An RF Channel Emulator-Based Testbed for Cooperative Transmission Using Wireless Sensor Devices

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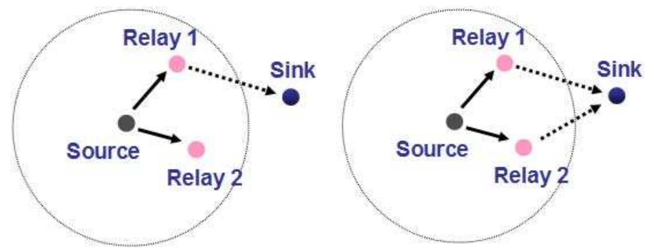
***Abstract*—In this paper, the issues and methods regarding setting up the testbed for measuring the performance of cooperative transmission is introduced. Also, some experiments on both the testbed and the performance of cooperative transmission is introduced and discussed. This testbed is novel in the sense that it uses actual sensor devices along with the channel emulator, which allows us to emulate the exact channels we want without looking for suitable channel environments. We consider the two-hop relay network for our target network model, and cooperative transmission scheme we have selected is decode-and-forward *fixed relaying* scheme introduced in [1].**

I. Introduction

In the context of multi-hop networks, cooperative transmission (CT) has been proposed as a relay technique that improves reliability and saves transmission energy by using the antennas from different radios to form a ”virtual array” [1]. Many authors have analyzed CT theoretically and through simulation, however, few works have been done to assess the performance of CT using actual wireless sensor devices. Since CT generally involves the physical (PHY), medium access control (MAC), and network layers, high fidelity simulation is difficult, and therefore experimental evaluation is valuable. Using an RF channel emulator is a good way to do a few-hop evaluation because the RF channel emulator enables control of the radio channel, so that changes in link quality metrics, e.g. the packet error rate (PER), can be attributed to algorithm and protocol changes rather than environmental changes. An important feature of experiment design is repeatability, by which we mean that the experiment gives the same results when the same parameter settings are used. This paper reports on the design of a testbed to do repeatable experiments in cooperative transmission with second-order post-detection combining using Micaz [2] motes.

There have been a few reports on testbeds that use the RF channel emulator to evaluate performance of WLANs [3] [4]. For wireless sensors, the authors in [5] tested a simple cooperative transmission technique using Micaz motes in a stadium environment. To our knowledge, there are no reports of the use of Micaz motes using an RF channel emulator to evaluate performance for Rayleigh and Rician channels.



(a) Non-cooperative Transmission (b) Cooperative Transmission

Fig. 1. The Network Model. Solid arrow represents the error-free link and the dotted arrow represents the fading channel

In Section II, we introduce our network models for our testbed setup. In Section III, we explain issues and methods regarding setting up a repeatable testbed using sensor devices and the channel emulator. The experiments and results regarding the testbed are discussed in Section IV, and some comments on our testbed and methods are given in Section V.

II. The Network Model

The target network models for our testbed are shown in Fig. 1. We consider the two-hop relay network in which the direct transmission from the source to the sink (destination) is not possible. There are two relays that decode and forward; in the case of non-cooperative transmission (non-CT), only one selected relay transmits (Fig. 1a). In the case of CT (Fig. 1b), two relays cooperate and obtain diversity. Although this network model for our testbed considers only two cooperators, it can be easily extended to more than two, which will be discussed in Section V. Since we are interested in the performance of the cooperators, we allow an error-free link between the source and the relays (cooperators), and the fading channel is emulated only between the relay(s) and the sink.

Most works on CT assume pre-detection combining, e.g.

