Cross-Layer Distributed Diversity for Heterogeneous Wireless Networks

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Abstract. In this paper, we introduce a cross-layer diversity framework for multi-air interface wireless communication devices. As an initial step, we focus on devices, of the cellular phones type, that have both long-range relatively low-rate communication air-interface (e.g., GSM) and short-range high-rate communication air-interface (e.g., IEEE802.11). The devices can cooperate through the energy-efficient high-rate interface to improve the performance of the long-range interface. Within this framework we propose a distributed signal-combining technique that accounts for the limited bandwidth of the short-range communication: *Threshold Maximum Ratio Combining*. We analytically derive the probability distribution function of the signal to noise ratio (SNR) of the combined signals as a function of the number of involved devices and show that significant improvement of the SNR is achievable which translates into a reduction of the overall system outage probability.

1 Introduction

Diversity has been used for many years to increase the robustness and efficiency of wireless communication systems [1,2,3]. However, to the best of our knowledge very little research has been done on cross-layer receive diversity for distributed cooperative systems with multiple air-interfaces (e.g., GSM and IEEE802.11) and that accounts for the unique characteristics of each of the interfaces.

For example, consider the scenario depicted in Figure 1. Three mobile users each with a GSM phone suffer from the typical channel-fading that impairs urban cellular communication. The cooperation of these three devices can significantly boost the signal to noise ratio (SNR) making use of both energy-combining gain and fading independence. This SNR improvement results in coverage and capacity increase. Furthermore, it reduces interference because the base stations do not have to increase their transmission power to overcome the fades in order to reach mobile nodes.

Unlike traditional diversity paradigms [1, 2, 3], our approach considers a distributed setup using the local high-rate wireless network. We account for the constraints of the local resources such as bandwidth, computation and energy. In this paper, we propose and analyze a novel technique in this setup to boost the SNR (and therefore the system throughput) of the system using the diversity and energy combining gains and still satisfying the local bandwidth limit.

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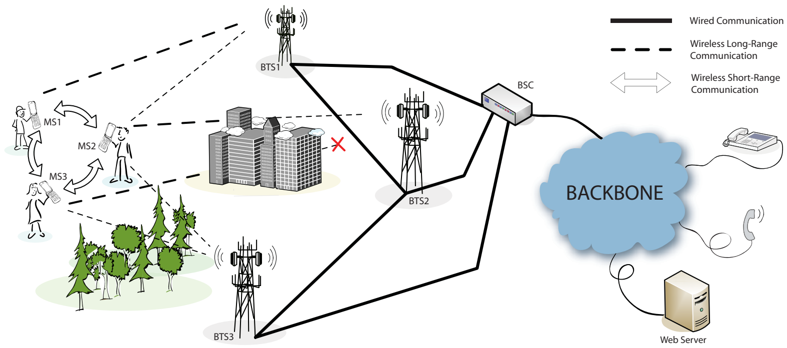

Fig. 1. Example of setup for distributed cross-layer diversity

Related Work: A lot of the previous work on diversity focusses on combining techniques for multiple-antennas/receivers that are co-located on a single device [1,2,3]. Given that all the antennas are directly interconnected, the combining algorithms have full access to the signals from all the antennas. Co-locating multiple antennas on a single *mobile* device is impractical for the current cellular systems. This is not only due to the form factor limitation and cost, but also because of the spatial separation needed between the antennas to achieve channel independence (See Section 2). Recently, distributed cooperative communication has received a significant interest [4,5,6,7,8,9,10,11] from the wireless communications research community. However, most of the work is focused on *transmit diversity* (uplink) [4, 5, 6, 8, 10], while there is very little research on the specific case of a cooperative *receive diversity* where a long-range air-interface subject to a fading channel is combined with a reliable bandwidth-limited short-range air-interface.

Contributions: We introduce a networking framework for distributed cross-layer cooperation. This framework can be implemented on today's cell phone with minimal access to the baseband of the cellular link. A practical technique is proposed for distributed combining that we call *Threshold Maximum Ratio Combining* (TMRC) which enables distributed diversity while accounting for the local communication constraints. We characterize the SNR performance of TMRC as a function of the number of nodes involved and an energy threshold parameter. We derive a closed form formula for the probability distribution function of the combined SNR. This allows us to determine the outage probability of the system and characterize the tradeoff between performance and bandwidth constraints. Our analysis indicates that a significant SNR/Outage improvement can be achieved with today's GSM/IEEE802.11 devices.

