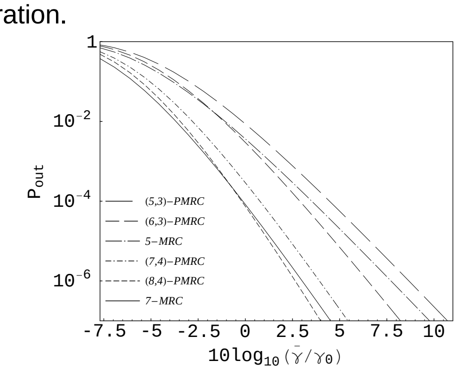


Fig. 3. Impact of M on the performance of PMRC.

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.

4.2 Bit Error Rate

Bit Error Rate (BER) is another important performance metric of communication systems. Determining the BER requires considering a specific modulation scheme. We use 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 [1] with $\beta = 1$ (where W is the used frequency bandwidth). Therefore $E_b/\mathcal{N}_0 = \gamma$ and the $BER = Q(\sqrt{\frac{2E_b}{\mathcal{N}_0}}) = Q(\sqrt{2\gamma})$. We obtain similar results considering Binary Phase Shift Keying (BPSK) modulation.

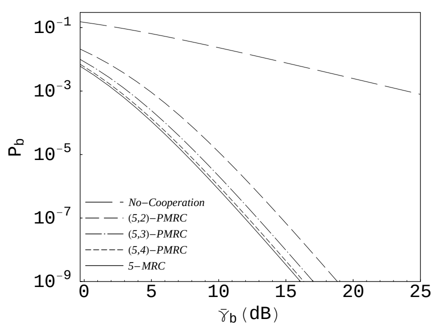


Fig. 4. BER of MSK under PMRC vs. MRC and Non-Cooperation.

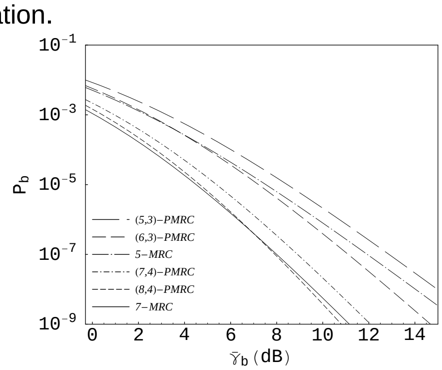


Fig. 5. Impact of M on the performance of PMRC in terms of BER.

First, 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. This analytical result indicates that most of the gain of MRC is obtained using the 2 to 3 strongest signals from neighboring nodes. This is inline with the principle of diminishing return of diversity in multi-antenna systems [21] . 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 calculate the bit error rate of Post Soft-Demodulation combining, let Pe be the error probability of the value from an assisting node, and$\vec{P}e_{\vec{\Gamma}}$ be the joint error probability for the vector $\vec{\Gamma}$ containing the values from multiple assisting nodes. For ease of analysis, we can assume the transmitter sends all 0's. So $Pr(y=0) = 1 - Pe$ and $Pr(y=1) = Pe$. The error happens if the combiner generates a 1.

Given $\vec{Y}$ and $\vec{P}e$, the bit error rate of the Maximum Likelihood Soft Combiner can be calculated as follows:

$$Pb_{\Sigma} = \int_0^{+\infty} \sum_{\vec{Y}} MLSC(\vec{Y}, \vec{P}e_{\vec{\Gamma}}) \cdot Pr(\vec{Y}) \cdot Pr(\vec{\Gamma})\, d\vec{\Gamma} \tag{23}$$

For a target BER of 10^{-3}, $(5,2)$-PSDC requires 17dB less power and with the contribution from only one cooperating neighbor (See Figure 6). Higher gains are achievable when the target BER is lower. We also observe most of the diversity gain can be obtained by using a few (2 to 3) *strongest* neighbors. Figure 7 shows the impact of M on the BER performance. As we can see the parameter M has a more dominant effect on the BER than N. So, it is always better, if possible, to include more nodes as potential contributors rather than increase the number of actively cooperating nodes (who are relaying to the master).

