# Practical Implementation and Evaluation of Intelligent Cooperative Ad-Hoc Networks

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**Abstract**

Cooperative- and direct-transmission wireless communication schemes each have their own advantages and disadvantages, dependent on the topography and power limitations of the network. A system that intelligently switches between either mode can fully utilize the advantages of each scheme. By fixing the transmission power level of each node in the network and measuring the data loss for each scheme independently, it can be observed that an intelligent switching system maximizes transmission efficiency. Temporal and spatial locality effects in wireless channels are predicted and tested. Finally, optimal relay positioning and power efficiency are analyzed through experimental results.

## I. Introduction

As wireless communication systems including cellular networks, wireless internet, and sensor networks become more prevalent in critical environments such as combat and law enforcement, a reliable, efficient transmission scheme becomes extremely important. Dependence on a costly centralized infrastructure can reduce efficiency and cause "weak points" that threaten the viability of the entire network. Furthermore, limited power availability can constrain the effective range of data transmission. As a result, many schemes have been proposed for adaptable, cooperative systems that can intelligently organize an optimal data route based on the surrounding environment.

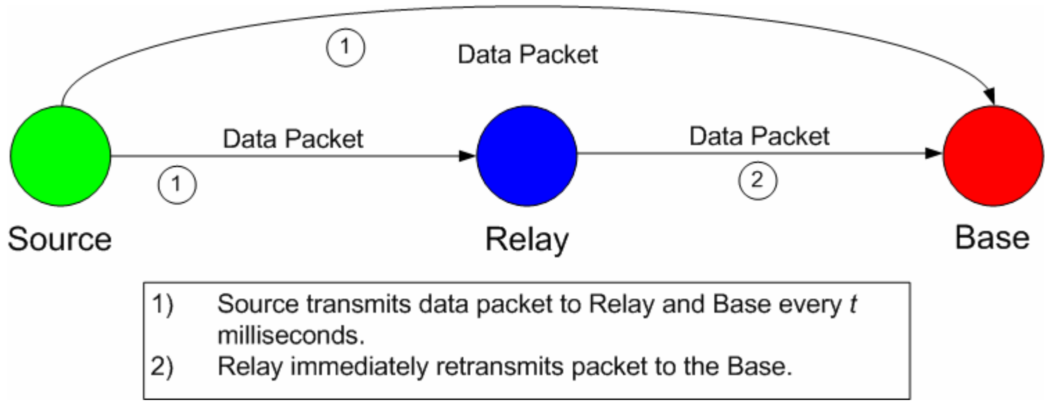



*Figure 1: Basic Cooperative Retransmission Scheme*

A typical scheme involves a source, for example a cellular phone; a base, for example a cellular tower; and any number of relays, such as a dedicated repeater or simply other cellular phones. In this system, the source broadcasts data packets at a fixed rate to the base as well as all of the relays. The naïve approach would be to have the relays continually rebroadcast the packets at the same rate as the source [Figure 1]. Packets can be uniquely identified so that duplicate packets are discarded by the base.

An alternative setup allows for power conservation by only activating the relays when necessary, to compensate for data loss via direct transmission from the source to the base. The base, upon successfully receiving a data packet, signals to the relays. If a signal is not sent to the relays within a predetermined interval, then it is assumed that the base did not successfully receive a data packet. The packet must then be retransmitted by one of the relays to the base [Figure 2]. In large networks, the problem of optimally choosing the relay to retransmit the packet becomes an extremely difficult problem to solve, and is the subject of study for many communication theoreticians. The focus of our experiments however, was the simplest nontrivial case of a single relay placed between the source and the base.

