Implementation and Evaluation of a Cooperative MAC Protocol for Smart Data Acquisition

Saad Amin, Sohaib Ashraf, Mohammad Shahzeb Faisal, Muhammad Shahmeer Omar, Syed Ahsan Raza Naqvi, Syed Ali Hassan and Muhammad Usman Ilyas
School of Electrical Engineering & Computer Science (SEECS)
National University of Sciences & Technology (NUST), Islamabad, Pakistan 44000
Email: {12beesamin, 12beesashraf, 12beemfaisal, 11beemomar, 11beesraza, ali.hassan, usman.ilyas}@seecs.edu.pk

***Abstract*—Smart meters are being deployed worldwide on a trial basis and are expected to enable remote reading and demand response among other advanced functions, by establishing a two-way communication network. However, it remains to be determined as to how these meters would transmit their data to an aggregation point. Our paper employs a medium access control (MAC) protocol for a cooperative network to address this problem. The said protocol has been developed on the GNU Radio platform, while the test-bed consists of universal software radio peripherals (USRPs) that serve as network nodes. The performance of the system has then been evaluated and compared with that of fully cooperative and single-input-single-output (SISO) networks. It has been shown that the proposed system outperforms the SISO network in terms packet error rates and throughput.**

***Index Terms*—Cooperative communication, GNU Radio, MAC, SDR, range, equal gain combining, USRP, SISO, multi-hop, packet error rate, throughput.**

I. Introduction

The prime intention behind smart cities is to promote a healthy economy and sustainable growth, while ensuring a control over resources and the optimization of existing infrastructure. One of the resources requiring ‘optimization’ is the electric grid. A *smart* grid is a self-healing network, that stablishes a two-way digital communication link between devices associated with the grid. Each device on the network can be given sensors to gather data, to be forwarded to the utility’s network operations center. One such device is the smart meter.

The smart metering system allows continuous reading and recording of various quantities, such as power quality, in addition to the early-stage failure detection. This system is important for various purposes, including interval data, time-based demand data, time-based energy data (usage and production), service interruption, service restoration, quality of service monitoring, distribution network analysis, distribution planning, demand reduction and customer billing. Needless to say, communication subsystem is a critical component of smart grid systems [1].

In literature, the most commonly used communication technologies in this respect are mobile phone networks using global system for mobile communications / general packet radio service / third generation / fourth generation technologies (GSM / GPRS / 3G / 4G), satellite communications, and licensed or unlicensed radio networks and power line communication (PLC) [2]. This paper considers a smart metering system, in which individual nodes cooperate to establish radio links for this purpose.

This paper posits a smart metering system that uses cooperative communication to relay data, in a multi-hop fashion, to distant aggregation points. Cooperative communication is one of the fastest growing areas of research and is considered to be a key instrument for efficient spectrum use. The motivation behind user cooperation is resource sharing between multiple nodes in a given network. This sharing of power and computation with neighboring nodes can help conserve network resources. Moreover, this technique helps overcome multipath fading effects by employing diversity. The consequent signal-to-noise ratio (SNR) advantage from cooperative transmission (CT) can be used to extend the coverage range of the transmissions [3] and increase the energy efficiency of the network [4].

Improved data rates and transmission range from single-input-single-output (SISO) networks either require wider bandwidth or greater transmission power, neither of which proves to be economical especially in energy constrained applications such as wireless sensor networks (WSNs). It goes without saying that such limitations reduce the energy efficiency of these networks. CT, in contrast, uses the concept of diversity to counter the effects of fading in the transmitted signals.

Cooperative medium access control (MAC) protocols in past works utilize multi-rate capabilities of IEEE 802.11 to attain higher throughput and shorter delay. This is achieved by transmitting a packet via a relay node by means of a two-hop link rather than a direct one-hop link. Recent works have attempted to implement cooperative MAC protocols in cognitive radio networks [5] as well as in advanced heterogeneous vehicular networks [6]. In addition, [7] proposes a cooperative MAC protocol that includes a retransmission scheme to reduce the retransmission time; that is, once data transmission fails, only the relays that receive the data frame assist in retransmission, instead of repeating the entire transmission cycle.