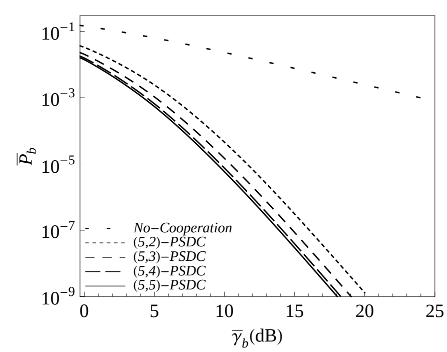


Fig. 6. Bit Error Rate of coherent MSK demodulator under PSDC ($N = 2, ..., 4$) vs. MRC and Non-Cooperation.

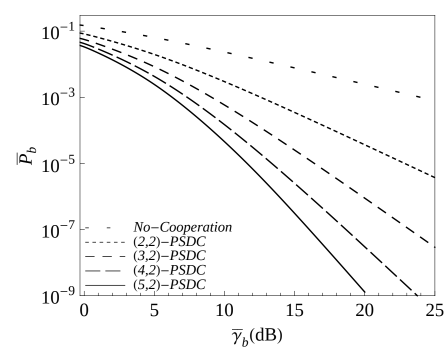


Fig. 7. Impact of M on the performance of Post-Soft Demodulation Combining in terms of Bit Error Rate.

Since PSDC is similar to PMRC, and PSDC aims at reducing the local communication footprint, we want to determine how much performance loss it causes. Figure 8 shows that the BER of PSDC is slightly higher

1. Similar to $sinc()$, but it is widely used in practice [2].

than PMRC under the same configuration. This can be explained by the fact that PSDC only benefits from the diversity gain; in contrast PMRC exploits both the diversity gain and the energy (antenna) gain.

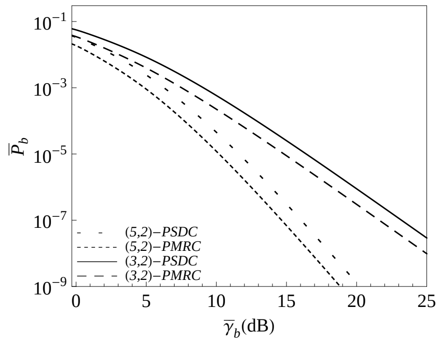


Fig. 8. BER comparison between PSDC vs PMRC.

4.3 Throughput

To measure the throughput of PMRC and PSDC, we only consider the packet overhead of 32 bits CRC necessary for error detection. The throughput can be calculated as

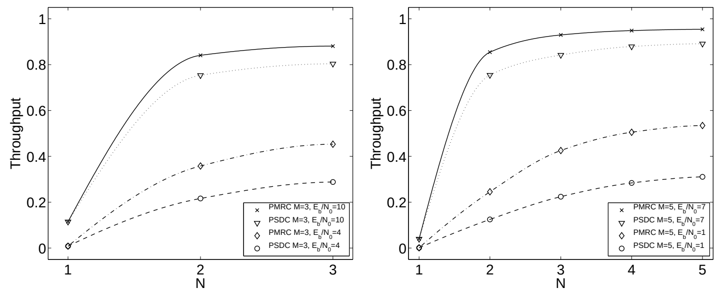
$$Throughput = \frac{(L - OH)(1 - BER)^L}{L}, \qquad (24)$$

where OH is the CRC length, L is the frame length. We determine and use the value of L that maximizes the throughput. For fairness, the packet size is normalized to maximizes throughput.

Figure 9 shows that the throughput of the master node can be tremendously increased by signal combining with a limited number of cooperative nodes in PMRC or PSDC. We also find that PMRC gives comparable performance of MRC by using fewer active branches. For example, for $N = 3$ and $M = 5$ (Figure 9c), besides the master's branch it uses only two active branches out of the four external diversity branches, but it still achieves a throughput of more than 0.9 with a fairly low $E_b/\mathcal{N}_0$ ($4dB$ or above). This tells us that its throughput performance must be at least 90% of the performance given by MRC (the maximum is 1) while it uses only half of the bandwidth required by MRC. With a very low $E_b/\mathcal{N}_0$ at value 1, it still maintains the throughput at 0.65.

Similarly, we can compute the throughput of PSDC. As we can observe the largest throughput growth happens when allowing one assisting node to transmit its soft-decision values to the master. For example in the case of $M = 4, N = 2$ (Figure 9e), the throughput jumps from 0.11 to 0.86 if $E_b/\mathcal{N}_0 = 10$, and from 0.01 to 0.33 if $E_b/\mathcal{N}_0 = 4$.