The paper is organized as follows. In Section 2, we present the framework and discuss the rationale for distributed cross-layer diversity. In Section 3, we introduce the TMRC technique, derive a closed form formula for the SNR distribution and analyze the performance tradeoff. In Section 4, we propose an abstract protocol for implementing and enhancing TMRC. Finally, in Section 5, we introduce and discuss RMRC a more generalized form of TMRC.

2 Cross-Layer Distributed Diversity Framework

The performance of a long-range link is limited by channel fading caused by multi-path propagation and mobility. This is a critical problem in cellular communication as it results in dead-signal areas and poor localized system performance. Consider a scenario in the GSM system where a Base-Transceiver-Station (BTS_1) is transmitting to a Mobile-Station (MS_1) , Figure 1. A GSM downlink (the uplink is similar) consists of one time-slot (out of 8) on a 200KHz frequency band. Assume that MS_1 and MS_2 have activated a distributed cooperation functionality and they are working in the following way. MS_1 informs MS_2 which 200KHz frequency band and time slot to listen to. MS_2 samples the signal from GSM RF channel and forwards the sampled signal to MS_1 over the short-range, low-power and high-rate link (i.e., IEEE802.11). MS_1 now combines the two signals. This cooperation relies on five key aspects: *Diversity*, *Local bandwidth limit*, *Cross-layer cooperation*, *Modes of operation* and *Fairness*.

Diversity: Implementing an efficient diversity mechanism on a single small device is difficult [4], because the antennas need to be spatially separated beyond a theoretical lower bound to obtain channel independence. In a uniform scattering environment with omnidirectional antennas, the minimum space for independent fading is approximately 0.4λ (where λ is the carrier wavelength) [3]. For GSM systems operating over the 850MHz and 1900MHz bands (in the US), the separation has to be at least $0.14m$. Furthermore, in cellular system directional antennas are usually used at the based stations. This requires an even larger separation due to the small multi-path angle. As a result, it is usually impractical to implement multiple antennas on a single mobile phone. In our setup the two mobile stations are well separated, thus the links BTS_1 to MS_1 and BTS_1 to MS_2 are independent. Therefore, signal combining from neighboring devices will provide a diversity gain in addition to the typical antenna gain.

Local Bandwidth Limit: In our framework, the RF signals received from the long-range interface have to be converted in order to be forwarded through the local short-range interface. We are currently prototyping our framework using the GNU Software Defined Radio (SDR) [12] with the Universal Software Radio Peripheral (USRP) [13]. The long-range RF signal will be down-converted to the intermediate frequency (IF) by the RF front end, sampled by analog-to-digital converter (ADC) and forwarded through the short-range interface. However transmitting the sampled analog waveforms requires a significant bandwidth. For example, in the GSM systems a frame consists of 8 time slots and takes 4.6ms. So each time slot is about 577μs. The symbol rate of GMSK in GSM is 270.833Ksps. Assume the ADC samples 8 times per symbol and with a dynamic range of 12 bits [14]. Therefore, to transmit a single time slot RF signal in every frame requires a data rate of 3261Kbps. IEEE802.11g (54Mbps) can support around 15 links while 802.11b (11Mbps) can only support 3 links.

Distributed Cross-Layer: Having multiple devices to combine the RF channel signals using separate air-interfaces is a novel communication paradigm where the physical layer is virtual and distributed over a set of nodes. It raises interesting questions on how to maximize the performance while satisfying the constraints of the short-range communication link in terms of bandwidth and energy consumption. Several combining techniques have been introduced in the past for centralized diversity (e.g., Maximum Ratio Combining, and Selective Combining [15, 1, 3]). We introduce a new diversity combining technique called Threshold Maximum Ratio Combining which is a special case of a larger set of randomized combining techniques (See Section 5).

Modes of Operation: Nodes can cooperate in two ways, Figure 2:

- *Master-Slave:* A node currently communicating over its long-range communication interface becomes a master. Surrounding nodes that are willing to help, become assisting nodes or slaves. The master node collects sampled signals from the slaves and dictates the cooperation strategy to satisfy the short-range communication requirements while maximizing the SNR of the combined signals at master side.
- *Peer-to-Peer:* The cooperation happens according to a distributed multi-round and multi-hop algorithm. All the nodes are assumed to operate with the common goal to help neighbors obtain higher throughput meanwhile being helped by others.