Our paper implements a MAC protocol in a cooperative network and investigates the SNR advantage of CT, along with the

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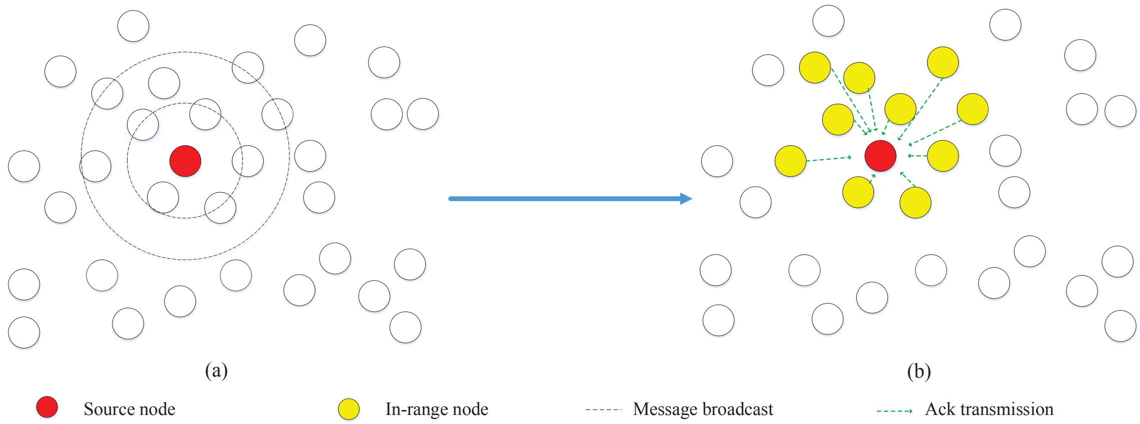

Fig. 1: (a): The source broadcasts its message, (b): The nodes that receive this message, transmit ACKs back to the source.

effects of cooperation on range and throughput. The protocol used is a part of the 'Poor Man's SIMO system' (PMSS), proposed in [8], which combines cooperative communication and diversity combination, to reduce packet losses over links in WSNs. The paper implements receiver side cooperation using exchange of messages. This message exchange follows a protocol termed 'the PMSS protocol'. The setup has been shown to achieve one order of magnitude reduction in packet losses.

In the subsequent sections, the authors will present a system model, for which the MAC protocol has been implemented, apart from outlining the salient features of the said protocol. They will then go on to compare the performance of SISO and the cooperative network using the aforementioned MAC protocol. The metrics for this comparison will be, among others, packet error rates (PER) and throughput which will be investigated for varying hop distances and transmission power. In this paper, *throughput* has been defined as the number of successfully decoded payload bits per second.

II. System Model and Implementation

The proposed MAC protocol consists of two stages, which are,

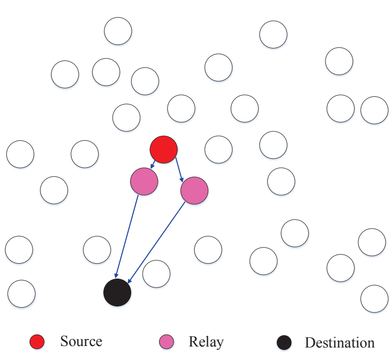

Fig. 2: Transmission to a distant node.

- discovery or *boot-up* phase, and
- cooperation phase.

The description of the phases is as given below.

A. Stage 1: Boot-up Phase

This phase is depicted in Fig. 1. When a 'live' node broadcasts a pilot message, the neighboring nodes receive and decode this message, given that the transmission meets a certain signal-to-noise ratio criterion, as shown in Fig. 1(a). The receiving nodes store the source node identity (say, A), and send back acknowledgment (ACK) signals to confirm the reception (shown in Fig. 1(b)). The source receives these signals and populates its records (*cooperation* table) with the node identities of the neighbors, such as B, C, D and so on. Our system follows a polling based technique, whereby the broadcast message from the live node is transmitted periodically.

B. Stage 2: Cooperation Phase

When the source needs to transmit its message to a node that is farther off and is outside the single-hop receiving range, denoted by the outer circle in Fig. 1(a), it broadcasts the intended message to the in-range relays. Upon receiving the broadcast message, the relays use the cyclic redundancy check (CRC) to determine if they can forward it to the destination. A relay only forwards packets to the destination if its received packet has successfully passed the CRC check. If the relays successfully decode the original message, they hold it for a certain period of time. If the destination transmits an ACK during this time, the relays discard the current packet and become idle. However, if the relays receive a cooperation request or there is no response from the receiver they forward the packet to the destination. This results in multiple copies of the signal being received at the destination, which are subsequently combined to obtain a an estimated version of the transmitted message originating from the source. The transmission of messages to a distant node in the given scenario is shown in Fig. 2.