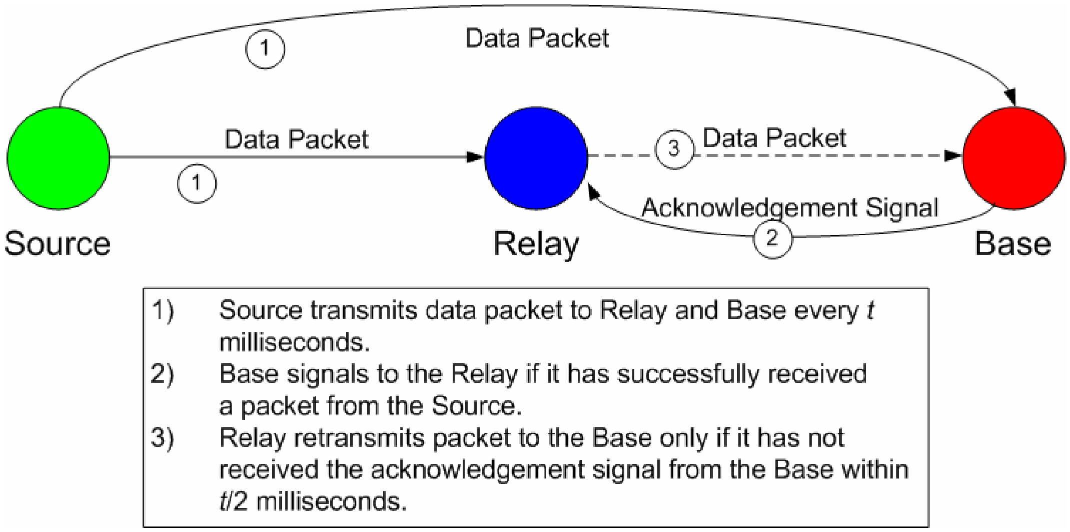



*Figure 2: Intelligent Cooperative Communication Scheme*

In this discourse, we examine several key factors and important parameters to consider when implementing ad-hoc cooperative networking in a practical environment. First, we experimentally confirm that the optimal placement for a single relay between a source and a base is in the exact middle. We analyze the packet loss trends over time to investigate the phenomenon of temporal locality, and the effect of small-scale (~5-10 cm) displacement of the relay on the Quality of Service (QoS). The study is concluded by testing the QoS at various fixed power levels. During testing, the power of the base is maximized, and the transmission powers of the source and relay are kept at equal levels for each power setting.

## II. Implementation

The physical implementation of a three-node network with the intelligent cooperation scheme is somewhat complex, and therefore only a brief description is provided. In order to achieve the desired behavior of the source, base, and relay, we programmed Crossbow MICAZ mote devices in the TinyOS environment. Specific applications for each device were developed in nesC, an event-driven variant of the C programming language.

The source is initially idle until it receives a specific signal from the base that specifies a certain number of unique data packets to be transmitted, containing ordinal integers beginning from zero. The relay and base then continuously listen for the data packets. When a packet is received by the base, it immediately forwards the packet over the serial port to a computer workstation, where it is processed by a Java application. When the relay received a packet from the source, it stores it for a short duration. If the relay does not receive a packet containing an acknowledgement signal from the base within that interval, it retransmits the data packet. If it does receive the acknowledgement signal, it simply discards the packet. The experiment terminates when the source has transmitted its final packet, upon which the Java application tallies the data and produces results such as the error percentage, and conditional probabilities that model the packet loss bursting behavior.

In order to develop a full sense of the real-life behavior of our communication scheme, we conducted experiments in a variety of locations. Indoor locations included the Cole Field House and the Comcast Center, two sporting stadiums at the University of Maryland, College Park. Outdoor locations were also chosen for their unique topographies, such as a parking garage, a grass field, and a dense wooded region. An experiment was also conducted in the office environment, although packet loss in this sort of setup is not sufficient to produce reliable results. Typical experiments involved 25,000 data packets, with motes placed at distances of a few hundred feet.

## III. Optimal Relay Positioning

The intuitive optimal location for the relay, in other words the location for which the relay maximizes QoS and minimizes power consumption, is at the exact middle of a line drawn from the source to the base. To actually show that this is true requires solving a constrained optimization problem. The problem is defined and solved in Sadek, et al [1]. We define the probability of data loss as the probability that the signal-to-noise ratio (SNR) of the received signal is less than some constant threshold. This is determined by the quality of the noise filtering performed by the MICAZ electronics, and the viability of the circular redundancy check (CRC) included in each transmitted packet.