Both operation modes are constrained by the limitations on local resources. In this paper, we focuse on the Master-Slave mode.

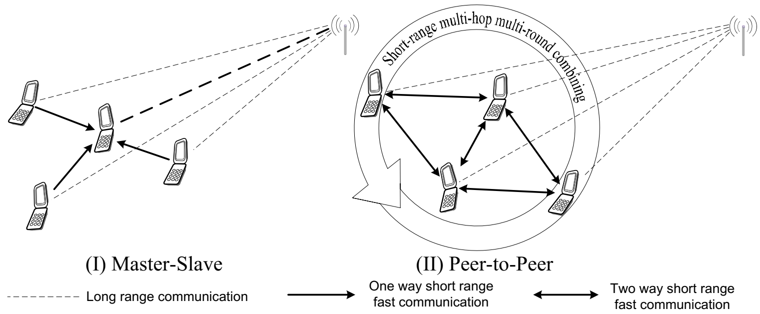

Fig. 2. Modes of operation

Mitigating Selfish Behavior: For such cooperation to be practical, there is a need to develop mechanisms that reward cooperating nodes, detect and punish selfish behavior [16, 17]. Such mechanisms are very important for the success of cross-layer distributed diversity but their study is outside the scope of this paper.

3 Diversity Combining for Distributed Systems

3.1 Traditional Maximum Ratio Combining(MRC)

Rayleigh fading is the typical fading model for cellular systems [2] and our analysis is based on this model. Let γ_i be the random variable for the SNR from the i^{th} branch and m be the number of diversity branches. Assume each fading channel is independent and identically distributed (i.i.d.) with the same noise power spectral density $N_0/2$. It has been shown that γ_i has an exponential distribution [3] (i.e., $p(\gamma_i) = \frac{1}{\bar{\gamma}} e^{-\frac{\gamma_i}{\bar{\gamma}}}$ where $\bar{\gamma}$ is the average SNR and $p(x)$ denotes the probability density function of random variable x.). MRC is basically a weighted sum of all branches. By choosing the weights to be the square root of the SNR of each branch, which leads to the combined SNR [15]:

$$\gamma_{\Sigma} = \gamma_1 + \cdots + \gamma_m$$

3.2 Threshold Maximum Ratio Combining (TMRC)

In MRC, the branch with higher SNR gets the higher weight and the branch with low SNR gets the lower weight. If the local resources are limited, it is better to keep the high SNR branches and discard the lower ones. The Threshold Maximum Ratio Combining is a simple extension of MRC adapting it to account for the limited bandwidth available in cooperative networks. In TMRC, each assisting node transmits the data to the master node *if and only if* its SNR is above a threshold γ_T which is preset by the master node according to the channel condition and local bandwidth. The master node then collects all the signals from the assisting nodes and combines them using MRC. In this paper, we show that under the same assumptions of MRC, the combined signal distribution with m assisting nodes and a threshold γ_T is as follows (See Theorem 2):

$$p_{TMRC}(\gamma) = \sum_{i=1}^{m} \binom{m-1}{i-1} \cdot C^{m-i} \cdot g^{(i)}(\gamma), \qquad \gamma \geq 0 \tag{1}$$

where

$$g^{(i)}(x) = \frac{(x - (i-1) \cdot \gamma_T)^{i-1}}{(i-1)! \cdot \bar{\gamma}^i} \cdot e^{-\frac{x}{\bar{\gamma}}}, \text{for } x \geq (i-1) \cdot \gamma_T \text{ and } C = 1 - e^{-\frac{\gamma_T}{\bar{\gamma}}}$$

Based on this distribution, we can further measure the performance of TMRC (e.g., outage probability, energy gain, bandwidth and energy consumption).

The structure of the proof is as follows. We first derive the signal distribution from each assisting node. Theorem 1 shows the probability distribution of the combined SNR for a simplified case in which all the nodes (including the master node) only use the signal above the threshold γ_T. Theorem 2 gives the distribution of the combined SNR for a more practical protocol. It differentiates the master node from the assisting nodes in the way that the master node uses the signal in the full SNR range because it does not consume any local bandwidth. And $g^{(i)}(x)$ is derived in Lemma 2.