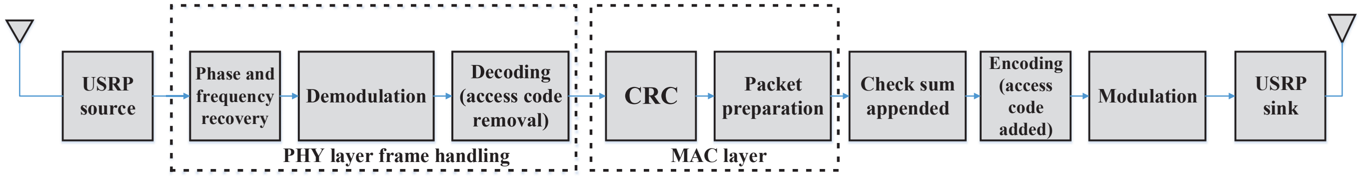

Fig. 3: Transceiver design.

Our paper employs a rudimentary carrier sense protocol for collision avoidance. Each node in the network senses the channel for transmissions and transmits its own data only when it finds the channel free. In case of collisions, contending nodes back off for a random time period.

C. Combining Technique

The combining technique used herein is similar to the post-detection combining technique mentioned by Ilyas et al. [8]. This combination technique is a variation of pre-detection equal gain combining (EGC). The receiver compares the bits for an odd number of input streams and uses an equally weighted voting algorithm to determine the bit value. For example, if the first bits of three relayed packets are 1, 1 and 0, the combined packet's first bit will be 1.

It should be noted that all relays follow the decode and forward (DF) technique. Hence, if the CRC fails at a certain relay, it will not forward the message. In our current system, if only two incorrect copies of a packet are available the combination algorithm fails and the packet is considered to be lost.

Fig. 3 outlines the block diagram for the proposed system. As a side note, the USRP sink and source are the radio frequency (RF) front ends for transmission and reception respectively. The aforementioned post-detection combining is depicted in Fig. 4.

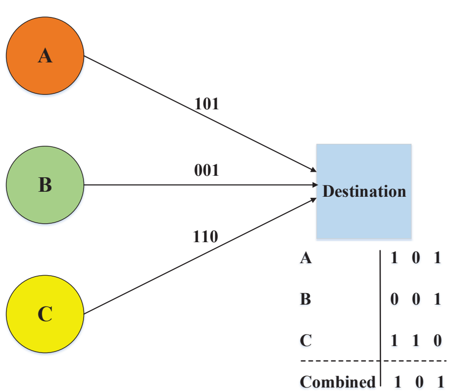

Fig. 4: Post-detection combining.

TABLE I: System Parameters

Parameter	Value
Modulation	GMSK
Source transmit frequency	2.6 GHz
Relay transmit frequency	2.8 GHz
Bit rate	250 kbps
Samples per symbol	4

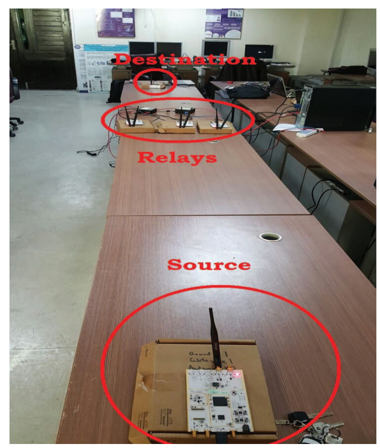

Fig. 5: The experimental setup.

III. Performance Evaluation

A. Experimental Setup

The arrangement for the tests is shown in Fig. 5. The proposed topology has been tested on USRP B200 nodes, which have an RF coverage from 700 MHz to 6 GHz in a typical indoor office environment. The setup uses VERT2450 antennas with 3 dBi gains. The cooperative network consists of 3 relays, each of which has been connected to a separate personal computer (PC), executing GNU Radio Companion (GRC) flow-graphs independently. For the purpose of this study we have changed the source and relay frequencies in order to force the relays to always participate in transmissions.

The first phase of testing involved increasing the source-destination (S-D) distance from 2m to 10m in fixed steps for both SISO and cooperative networks. The transmit power of each node was then progressively increased and the PER at the destination node was noted. As previously stated, the source-relay and relay-destination distances were kept equal.