Figure 10a and Figure 10b reveal the throughput difference between PSDC and PMRC. We observe that the throughput difference is smaller when $E_b/\mathcal{N}_0$ is high but larger when $E_b/\mathcal{N}_0$ is low. For example, if $M = 5, N = 2$ and $E_b/\mathcal{N}_0 = 7$ the throughput difference between the PSDC and PMRC is 10%; if $M = 5, N = 2$ and $E_b/\mathcal{N}_0 = 1$ the throughput difference is 50%. This can be explained by the fact that if the signal quality is good, the diversity gain is far more dominant than the energy gain and both PSDC and PMRC are able to benefit most from the diversity gain; if the signal quality is bad, the energy gain rises, but PSDC is incapable of exploiting the energy gain. Therefore, the PSDC should be used when the signal level is not too low, otherwise PMRC would be a better choice if the performance is critical.



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

Fig. 10. Throughput PSDC vs. PMRC.

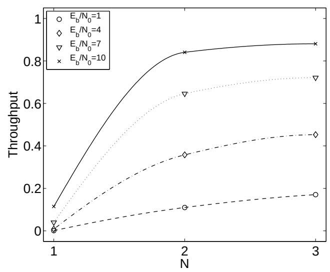
4.4 Local Bandwidth Usage

The sole PMRC/PSDC scheme has fixed local bandwidth usage. For (M, N)-PMRC/PSDC, the local bandwidth usage constant is always $N - 1$. We consider a two-level HPC strategy which consists of Decode-and-Forward Combining and PMRC or PSDC. The local bandwidth can be computed by considering three cases: (1) The master can correctly decode the frame/packet (this occurs with probability $1 - FER$). (2) The master is unable to decode the packet but at least one of the $M - 1$ assisting nodes is capable of decoding it (this occurs with probability $FER * (1 - FER^{M-1})$). (3) None of the nodes can correctly decode the packet, so nodes execute PMRC/PSDC combining. The $N - 1$ assisting nodes with the strongest signals send their sampled signals/soft-decision values to the master (this happens with probability FER^M). Thus, the average local bandwidth requirement is

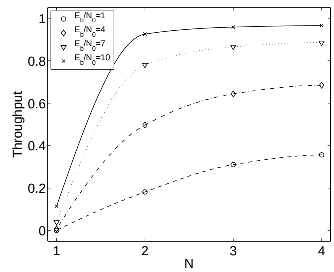
$$\begin{aligned} Avg - Throughput_{local} =& L \times FER \times (1 - FER^{M-1}) + \\ & N \times L \times R \times FER^M \end{aligned} \qquad (25)$$

where L denotes the frame size and R denotes the average number of bits used to represent each signal. R can be 6 bits in the case of soft-decision value, and as high as 64 bits for coherent decoding (4 over-sampling factor, 8 bits quantization for I & Q).

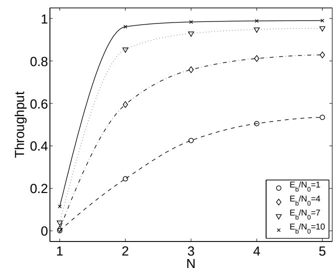
The main benefit of the PSDC over PMRC is that its potential to significantly reduce the local communication bandwidth usage with little performance degradation. In contrast to sampled signal which costs tens of bits