3.3 Probability Distribution of SNR for TMRC

We keep the MRC assumption that the nodes long-range signals' SNR are i.i.d. with parameter $\bar{\gamma}$ and $p(\gamma) = \frac{1}{\bar{\gamma}} e^{-\frac{\gamma}{\bar{\gamma}}}$, where $\gamma \geq 0$. In TMRC, each assisting node does not relay the signal below the threshold γ_T. The master node collects the signals from each assisting nodes. Let $p_T(\gamma)$ be the distribution for each branch at the master side. We have $p_T(\gamma)$ equals $p(\gamma)$ when $\gamma \geq \gamma_T$, and $p_T(\gamma)$ equals 0 when $0 < \gamma < \gamma_T$ because the master will not get any signal from the assisting node in that range. The formal definition of $p_T(\gamma)$ is given in Equation 2.

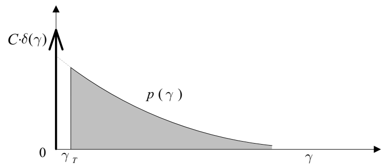

Fig. 3. PDF of γ of each branch at master side in TMRC

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Let $\delta(x)$ denote the Dirac delta function defined as follows:

$$\delta(x) = \begin{cases} \infty, & x = 0 \\ 0, & x \neq 0 \end{cases} \quad \text{and} \quad \int_{-\infty}^{+\infty} \delta(x)\,dx = 1.$$

We define the distribution of SNR T for each branch under TMRC, Figure 3,

$$p_T(\gamma) = \begin{cases} \int_0^{\gamma_T} \frac{1}{\bar{\gamma}} e^{-\frac{\tau}{\bar{\gamma}}}\,d\tau \cdot \delta(\gamma), & \gamma = 0 \\ 0, & 0 < \gamma < \gamma_T \\ \frac{1}{\bar{\gamma}} e^{-\frac{\gamma}{\bar{\gamma}}}, & \gamma \geq \gamma_T \end{cases}$$

Let $f(x) = \begin{cases} \frac{1}{\bar{\gamma}} e^{-\frac{x}{\bar{\gamma}}}, & x \geq \gamma_T \\ 0, & x < \gamma_T \end{cases}$ and $C = \int_0^{\gamma_T} \frac{1}{\bar{\gamma}} e^{-\frac{\tau}{\bar{\gamma}}}\,d\tau = 1 - e^{-\frac{\gamma_T}{\bar{\gamma}}}$, so the probability distribution function for the SNR of each branch can be written as:

$$p_T(\gamma) = C \cdot \delta(\gamma) + f(\gamma) \qquad (2)$$

Definition 1. *For a function $h(x)$, recursively define $h^{(i)}$, where $i \geq 0$, as follows, $h^{(0)}(x) = 1$, $h^{(1)}(x) = h(x)$ and $h^{(i)}(x) = h(x) * h^{(i-1)}(x)$, where $*$ is the convolution operator.*

Lemma 1

$$f^{(i)}(x) = \frac{(x - i \cdot \gamma_T)^{i-1}}{(i-1)! \cdot \bar{\gamma}^i} \cdot e^{-\frac{x}{\bar{\gamma}}}, \quad \text{for } x \geq i \cdot \gamma_T, \quad i \geq 1 \qquad (3)$$

Proof. By induction.

Base case: $i = 1$,

$$f^{(1)}(x) = \frac{(x - \gamma_T)^0}{0! \cdot \bar{\gamma}} \cdot e^{-\frac{x}{\bar{\gamma}}} = \frac{1}{\bar{\gamma}} e^{-\frac{x}{\bar{\gamma}}}, \quad x \geq \gamma_T$$

Hypothesis: assume Equation 3 holds for $i = j$.
On $i = j + 1$,
According to the definition of $f^{(j+1)}(x)$, we have

$$\begin{aligned} f^{(j+1)}(x) &= f(x) * f^{(j)}(x) \\ &= \int_{\gamma_T}^{x-j\cdot\gamma_T} f(\tau)\cdot f^{(j)}(x-\tau)\,d\tau, \quad \tau \geq \gamma_T; x-\tau \geq j\cdot\gamma_T \\ &= \int_{\gamma_T}^{x-j\cdot\gamma_T} \left(\frac{1}{\bar{\gamma}}e^{-\frac{\tau}{\bar{\gamma}}}\right)\cdot\left(\frac{(x-\tau-j\cdot\gamma_T)^{j-1}}{(j-1)!\cdot\bar{\gamma}^j}\cdot e^{-\frac{x-\tau}{\bar{\gamma}}}\right)d\tau \\ &= \frac{(x-(j+1)\cdot\gamma_T)^j}{j!\cdot\bar{\gamma}^{j+1}}\cdot e^{-\frac{x}{\bar{\gamma}}}, \qquad x \geq (j+1)\cdot\gamma_T \end{aligned}$$