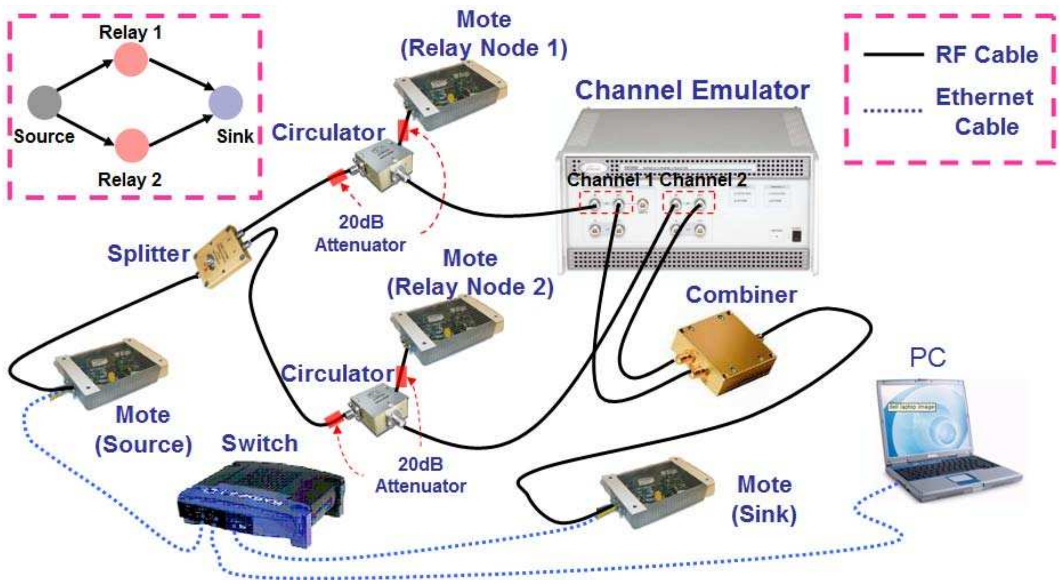


Fig. 2. The Testbed

maximal ratio combining. However, the Micaz motes do not do diversity combining. Although they use spread spectrum (for interference rejection), they do not have Rake receivers. In order to use the Micaz motes for diversity, one relay transmits a packet, and then, in the next time-slot, the same packet is relayed through the other relay. This is similar to the ”fixed relay” strategy of Laneman [1], but in our case, the combining is done at the packet level and after the bits have been detected. While this strategy will not perform as well as pre-detection combining, it still gives a substantial diversity gain, and it can be implemented at the MAC layer using Micaz motes. To achieve the time-division channel allocations, we deliberately implement transmission delays between two relay nodes, that is, the first relay node relays data immediately and the second one waits for t_d secs and relays. In the case of CT, the sink node waits for two same packets from the relay nodes. If the sink node receives both packets correctly, it ignores the second one.

III. The Testbed Setup

The testbed for our experiment is shown in Fig. 2. To emulate the relay-to-sink channels, we used the Spirent Communications SR5500 channel emulator [6], which can support up to 2 independent channels with 12 paths each. The channel emulator is unidirectional (i.e. it has separate input and output ports), therefore, there is no return path. In order to transmit a signal through the channel emulator, a wireless sensor should be connected to RF cables. To do this, the wireless antennas of the motes were pulled off and replaced by the cables. The source was connected to both relays by a splitter and the sink was connected to the outputs of the channel emulator by a combiner (we used Mini-Circuits’ ZN2PD-2G for the splitter/combiner). To connect the relay mote to both the source mote and the channel emulator, without allowing a direct connection from the Source Mote to the channel emulator, we used a circulator (MECA Electronics’ CS-3.000). As shown in Fig. 3, the circulator is a 3-port device that allows signals to flow from Port 1 to Port 2, from Port 2 to Port 3, and from Port 3 to Port 1. However, ideally, signal flows in the opposite directions (e.g. from Port 2 to Port 1) are blocked. How we dealt with the non-ideal circulator is explained in Section II.B.