$$P_o = P(SNR(r) \le \gamma)\,. \tag{1}$$

The constrained optimization problem is then given as

$$\begin{gathered} P_{oc}(r_{sd}, r_{sl}, r_{ld}) = \left(1-\exp(-\frac{N_o \gamma r^{\eta}{}_{sd}}{KP_{TC}})\right)\left(1-\exp(-\frac{N_o \gamma (r^{\eta}{}_{sl} + r^{\eta}{}_{sd})}{KP_{TC}})\right), \\ r_{sl}^{*} = \arg\min_{r_{sl}} P_{oc}(r_{sd}, r_{sl}), \forall\, 0 \le r_{sl} \le r_{sd} \end{gathered} \tag{2}$$

where $r_{sd}$, $r_{sl}$, and $r_{ld}$ are the distances from the source to the base, the source to the relay, and the relay to the base, respectively. Note that when all three nodes are placed in a straight line, $r_{sd} = r_{sl} + r_{ld}$. $P_{OC}$ is the outage probability in cooperative transmission, and is defined using parameters for power, noise, and distances. The solution which minimizes $P_{OC}$ by changing the distance between the source and the relay, and thus also the distance from the relay to the base, is given:

$$r_{sl}^{*} = \frac{r_{sd}}{2} \quad for\ \eta > 1\,. \tag{3}$$

To prove this theoretical optimum, we performed a series of tests on the roof of a parking garage, fixing $r_{sd}$ to 220 feet. No cars or other direct obstacles were present, and radio reflections occurred primarily off of white-painted concrete surfaces such as the surrounding wall and the lot dividers. We first placed the relay at the theoretically optimal position, so that $r_{sl} = r_{ld} = 110$ feet. We measured the percentage of packet loss to approximate the outage probability with an experiment of 25,000 packets. We then moved the relay in increments of 10 feet in either direction along the direct path between the source and the base, and repeated the experiment. Results are presented in Figure 3, showing that the theoretical optimum does in fact give the least amount of packet loss. It is important to observe that this only holds at distances that are near the optimum; in other words, we only see degradation of the signal when the relay is moved short distances from the center. At larger distances, the issue of channel fading due to reflective surfaces comes into play. If the source or base is placed in a location that contains many reflective surfaces, such as the corner of the parking lot, placement of the relay close to one or the other can actually provide better reliability than the optimal center location, where fading may be stronger. The theoretical calculations cannot model all practical situations, and therefore is not expected to account for this effect.

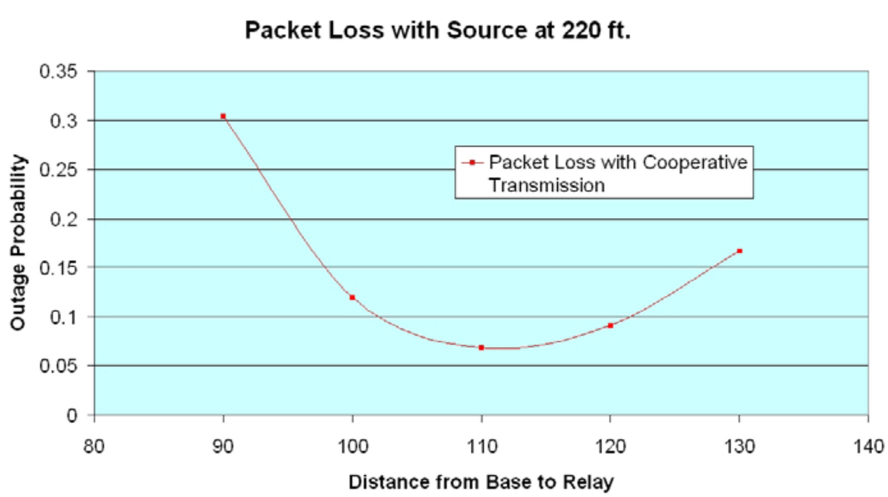



*Figure 3: Results demonstrating that packet loss is minimized at a set power by placing the relay at the center. Only localized displacement of the relay is considered.*

## IV. Temporal Locality

Part of the justification for a cooperative networking scheme assumes that channel errors are durational, and do not change instantaneously. Therefore, the relay can be powered down during periods when the direct channel between the source and base is strong. It is thus necessary to experimentally confirm that channel quality is fairly consistent over short periods of time, and that packet loss occurs in bursts.