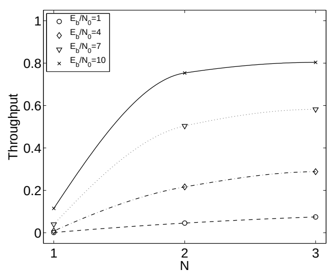
(a) PMRC $M = 3$



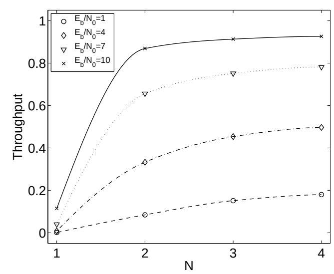
(b) PMRC $M = 4$



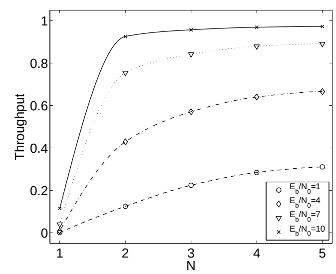
(c) PMRC $M = 5$



(d) PSDC $M = 3$

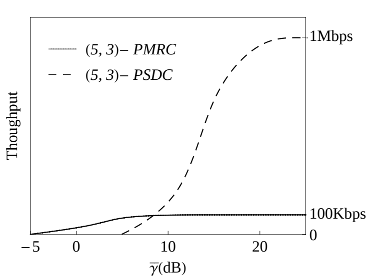


(e) PSDC $M = 4$

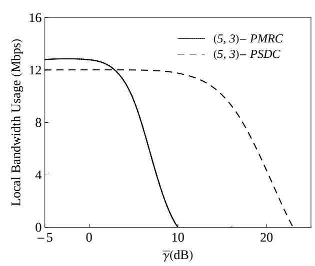


(f) PSDC $M = 5$

Fig. 9. Throughputs in PMRC and PSDC cooperation scenarios and $E_b/\mathcal{N}_0$(dB).



(a) Throughput



(b) Local bandwidth

Fig. 11. Performance of HPC under PMRC (long-range data rate=100Kbps, $R = 64$) and PSDC (long-range data rate=1Mbps, $R = 6$). Packet Length is 1500B.

to represent one symbol (i.e. 64 bits), the soft-decision values only use a few bits to represent one bit of source information. From our experiments (Section 5), with an adequate quantization the soft-decision values can be lower than 6 bits which is less than one tenth of a sampled symbol. Although it still causes several times more local traffic in comparison with the long-range communications, but it is still not a major burden over the local bandwidth assuming the local short-range wireless link (e.g., WiFi) is much faster than the long-range wireless link.

In terms of performance, if $E_b/\mathcal{N}_0$ is not too low PSDC exhibits only a slight downgrade of throughput in comparison to PMRC (See Section 4.3). This supports the proposed HPC strategy to use PSDC as a substitute for PMRC if the signal level is moderately low. In conclusion, we envision two typical scenarios for using the proposed protocols: (1) a high/moderate long-range data rate (typically above 1Mbps, resulting in 2-6Mbps of soft data per branch) with PSDC cooperation, and (2) a low rate (typically above 100Kbps, resulting in 6.4Mbps of baseband data per branch) with PMRC cooperation. (1) corresponds to an urban areas with limited coverage, and (2) corresponds to a military scenario where a distributed multi-radio system can boost the performance of a group of mobile soldiers. Figure 11, shows the performance of PMRC and PSDC for these scenarios (100Kbps vs. 1Mbps). The throughput was computed accounting for the implication of higher rate on the receiver $E_b/\mathcal{N}_0$. The results show if the signal quality is low (such as $\bar{\gamma} = 0dB$), the local bandwidth usage is high for both techniques, because the assisting nodes are transmitting all the time; As the signal quality rises, the the local bandwidth usage is reduced sharply. The results also show that when the $E_b/\mathcal{N}_0$ starts increasing PSDC becomes more interesting than PMRC for the same local bandwidth constraint.

4.5 Local Delay

Cooperation using the short-range link necessitates that the local network capacity is sufficient for the information transfer rates and that the delay is small. Excessive delay can result in unacceptable storage requirements for the receivers specially given that every bit of data is stored as several samples or soft values.

The proposed cooperation protocols have two phases. Given the limited amount of data transferred during the first Phase I, the delay of phase II will dominate. Two extreme approaches (with several variants in between) can be used to limit the delay: (1) using a dedicated hardware and protocol stack with a traffic scheduler