□

Let X_1 and X_2 be two independent random variables and $X_{1+2} = X_1 + X_2$. By basic probability rule, the distribution of the sum of two independent random variables is the convolution of their distributions. So $p_{X_{1+2}}(x) = p_{X_1}(x) * p_{X_2}(x)$. It can be generalized to the sum of m independent random variables:

$$p_{T_{\Sigma m}}(\gamma) = p_T^{(m)}(\gamma) = (C\cdot\delta(\gamma) + f(\gamma))^{(m)} \tag{4}$$

Theorem 1. *The distribution of $\gamma_{T_{\Sigma m}}$ which is the sum of m channels under i.i.d. Rayleigh fading with threshold γ_T is:*

$$p_{T_{\Sigma m}}(\gamma) = \sum_{i=0}^{m}\binom{m}{i}\cdot C^{m-i}\cdot f^{(i)}(\gamma), \qquad \gamma \geq 0$$

Proof. Expand the equation (4) and simplify using the Dirac function property:

$$\delta(x) * f(x) = f(x)$$

□

Let $g^{(i)}(x) = \begin{cases} p(x) * f^{(i-1)}(x), & x \geq (i-1)\cdot\gamma_T \\ 0, & x < (i-1)\cdot\gamma_T \end{cases}, \quad i \geq 1$

Lemma 2

$$g^{(i)}(x) = \frac{(x-(i-1)\cdot\gamma_T)^{i-1}}{(i-1)!\cdot\bar{\gamma}^i}\cdot e^{-\frac{x}{\bar{\gamma}}}, \quad \textit{for } x \geq (i-1)\cdot\gamma_T, \quad i \geq 1$$

Proof

$$\begin{aligned} g^{(i)}(x) &= p(x) * f^{(i-1)}(x) \\ &= \int_0^{x-(i-1)\cdot\gamma_T} p(\tau)\cdot f^{(i-1)}(x-\tau)\,d\tau, \quad \tau \geq 0; x-\tau \geq (i-1)\cdot\gamma_T \\ &= \int_0^{x-(i-1)\cdot\gamma_T} \left(\frac{1}{\bar{\gamma}}e^{-\frac{\tau}{\bar{\gamma}}}\right)\cdot\left(\frac{(x-\tau-(i-1)\cdot\gamma_T)^{i-2}}{(i-2)!\cdot\bar{\gamma}^{i-1}}\cdot e^{-\frac{x-\tau}{\bar{\gamma}}}\right)d\tau \end{aligned}$$

$$= \frac{(x - (i-1) \cdot \gamma_{_T})^{i-1}}{(i-1)! \cdot \bar{\gamma}^i} \cdot e^{-\frac{x}{\bar{\gamma}}}, \quad x \geq (i-1) \cdot \gamma_{_T} \qquad \square$$

To get the distribution $p_{_{TMRC}}(\gamma)$ of the cooperative network with size m, we need to add the γ of the master node to the $\gamma_{T_{\Sigma_m}}$ of the $m-1$ assisting nodes.

Theorem 2. *$\gamma_{_{TMRC}}$ is the sum of m channels under i.i.d. Rayleigh fading in which $m-1$ branches are with threshold $\gamma_{_T}$ and one master node which always uses its received signal, i.e., $\gamma_{_{TMRC}} = \gamma + \gamma_{T_{\Sigma_{m-1}}}$. The distribution of $\gamma_{_{TMRC}}$ is:*

$$p_{_{TMRC}}(\gamma) = \sum_{i=1}^{m} \binom{m-1}{i-1} \cdot C^{m-i} \cdot g^{(i)}(\gamma), \qquad \gamma \geq 0$$

Proof

$$\begin{aligned} p_{_{TMRC}}(\gamma) &= p(\gamma) * p_{T_{\Sigma_{m-1}}}(\gamma) \\ &= p(\gamma) * \left(\sum_{i=0}^{m-1} \binom{m-1}{i} \cdot C^{m-i-1} \cdot f^{(i)}(\gamma) \right) \\ &= \sum_{i=1}^{m} \binom{m-1}{i-1} \cdot C^{m-i} \cdot g^{(i)}(\gamma), \quad \gamma \geq 0 \end{aligned}$$