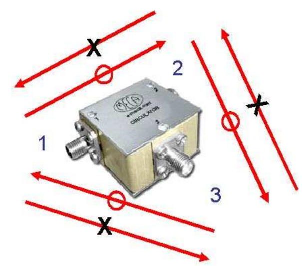


Fig. 3. The Circulator

We used packet error rate (PER) to evaluate performance. The embedded software programming used to program Micaz was TinyOS [7] and Java [8] was used for PC applications.

In the following subsections, we introduce implementations and issues regarding our testbed setup.

A. The Control Network

We created an Ethernet network to measure the PER and to control the motes, as shown in the lower part of Fig. 2. The Source and Sink Motes were each controlled through their respective MIB600 programming boards [9], as shown in Fig. 4. The MIB600s were controlled by one PC through a switch. We controlled our tests by sending one of our command messages to the Source Mote. The messages consisted of message type, number of packets to be sent, transmit period,

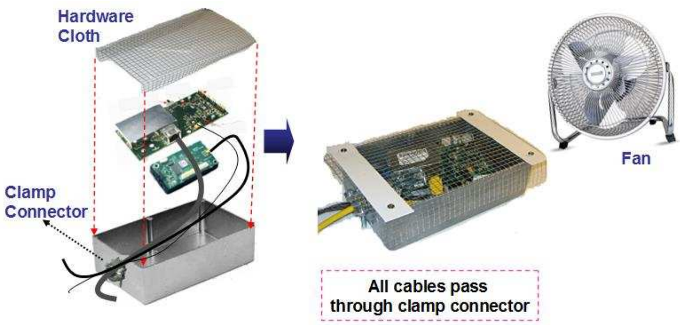


Fig. 4. The Isolation of the Motes and Cooling

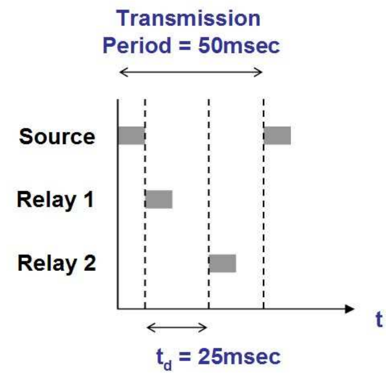


Fig. 5. The Timing Diagram.

number of test repetition, and the test ID (for logging). For PER measurements, we used a 29-byte payload (application layer) consisting of message type, sequence data, and random numbers.

B. The Circulator Problem

As already mentioned in the beginning of this section, we used a circulator to prevent the direct data flow from the source to the destination (from the Port 1 to Port 3). However, it turned out that the path between the Ports 1 and 3 was not unidirectional because the Port 2 connected to the Micaz (the relay) was not perfectly matched. To cope with this problem, we put one 20dB attenuator (MCL's BW-S20W2) on Port 1 to reduce the incoming signal and one 20dB attenuator on Port 2. The signal attenuation from the attenuators did not affect the error-free transmission from the Source to the Relay even though the source was using the lowest transmit power, -25dBm. The presence of the attenuators made negligible the direct transmission from the Source at the Sink.

C. Isolation of the Motes and Cooling

Although the wireless antennas of the motes were replaced with cables, the motes were still able to communicate through the air. In other words, significant signal power was leaking out of the connectors. This leakage is undesirable because it nullifies the effect of the channel generated by the channel emulator. To prevent this problem, we had to isolate the motes. A metal enclosure was designed to overcome this problem. We used a hardware cloth as the cover of the enclosure to see what was going on inside, and by performing the test described in IV-A, we could verify that the enclosure sufficiently isolated the mote. We put the Micaz (attached to the MIB600) inside of the metal enclosure as shown in in Fig. 4.

During our experiments, we noticed that the PER value increased as we repeated the same test consecutively, which indicated some non-repeatability of the performance measurement. This phenomenon was eliminated after we used small fans to cool the motes (Fig. 4). Although we didn't do further tests to confirm that the fans were the cause of this problem (by testing again without the fans), we recommend using the fan for a possible overheating problem. To simplify Fig. 2, the fans placed at the top of the enclosures are not illustrated.