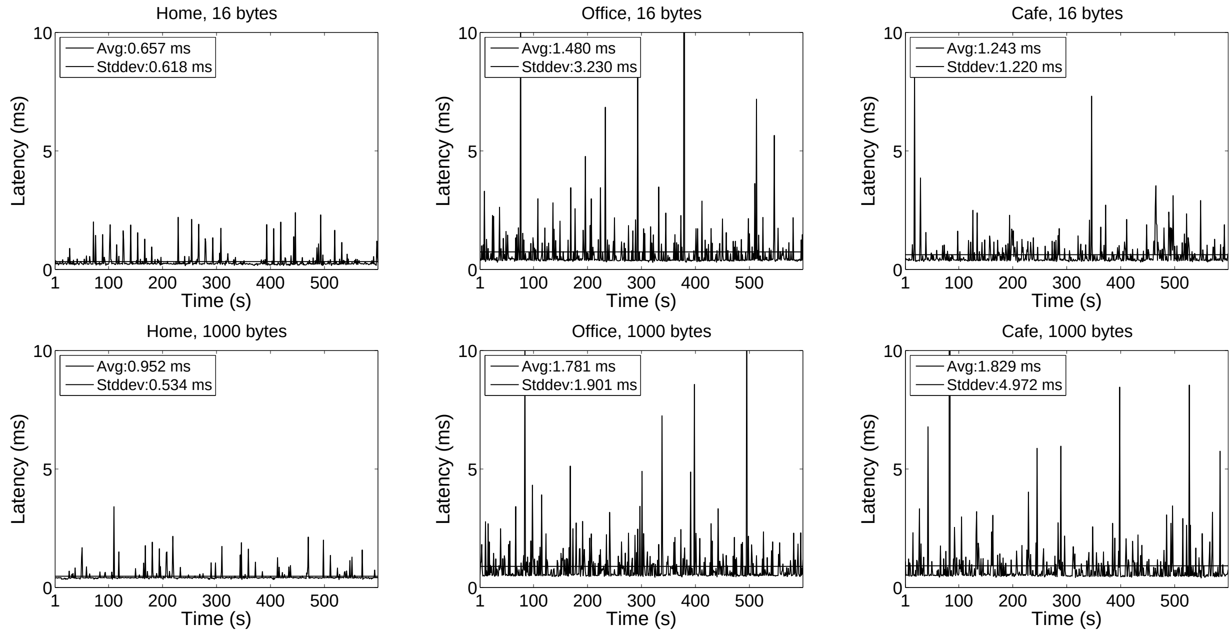


Fig. 12. Delay for IEEE802.11 ad hoc mode in three locations for 16 and 1000 bytes packet size.

to minimize the delay, (2) relying on existing wireless local area networks hardware and network stacks. In the following, we discuss the use of the pervasive IEEE802.11 (ad hoc mode) as the underlying protocol. More dedicated hardware and software would provide better performance.

Analytical and Simulation Estimation: A Markov chain model for IEEE802.11 CSMA/CA was developed in [22]. The model included the multi-stage back-off mechanisms and provided a fairly accurate analytical estimation of the capacity of such networks in ad hoc mode. It was extended to estimate the delay incurred by packets transmissions in [23], [24], [25]. Considering a saturated IEEE802.11 at 1Mbps, a packet size of 1000 bytes and a number of stations $n < 50$, the average delay is below 100ms and the standard deviation is below 200ms. These analytical estimation were confirmed through simulation [22], [23], [25]. Adjustments of the model to the higher rate of 54Mbps, packet size of 1500 bytes, and limiting the number of stations to $n < 20$ leads to an average delay below 20ms and a standard deviation below 40ms in saturation conditions.

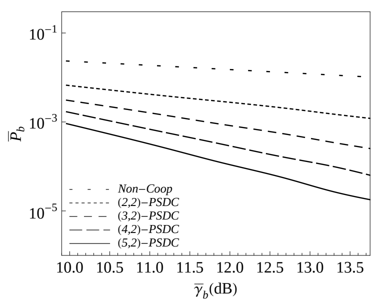
Experimental Estimation: We carried a set of experiments to validate the analytical and simulation estimations. We evaluated the average delay of an ad hoc network in 3 locations (residential, office, and urban cafe), measuring both the delay and standard deviation for two packet sizes (16 and 1000 bytes). While the experimental results are highly dependent on the location, distance between the communication nodes (See Figure 12); our experiments point to an average delay well below 5ms and a standard deviation well below 20ms. Indicating that most of the packets on each cooperation branch can be delivered within 25ms.

To derive the buffer size requirement, we take a worst case delay of 100ms (which is higher than the analytical and experimental estimation) for all cooperation packets to reach the master node. We also consider that most of the benefit of cooperation is achieved by $(M, N \leq 3)$-PMRC/PSDC. Considering the two envisioned scenarios described in the previous section. Scenario (1), a 1Mbps long-range rate with 6 bits quantization for the soft values, would necessitate a buffer of 600 Kbits (<100KB) per branch. Scenario (2), a 100Kbps long-range rate, 4 samples per symbol and 16 bits per sample, would necessitate a buffer of 640 Kbits per branch. These estimates indicate that existing WiFi networks would be sufficient to support local cooperation for the considered long-range communication scenarios.