$\square$

By taking the limit of $\gamma_{_T} \to 0$, we get

$$\lim_{\gamma_T \to 0} p_{_{TMRC}}(\gamma) = \frac{\gamma^{m-1}}{(m-1)! \cdot \bar{\gamma}^m} \cdot e^{-\frac{\gamma}{\bar{\gamma}}}.$$

It is also the distribution of $\gamma_{_\Sigma}$ of the traditional MRC. Therefore, MRC can be viewed as a special case of TMRC with zero threshold.

3.4 Performance, Bandwidth and Energy Tradeoffs

In wireless communication systems, transmissions account for most of the energy consumption. For simplicity purpose, as a first step, we will use the amount of transmissions to account for the system constraints. Since MRC achieves the full diversity order and TMRC as a variation of MRC intentionally discards the low SNR signals at assisting nodes, intuitively its performance should be in-between MRC and no diversity. TMRC has the advantage of being able to satisfy the local bandwidth requirements. We discuss the tradeoff between the performance and bandwidth in terms of outage probability and energy gain.

Let γ_0 be the minimum SNR for acceptable performance of the demodulator. The outage probability is defined as

$$P_{out} = p_{_{TMRC}}(\gamma < \gamma_0) = \int_0^{\gamma_0} p_{_{TMRC}}(\gamma)\, d\gamma.$$

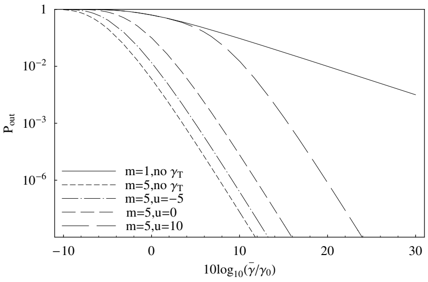

Fig. 4. The outage prob. of the master node with different γ_T in TMRC compared to MRC and no diversity (case $m = 1$). [u denotes $10log_{10}(\gamma_T/\gamma_0)$].

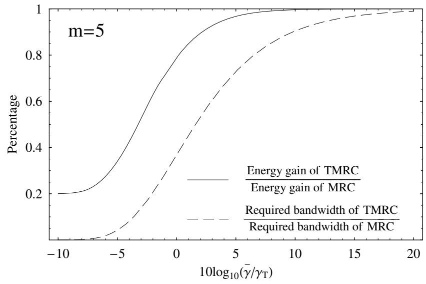

Fig. 5. Percentages of the energy gain and the bandwidth requirement of TMRC over MRC when setting the threshold γ_T to different values

When setting $\gamma_T = 0$, as expected, the outage probability of the master node in TMRC is the same as the one in MRC for the same m. As we increase γ_T the outage probability increases until γ_T reaches infinity where it becomes the same as the one with no diversity. This is reasonable because when γ_T is set to infinity basically no assisting node transmits; the master only uses its own received signal which is the case of no diversity. Figure 4 shows examples of $m = 5$ (i.e., 4 assisting nodes) with different γ_T, $m = 5$ in MRC (full diversity) and $m = 1$ (no diversity). Note that if γ_T is in the order of γ_0, the outage probability of TMRC is very close to MRC.

The increase in averaged SNR of the combined signal over the average SNR of each branch is called *Energy Gain* or *Array Gain*. In TMRC, it starts as the full diversity MRC case when $\gamma_T = 0$, it goes down as γ_T increases and finally converges to the no diversity case. We also observe that the required bandwidth drops as γ_T increases and finally down to 0 when γ_T reaches infinity. But with the same γ_T the drop percentage of energy gain is always less than that of bandwidth requirement. It means we can always lower the amount of wireless communication at the expense of less loss of energy gain. For the case of $m = 5$, Figure 5, if we set $\gamma_T = \bar{\gamma}$ which is at position 0, the energy gain of TMRC is 79% of MRC while it needs only 36% of the local bandwidth of MRC. This justifies the performance and bandwidth tradeoff in TMRC.