D. Channel Emulation

The channel emulator SR5500 can emulate Rayleigh and Rician fading with various fading parameters [6]. It supports up to 2 channels which can be either correlated or uncorrelated. The channel emulation is done between the relay motes and the sink mote. We let the relay signals pass through different channels and made the channels independent.

For each channel we can set the output power of the channel (in dBm) which can be viewed as the received signal power when fading is not present (neglecting cable and connector losses). By adjusting this value, we can obtain the same effect as adjusting the transmit power of the relay. This is very useful because there is a limitation, -25dBm, of the transmit power of Micaz, and if we want to lower the power below -25dBm, attenuators are required. Therefore, changing the output power of the channel emulator instead of changing the transmit power of the relay mote is more tempting. Using this feature in our experiments will be introduced in Section IV-B.

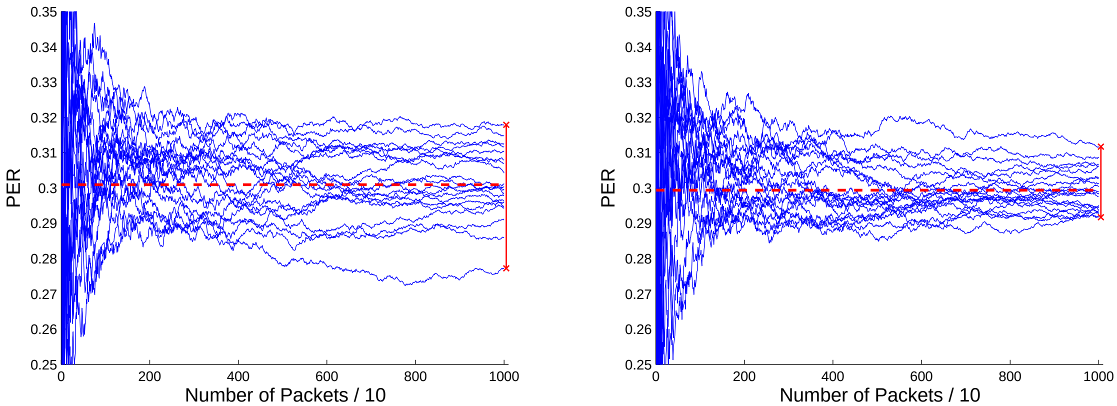
IV. Experiments and Results

The experiments that we have conducted using the testbed illustrated in Fig. 2 fall into two categories: testbed evaluation and the network performance. These experiments and outcomes are discussed in this section.

A. Experiments on the Testbed

In order to get valid and repeatable test results from the experiments, one must perform series of tests that verify if the test setup in Fig. 2 has no flaws. Such tests include

1) ***Test if without fading emulation, we get PER value of 0.***
   This test can be done by using non-fading channel settings on the channel emulator, with sufficiently low output attenuation for error-free reception, while keeping the testbed as in Fig. 2.
2) ***Test if isolation is done properly so that there can be no communication through the air.***
   This test can be done by disconnecting the RF cable connected to the sink node during error-free transmission and see if the sink receives. If it receives despite the disconnection of the cable, it means that the nodes can



(a) Without fans (mean = 0.3009, std dev = 0.0102)

(b) With fans (mean = 0.2994, std dev = 0.0062)

Fig. 6. Cumulative PER graphs showing improvement of the repeatability

TABLE I
IMPROVEMENT ON REPEATABILITY

Without Fan		With Fan	
mean	std dev	mean	std dev
0.3009	0.0102	0.2994	0.0062
0.3196	0.0154	0.2909	0.0043
0.2993	0.0079	0.2890	0.0067

TABLE II
THE FADING PARAMETERS

Field	Setting	Field	Setting
Fading Doppler (Hz)	111.19	Phase Shift (Deg)	0
Fading Doppler Vel (km/h)	50	Delay Mode	Fixed
Fading Spectral Shape	Classic 6dB	Delay Value (ns)	0
Relative Path Loss (dB)	0	Freq Shift (Hz)	0
Log Normal Enabled	No	LOS AOA (Deg)	90
Log Normal Rate	0	LOS Doppler (Hz)	0

communicate through the air and the isolation needs to be fixed.