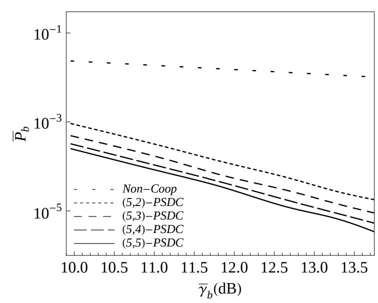
5 Prototype Experiments

We have implemented a prototype testbed of our system on the GNU Radio/USRP platform, and have measured the performance of PSDC technique experimentally. GNU Radio is an open-source software-defined radio (SDR) platform and the Universal Software Radio Peripheral (USRP) is a popular hardware implementation compatible with GNU Radio [26], [27]. The purpose of software-defined radio is to bring the software as close to the radio antenna as possible. The key benefit is that we can do all the signal processing in software on a general purpose computer. This allows a tremendous flexibility during prototyping and at a relatively low cost.

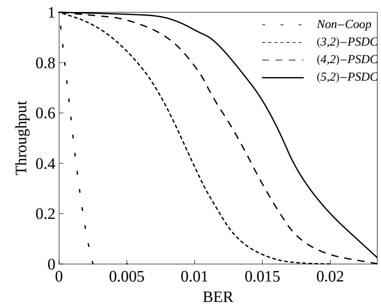
In our experiments, we use a GMSK modulation at 500 kbps on the 2.4GHz ISM band. The GMSK demodulator is modified to output the soft-decision values. In order to obtain reproducible results that are not impacted by external interference from other systems operating over the 2.4GHz band, we use an RF cable to connect the



(a) BER $(N = 2)$



(b) BER $(M = 5)$



(c) Throughput

Fig. 13. PSDC experiment results.

communication boards. This also allow us to precisely control the $\frac{E_b}{N_0}$. A precise Rayleigh fading channel is difficult to experiment with using relatively large software radio setups, so we use a software technique to emulate the Rayleigh fading effect.

We conducted experiments for a long period of time with various transmission power levels. The total amount of recorded data is over 200GB. Due to our hardware limitations we only were able to complete the BER experiments in the range from 10^{-1} to 10^{-6}, but our experimental result can already show a significant improvement in BER on the current hardware. Figure 13a and Figure 13b summarize the results. For a target BER of 10^{-3}, $(5, 2)$-PSDC requires $15dB$ less power than the non-cooperative case and with the contribution from only one cooperating node. Higher gains are achievable when the target BER is lower. Figure 13c shows the system throughput derived from the BER and with the packet size 500 bytes and a 32-bit CRC overhead. As we can see, the PSDC technique is able to effectively boost the throughput in the high BER situations. Those confirm our analysis.

Figure 15 shows a comparison between the experimental results of BER and the theoretic results from Section 4.2. We observe a gap between our experimental results and the theoretic results. This phenomena can potentially be explained by the following reasons related to our testbed. The USRP hardware has limitations. From Figure 14, we see that the distribution of the soft-decision values on an AWGN channels is not exactly Gaussian. Furthermore, the soft-decision values generated by the current algorithm are inaccurate. The GMSK demodulator, we used in our experiments, is a quadrature demodulator [2]. It calculates the angle difference by subtracting the angle of each adjacent complex sample. The soft-decision value is this angle difference multiplied by a gain, which does not exactly represent the confidence or the probability value. A better calculation algorithm for soft-decision values is needed. Nevertheless, the purpose of our experiments is to show that PSDC, as a cooperation mechanism, is feasible to implement in practical systems to improve the bit error rate.

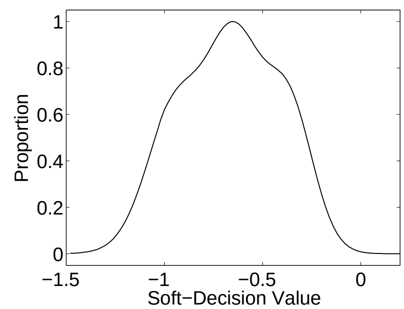


Fig. 14. The distribution of the soft-decision values from the receiver if zeros are sent out.