4 Protocols for TMRC Implementation

The packet containing the sampled signal is large (See Section 2) and requires significant bandwidth. Even though in TMRC the low SNR signals are dropped, inspired by [6] we can still further lower the bandwidth requirement by introducing another threshold γ_D. When an assisting node finds the received signal SNR is beyond γ_D, it believes that the signal is good enough for demodulation and does not need any further combining. So it just sends the demodulated bits to

Protocol 1. The master node protocol

```
initialize the local cooperative network
broadcast the control packet {SINFO, γ_T, γ_D and G}
/* SINFO is the session info. (eg., frequency, modulation and
   time slot allocation                                         */
/* γ_T is the signal discarding threshold.                      */
/* γ_D is the demodulation threshold.                           */
/* G is a set of nodes which will be active in this session
   for helping the master node.                                 */
buf ;                    /* a queue to save the received signals */
Start the following two threads
Thread 1: for the long range interface
begin
    while until the session ends do
        data_lr←receive signal at next expected time slot
        measure γ
        enqueue(buf,[data_lr, γ])
end
Thread 2: for the local interface and combining
begin
    while until the session ends and buf becomes empty do
        [data_buf, γ]←dequeue(buf);    /* block if queue is empty */
        if γ ≥ γ_D then
            demodulate(data_buf) and pass it to upper layer
            continue
        /* bm is the bit mapping structure                       */
        bm←receive the bit mapping for the current time slot
        if bm indicates a demodulation from an assistant node then
            receive the demodulated data and pass it to upper layer
            continue
        if bm indicates at least one over threshold receiving then
            data_loc[ ]←receive signals from each node sequentially
            according to the bit mapping
            data_out←mrc_combine(data_buf,data_loc[ ])
        else
            data_out←data_buf
        demodulate(data_out) and pass it to the upper layer
end
```

Protocol 2. The assisting node protocol

```
Join the cooperative network
Receive the control packet {SINFO, γ_T, γ_D and G}
if the current node is not in set G then
    go to inactive mode (It's excluded from the current session)
buf ;                    /* a queue to save the received signals */
Start the following two threads
Thread 1: for the long-range interface
begin
    while until session ends do
        data_lr←receive signal at next expected time slot
        measure γ
        enqueue(buf, [data_lr, γ])
end
Thread 2: for the local interface
begin
    while until session ends and buf becomes empty do
        [data_buf, γ]←dequeue(buf);    /* block if queue is empty */
        Wait until the next bit mapping slot time
        /* This can be done, because each node knows the last
           bit mapping information (use a default value for the
           first time), so it knows how long for all the
           assisting nodes to finishes the last round.          */
        if γ ≥ γ_D then  indicate a demodulation in the bit mapping slot
        else if γ ≥ γ_T then  indicate a over threshold receiving
        else
            indicate nothing in the bit mapping slot and discard the packet
            continue
        waiting until the bit mapping slot ends
        if the current node is the first node indicating a demodulation
        then demodulate(data_buf) and send the demodulated data
        else if no others indicate a demodulation then
            Waiting a period to allow other nodes which are indicating an
            over threshold receiving before the current node to finish their
            transmissions
            Send the sampled signal
        else  discard the packet
end
```

the master meanwhile informing other assisting nodes not to send their signals. Once the master receives the demodulated data, it just uses it without combining with others.

In the general case, the implementation of the above strategy can be difficult and complex. The major reasons are the channel characteristics may not be known in real time; the current TDMA system may not be compatible for implementing diversification; and the local network requires a fast MAC protocol. However, we can design a simple abstract protocol (See Protocol 1 and Protocol 2) if we assume that the channel coherence time is larger than the duration of the time slot (as noted in [18]); and the computation capability on each mobile node is sufficient. To simplify the MAC operation the protocol introduces a short bit mapping period which allows the assisting nodes to indicate if they will transmit. That period is designed to be very short such that it does not impact the analysis of the system. Figure 6 shows a snapshot of the running protocol.

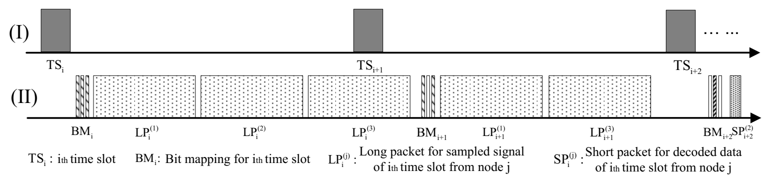

Fig. 6. A running instant of TMRC with 1 master node and 3 assisting nodes. (I) shows the long-range TDMA channel, and (II) shows the short-range fast channel.