3) ***Test if the transmit period and the delay values are suitable.***
The transmit period of the source and the delay of the relay are illustrated in a timing diagram in Fig. 5. A test for these parameters is necessary because if the packets are transmitted at too high a rate so that the hardware or software cannot process them properly, errors can be generated not by the fading channel but by the fast transmission. If the PER value of the error-free transmission is not 0 with a certain transmit period of the source, the selected transmit period is not appropriate. By doing tests with different transmit periods, we figured out that 25msec transmit period is more than enough when one relay node is used. Using this result, we chose the delay of the second relay as 25msec ($t_d = 25$msec), and the transmit period of the source as 50msec, which worked properly for both models.

These tests helped us figure out the problems of the testbed and improve the repeatability. One of the results regarding the improvement of the repeatability of the testbed is introduced below.

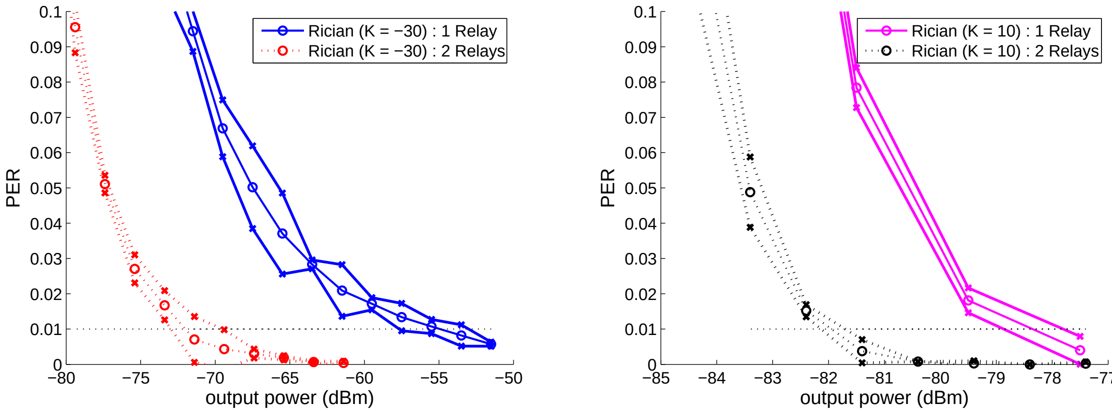
Fig. 6 shows the improvement of the repeatability when fans are used. Each line in the graph indicates one cumulative PER result for 10000 packets transmission (took around 2 minutes) which is calculated as follows. At every 10th packet, we calculated PER based on the accumulated number of correctly received packets. The x-axis indicates $x \times 10$ packets and its corresponding y value (cumulative PER) is "the number of error packets so far"/($x \times 10$). The graph contains 20 lines which are the results of 20 consecutive simulations. One can easily see that the way that the final PER values (the values at $x = 1000$) are dispersed is notably different (0.04 vs 0.02). The dashed horizontal line indicates the mean of the 20 final PER values, and the smaller standard deviation when fans are used shows that the repeatability is improved. The mean and the standard deviation for six results regarding using fans are shown in Table I.

If the experiment is perfectly repeatable, then the PER can be viewed as a sample mean of a Bernoulli random variable X, such that $Pr(X = 1)$ = the true mean. If we assume that the true mean is 0.3, then the standard deviation of the sample mean with 10000 trials is $\sqrt{0.21/10000} = 0.0046$. We see that the standard deviations with the fan are close to this value.

B. Evaluations of Network Performance

Using the testbed setup illustrated in Fig. 2, simulation of both non-CT and CT were be performed (for non-CT, we can either disconnect any cables related to the relay node 2 or just turn the mote off).