In practice, the soft-decision values are transferred over the short-range wireless links. Although the short-range links can have much higher bandwidth, it is still necessary to minimize the amount of local traffic to be transmitted. We evaluate how quantization impacts the performance. We conducted several experiments using multiple quantization values. The results for bit error rate are shown in Figure 16. We find that if the soft-decision values are quantized to 6 bits, it has a performance close to a 32-bit float number (the required transmission energy is around $0.25dB$ higher). However, it still requires transferring 6 bits for 1 bit of data. When reducing the quantization level to 3 bits, the bit error rate start degrading, however the results are still acceptable considering the amount of bandwidth it saves. Here we use the uniform quantization. In the future, our implementation can be further improved by using non-uniform quantization, but our current experimental results show that the uniform quantization already reaches a good performance.

6 CONCLUSION

In this paper, we introduced a framework for distributed cooperation and diversity over two radio interfaces. We proposed a Priority Maximum-Ratio Combining (PMRC) technique, and a Post Soft-Demodulation Combining

2. The GNU Radio block *gr.quadrature_demod_cf*.

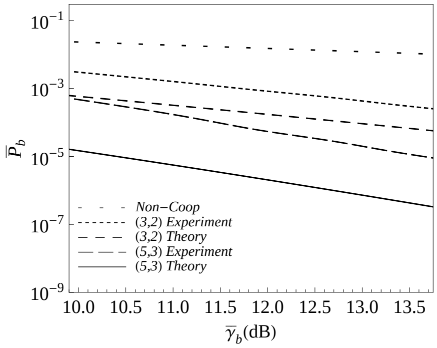


Fig. 15. BER of PSDC theory vs. experiments.

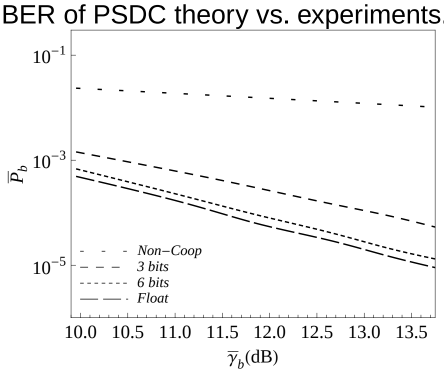


Fig. 16. BER of $(5,3)$-PSDC at different quantization.

(PSDC) technique that leverage distributed diversity while limiting the local communications. We analysed and compared PMRC and PSDC in terms of SNR gain, outage probability, bit error rate, throughput, and delay. Our analytical and experimental results show 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. It allows robust communications with an order of magnitude weaker signals for typical scenarios (e.g., 5 cooperating nodes and two actively assisting nodes). This types of cooperation also opens several directions of future research on security for a realistic use of the proposed mechanisms.

References

[1] M. Rumney, "Identifying technology to deliver the next 100x capacity growth in wireless," *The 3rd LTE World Summit*, 2008.

[2] J. Proakis, *Digital Communications 4 edition*. McGraw-Hill, 2000.

[3] T. S. Rappaport, *Wireless Communications: Principles and Practice 2 edition*. Prentice Hall PTR.

[4] A. Goldsmith, *Wireless Communications*. Cambridge University Press, 2005.

[5] A. Sendonaris, E. Erkip, and B. Aazhang, "User cooperation diversity– part i and part ii," *IEEE Transactions on Communications*, vol. 51, no. 11, pp. 1927–1948, 2003.

[6] D. G. Brennan, "Linear diversity combining techniques," *Proceedings of the IEEE*, vol. 91, no. 2, 2003.

[7] F. H. P. Fitzek and M. D. Katz, *Cooperation in Wireless Networks: Principles and Applications: Real Egoistic Behavior is to Cooperate!* Secaucus, NJ, USA: Springer-Verlag New York, Inc., 2006.

[8] J. Winters, "Smart antennas for wireless systems," *IEEE Personal Communications Magazine*, 1998.

[9] T. Eng, N. Kong, and L. B. Milstein, "Comparison of diversity combining techniques for Rayleigh-fading channels," *IEEE Transactions on Communications*, vol. 44, no. 9, pp. 1117–1129, 1996.