For our test, we chose a location in the middle of a heavily wooded area, and placed our source and base 90 feet apart. We then placed the relay at the optimal position of 45 feet from both the source and the base. By fixing the error and recording the transitions from "packet lost" to "packet received", and vice versa, we were able to calculate the conditional probabilities of each type of transition. The values can be modeled by a two-state Markov chain [Figure 4], as proposed by Sadek [2]. By counting transitions from failure to success, and dividing by the total number of failures, we were able to calculate $P_{1|0}$. We used similar calculations to obtain values for $P_{0|0}$, $P_{0|1}$, and $P_{1|1}$:

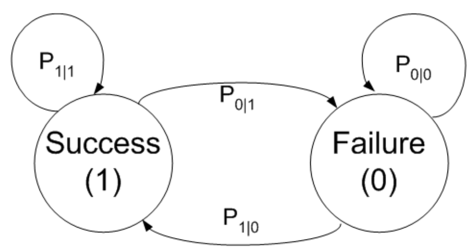
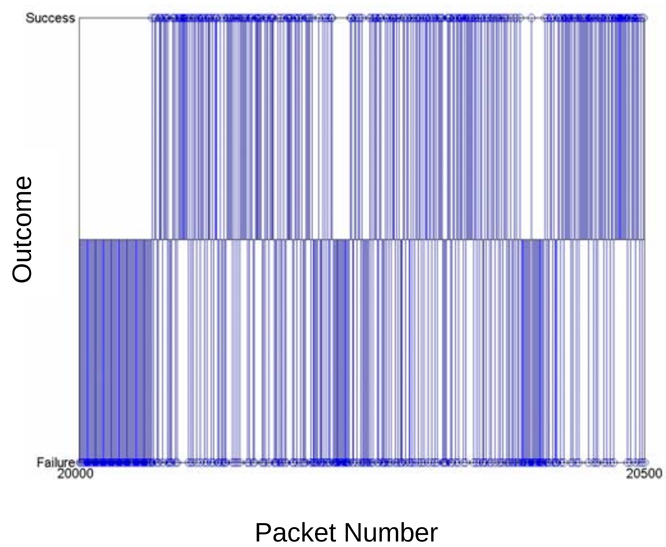



*Figure 4: Two-state Markov chain modeling temporal locality of packet loss*

$$\begin{aligned} P_{0|0} &= 0.5015,\ P_{0|1} = 0.4207 \\ P_{1|0} &= 0.4985,\ P_{1|1} = 0.5793 \end{aligned} \tag{4}$$

These values diverge considerably from those in Sadek [2], and do not demonstrate consistent bursting. This can be accounted for by the high amount of packet loss received during this experiment, which approached 40%. Thus, the temporal locality effect observed in [2] cannot be considered relevant for channels which are intrinsically unstable throughout operation. Even so, some bursting was observed, and an interval of packet error is shown in Figure 5. Lines in the positive direction indicate a successful packet transmission, while lines in the negative direction indicate a failure. Further experimentation can be expected to show that as packet loss approaches 0%, values of $P_{0|0}$ and $P_{1|1}$ will approach 1.

*Figure 5: Packet Loss over Time*




**V. Spatial Locality**

In any practical application of ad-hoc cooperative networking, it is important to consider how small variations in the location of the relay outside of the direct path between the source and base can affect packet loss. Therefore, the issue of the spatial locality of channel stability becomes relevant. It has already been demonstrated that variation by large distances, on the order of tens of feet, can greatly change the quality of service. However, even small-scale movements of only a few centimeters can cause a stable channel to become unreliable, or even completely unusable. To test this effect, we set up our source and base in the basement of a parking garage, populated by a large number of reflective vehicles. We performed several experiments, all in the same neighborhood of a few centimeters, and noticed drastic changes in packet error rate. This can be attributed to the effects of shadowing in environments where wave reflection is critical. The signal received by the base in a situation with many reflectors can be modeled as

$$y(t) = \sum_{i=1}^{N} a_i(t) x(t - \tau_i) + \xi(t) , \tag{5}$$

where $a_i(t)$ represents the gain of a signal reflected at a specific angle, $x(t-\tau_i)$ represents the transmitted signal with an associated path delay, and $\xi(t)$ is additive channel noise [3]. Assuming that channel delay is negligible over short distances, we can simply the equation as

$$y(t) \approx x(t) \sum_{i=1}^{N} a_i(t) + \xi(t) , \tag{6}$$

and therefore observe that the total gain of the received signal depends entirely on the exact angles at which radio waves are reflected towards the relay from the source.

## VI. Power Efficiency

In harsh climates, a steady supply of power to each node can be infeasible, and therefore nodes must rely on battery power sources. Since conserving this limited power to allow for long-term operation may involve transmitting at lower power settings, we tested the behavior of both direct- and cooperative- mode networks at various power settings. We placed the source and base approximately 250 feet apart in the bleachers of the Comcast Center at the University of Maryland, College Park. A relay was placed at 125 feet in the exact middle of the path between the source and base [Figure 6].