In this test, we assume the scenario that the relay1-to-sink link and relay2-to-sink link have almost the same attenuation



(a) K = -30dB

(b) K = 10dB

Fig. 7. PER vs Output Power (dBm) graphs with 95% confidence interval. Line with 'o' indicates the means and 'x' is the confidence intervals

so that it could be fair for both CT and non-CT (if the first relay is closer or farther to the sink than the second, the relative performance of non-CT becomes better or worse respectively).

We set the channel emulator to have one Rician-faded path for each channel, using the same K factor for both paths and setting the two paths to be uncorrelated. We used the default fading parameters of the channel emulator and changed the K factor only. These parameters are shown in Table II, and they are named according to the Spirent SR5500 TestKit Instrument Control Software [6]. For example, "Fading Doppler" is the half-width of the path's fading spectral shape and "Fading Spectral Shape" is the Doppler spectrum shape. "Fading Doppler Vel" together with "LOS AOA" determine the Doppler shift of the carrier frequency; LOS AOA = 90 degrees corresponds to a zero Doppler shift. For more information, refer to [6]. The tests were done for two extreme cases; one with strong line-of-sight signal (K=10dB), the other with nearly no line-of-sight signal (K=-30dB), which can be viewed as Rayleigh fading channel.

The transmission period of the source mote was 50msec, and the first relay node relays the packets immediately and the second one relays the packets after waiting 25msec.

5000 packets (29 bytes payload for each packet) were transmitted for each trial, and a final PER value for each trial was computed. To check repeatability of the PER test, we performed 3 trials, and applied the Student-t distribution with 2 degrees of freedom [10], to obtain the 95% confidence interval. The three final PER values were averaged to get a "mean PER."

Fig. 7 shows the mean PERs of CT (dotted lines) and non-CT (solid lines), along with their 95% confidence intervals, versus the output power of the channel emulator. Here, adjusting the output power of the channel emulator gave the same effect as adjusting the transmit powers of the relays. The output powers for each relay transmission in the CT case are the same as the output power for the non-CT case.

Based on Fig. 7, we can analyze our results as follows. For 1% PER (dashed horizontal line in Fig. 7), CT shows a 13 to 20dBm SNR advantage over non-CT(the range is due to confidence interval) in the presence of the Rayleigh fading, and a 3 to 4dBm SNR advantage in the case of K=10dB Rician. The SNR advantage of CT can be used in different ways: to transmit a higher data rate [11], to extend range or overcome a 13 dB obstruction, or to reduce transmitted energy. We note that a significant reduction in transmitted energy does not always correspond to a reduction in the total energy consumed in the network because of the energy consumed by the electronic circuits in the motes, especially during reception.

V. Remarks

The testbed setup in Fig. 2 can be extended to support more than two nodes by just modifying some of the hardware. The splitter/combiner would need more ports. More motes, circulators and emulated channels need to be added. Since the channel emulator is a very expensive device, one would probably encounter the limitation in adding a large number of relay nodes.

If the Sink node could be programmed to send a "NACK" when it fails to decode the first relayed packet, then a post-detection version of the *incremental relay* strategy [1] could be implemented with Micaz motes. The advantage of the incremental relay strategy is that resources are not wasted by a cooperator if the packet is successfully received the first time [1].

VI. Conclusion

In this paper, we introduced issues and methods regarding setting up a testbed using actual wireless sensor device and the channel emulator that can repeatably evaluate the performance of CT. Using this testbed, we can obtain the performance for a particular channel environment without looking for suitable channel environments and positioning the sensor devices. We focused on not only setting up the testbed but also making it repeatable, which gives credibility to our results. The sample tests we have introduced here are only the cases of two Rician fading channels and only for Micaz, however, tests using different fading characteristics and with a different kind of mote can be easily performed using our testbed, assuming the mote RF band is included in the RF range of the channel emulator.

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