5 Generalization of TMRC

Generalizing the idea of TMRC, we introduce a class of techniques called Randomized Maximum Ratio Combining (RMRC). In RMRC each node transmits the sampled signal to the master in a randomized way with the probability determined by the signal SNR.

Let $TX(\gamma)$ denote the function generating the probability of transmission. It takes the SNR as the input and outputs the probability of replaying the signal to the master. First, let $TX(\gamma)$ be an exponential function, Figure 7(I), $TX'(\gamma) = 1 - e^{-c'\cdot\gamma}$, where c' is a parameter. When γ is low, the probability of transmitting the sampled signal is small. As γ increases, the probability of transmitting goes up by following an exponential function. Similarly, we can define $TX(\gamma)$ to be a linear function, Figure 7(II), $TX''(\gamma) = c'' \cdot \gamma$ if $\gamma < 1/c''$; $TX''(\gamma) = 1$ if $\gamma \geq 1/c''$, where c'' is a parameter. Actually if we review the TMRC, we find that it is exactly a special case in RMRC. In this case, Figure 7(III), $TX'''(\gamma) = 0$ if $\gamma < \gamma_T$; $TX'''(\gamma) = 1$ if $\gamma \geq \gamma_T$. Similarly, we can get the distribution of γ for each branch.

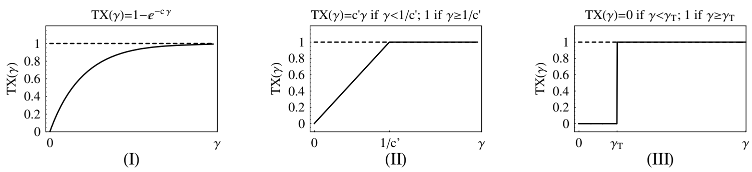

Fig. 7. Potential $TX(\gamma)$ functions for RMRC combining

For $TX'(\gamma)$, we have

$$p(\gamma) = C' \cdot \delta(\gamma) + \frac{1}{\bar{\gamma}} e^{-\frac{\gamma}{\bar{\gamma}}} \cdot (1 - e^{-c'\cdot\gamma}), \quad C' = \int_0^{+\infty} \frac{1}{\bar{\gamma}} e^{-\frac{\tau}{\bar{\gamma}}} \cdot e^{-c'\cdot\tau}\, d\tau = \frac{1}{c' \cdot \bar{\gamma} + 1}$$

For $TX''(\gamma)$, we have

$$p(\gamma) = \begin{cases} C'' \cdot \delta(\gamma) + \frac{1}{\bar{\gamma}} e^{-\frac{\gamma}{\bar{\gamma}}} \cdot (c'' \cdot \gamma), & \gamma < \frac{1}{c''} \\ \frac{1}{\bar{\gamma}} e^{-\frac{\gamma}{\bar{\gamma}}}, & \gamma \geq \frac{1}{c''} \end{cases},$$

$$C'' = \int_0^{\frac{1}{c''}} \frac{1}{\bar{\gamma}} e^{-\frac{\tau}{\bar{\gamma}}} \cdot (1 - c'' \cdot \tau)\, d\tau = c''\bar{\gamma} \cdot e^{-\frac{1}{c''\cdot\bar{\gamma}}} - c'' \cdot \bar{\gamma} + 1$$

RMRC techniques can be analyzed in the exact same manner as TMRC. Due to the lack of space, we will skip this part.

6 Conclusion

In this paper, we introduce a cross-layer distributed diversity framework where neighboring nodes collaborate to boost their performance. We consider the specific case of cellular nodes with two wireless communication interfaces a long-range low-rate and a short-range high-rate. We introduce a novel diversity combining technique called TMRC that takes into account the bandwidth constraints of the short-range communication air-interface. We analyze and derive a closed form formula for the probability distribution function of the SNR for TMRC. This allows us to characterize the outage probability and energy gain as a function of cooperating nodes, local bandwidth, and channel conditions. We show that TMRC leads to significant channel boosting and provide an abstract protocol for implementing it. In the future, we plan to develop protocols that optimize the tradeoffs in involving more assisting nodes (higher m) or reducing the TMRC threshold (γ_T) while satisfying the local bandwidth constraint. We are currently working on a prototype for cross-layer distributed diversity using the GNU Radio and USRP SDR platform.

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