We then performed a series of experiments, both with and without activating the relay, at power levels of -20 dBm, -10 dBm, 0 dBm, and 5 dBm. Each experiment consisted of sending 25,000 data packets and observing the packet loss. The rate of data loss was obviously higher for direct transmission than for cooperative transmission, and for lower transmission powers than higher settings. Beyond these intuitive observations, however, we noticed that the rate of change of packet loss from lower to higher transmission power is different for the cooperative scheme over direct transmission. On the logarithmic scale, we notice that as transmission power increases, packet loss from the direct scheme decreases with a slope of -1, referred to as "diversity 1" [4] . However with the cooperative scheme, packet loss decreases with a slope of -2, or "diversity 2 [Figure 7]."


*Figure 6: Cooperative networking at the Comcast Center, University of Maryland, College Park*

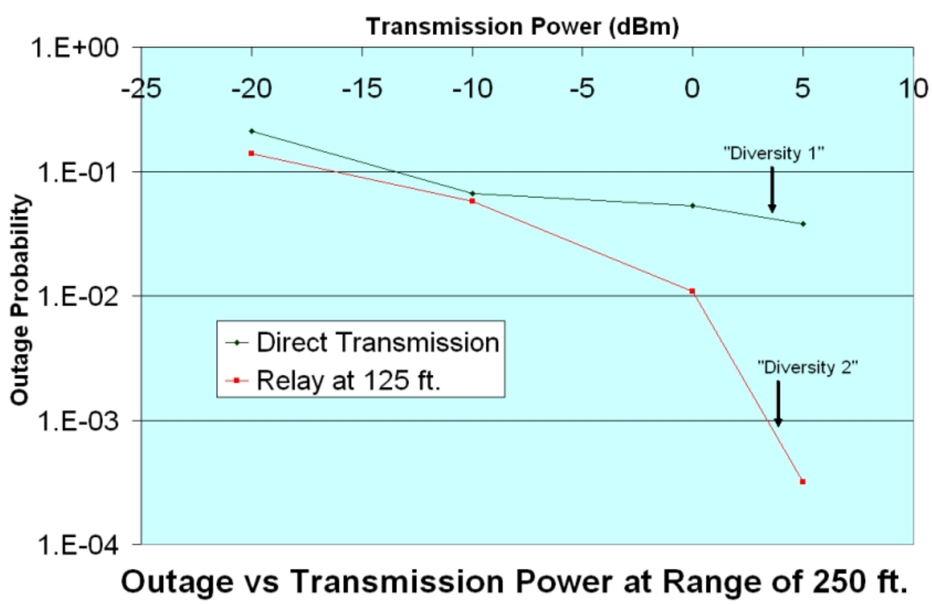



*Figure 7: Power variation in both direct- and cooperative-mode networks*

## VII. Conclusions

Our goals were to investigate the practical aspects of an intelligent, cooperative wireless network. The proper placement of the relay, although theoretically in the exact center of the path between source and base, can take advantage of reflective surfaces close to either the source or base to increase performance beyond the theoretical optimum. Temporal locality effects are largely dependent on the overall percentage of data error, and bursting increases as overall packet loss diminishes. Power results show that variation of power with a direct transmission scheme occurs with diversity 1, whereas with a cooperative scheme it changes with diversity 2. Future testing will focus on observing the change in bursting behavior with respect to overall packet loss. A more diverse network with multiple relays and an optimal selection algorithm can be implemented to further improve efficiency.

## References

[1] *A. K. Sadek , Z. Han, and K. J. R. Liu, ``An efficient cooperation protocol to extend coverage area in cellular networks", to appear in IEEE Wireless Communications and Networking Conference (WCNC), Las Vegas, NV , 2006.*

[2] *A. K. Sadek, W. Yu, and K.J. Ray Liu, "When Does Cooperation Have Better Performance in Sensor Networks," to appear in SECON, 2006.*

[3] J.G. Proakis, "Digital Communications", McGraw Hill, 4th ed, 2000.

[4] A. K. Sadek, W. Su, and K. J. R. Liu, ``Multi-node cooperative communications in wireless networks", accepted in *IEEE Trans. on Signal Processing*.