[10] M.-S. Alouini and M. K. Simon, "An MGF-based performance analysis of generalized selection combining over Rayleigh fading channels," *IEEE Transactions on Communications*, vol. 48, pp. 401–415, 2000.

[11] A. Chindapol and J. A. Ritcey, "Performance analysis of coded modulation with generalized selection combining in Rayleigh fading," *IEEE Transactions on Communications*, vol. 51, no. 8, pp. 1348–1357, 2003.

[12] J. N. Laneman and G. W. Wornell, "Energy-efficient antenna sharing and relaying for wireless networks," *Proc. IEEE Wireless Communications and Networking Conference (WCNC)*, Sep. 2000.

[13] T. E. Hunter and A. Nosratinia, "Diversity through coded cooperation," *IEEE Trans. on Wireless Commun.*, vol. 5, no. 2, 2006.

[14] A. Khandani, E. Modiano, J. Abounadi, and L. Zheng, "Reliability and route diversity in wireless networks," *Conference on Information Science and System*, 2005.

[15] R. Ramanathan, "Challenges: A radically new architecture for next generation mobile ad hoc networks," *Proceedings of ACM Mobicom*, 2005.

[16] A. Özgür, O. Lévêque, and D. Tse, "Hierarchical Cooperation Achieves Optimal Capacity Scaling in Ad Hoc Networks," *IEEE Transactions on Information Theory*, 2007.

[17] P. Bahl, A. Adya, J. Padhye, and A. Walman, "Reconsidering wireless systems with multiple radios," *SIGCOMM Comput. Commun. Rev.*, vol. 34, no. 5, pp. 39–46, 2004.

[18] H. Luo, R. Ramjee, P. Sinha, L. E. Li, and S. Lu, "Ucan: a unified cellular and ad-hoc network architecture," *MobiCom '03: Proceedings of the 9th annual international conference on Mobile computing and networking*, 2003.

[19] H. Javaheri, G. Noubir, and Y. Wang, "Cross-layer distributed diversity for heterogeneous wireless," *Wired/Wireless Internet Communications (WWIC)*, pp. 259–270, 2007.

[20] J. N. Laneman and G. W. Wornell, "Exploiting distributed spatial diversity in wireless networks," *Proc. Allerton Conf. Communications, Control, and Computing*, 2000.

[21] G. L. Stuber, *Principles of Mobile Communication*. Springer, 2005.

[22] G. Bianchi, "Performance analysis of the ieee 802.11 distributed coordination function," *IEEE Journal on Selected Areas in Communications*, vol. 18, no. 3, pp. 535 –547, March 2000.

[23] M. M. Carvalho and J. J. Garcia-Luna-Aceves, "Delay analysis of ieee 802.11 in single-hop networks," in *In Proceedings of IEEE Internation Conference on Network Protocols, ICNP'03*, 2003, pp. 146–155.

[24] P. Raptis, V. Vitsas, K. Paparrizos, P. Chatzimisios, and A. Boucouvalas, "Packet delay distribution of the ieee 802.11 distributed coordination function," in *Proceedings of the Sixth IEEE International Symposium on a World of Wireless Mobile and Multimedia Networks, WoWMoM'05*, june 2005, pp. 299 – 304.

[25] T. Sakurai and H. L. Vu, "Mac access delay of ieee 802.11 dcf," *IEEE Transactions on Wireless Communications*, vol. 6, no. 5, pp. 1702 –1710, May 2007.

[26] *The GNU Software Defined Radio, GNU FSF Project*. http://www.gnu.org/software/gnuradio/.

[27] E. Blossom, "Exploring gnu radio," 2004.

Yin Wang Yin Wang is currently a Ph.D student in the College of Computer and Information Science at Northeastern University. Previously, he received a B.S. degree in Computer Science from Nanjing University, China and an M.S. degree in Computer Science from Northeastern University His research interests include Mobile Ad hoc Networks, Cellular Networks, Mobile Devices and Embedded Systems.

Guevara Noubir Guevara Noubir's research covers both theoretical and practical aspects of secure and robust wireless communication systems. He holds a PhD in computer science from the Swiss Federal Institute of Technology in Lausanne (EPFL, 1996). He is now an associate professor of computer science in Northeastern University. He is a recipient of the NSF CAREER Award and held visiting positions at Eurecom, MIT, and UNL.