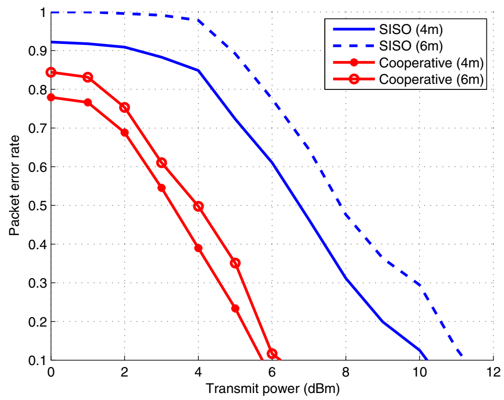

Fig. 6: Comparison between SISO transmissions and CT for S-D distances of 4m and 6m, in terms of PER for varying transmit power.

The number of correctly received packets was also recorded in order to determine system throughput.

The second phase of testing aimed to determine the number of times cooperation was necessary in order to determine energy consumption of our algorithm compared to fully cooperative and SISO networks.

The primary objective of these experiments was to determine whether cooperative communication provides improved performance, in terms of PER, throughput and energy for a given source-destination distance compared to a SISO topology in a rich scattering environment.

B. Performance Analysis

We will now begin the analysis of the system in terms of the metrics that have been previously mentioned. Fig. 6 plots the PER for SISO and cooperative links for increasing values of node transmit power. PER may be defined as the ratio of the number of packets that pass the CRC to the total number of packets originally transmitted. The first observation to note in this figure is that both systems show a progressive decrease in PER for an increase in transmit power, which is an expected outcome. Furthermore, cooperative networks at both distances consistently outperform the SISO setup. The graphs for CT exhibit PER values that are similar to those seen for

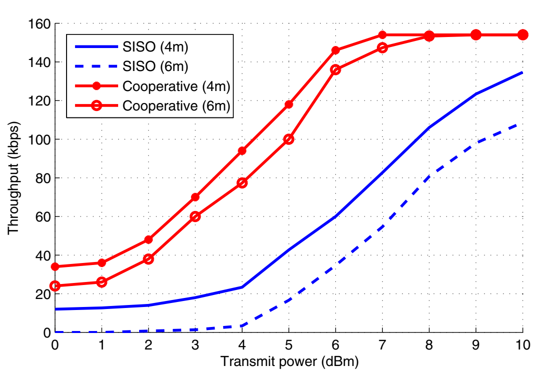

Fig. 7: Throughput versus transmit power for SISO and cooperative links.

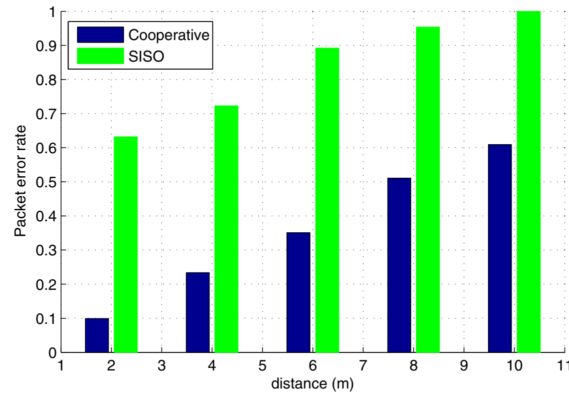

Fig. 8: PER for the two network topologies versus S-D distance at transmit power = 5dBm.

the SISO system. However, the PER for CT falls at a sharper rate for higher values of node transmit power, as compared to its single relay counterpart. As an indicator, at a transmit power of 2dBm, the PER for the SISO network with S-D distance 6m is approximately 30% greater than that for CT at the same distance. In contrast, this figure rises to nearly 150% at 5dBm. This trend represents that at high transmit powers, diversity gain starts to play its role and the PER of the system improves as compared to the conventional SISO link.

Fig. 7 is a comparison of the observed throughput for the two network topologies at S-D distances of 4m and 6m. As bit decoding depends on the SNR, all four graphs demonstrate an increase in throughput for increasing transmit powers. It may also be noted that the graphs for CT are closer to each other as compared to those for SISO. In fact, beyond 8dBm the graphs for CT maintain the same throughput of nearly 155kbps. Owing to a lack of cooperation and a greater hop distance, the SISO network for an end-to-end distance of 6m performs the worst of the 4 setups. As an example, the throughput for this case is only 5kbps at 4dBm, while at the same power, CT at S-D distance of 4m yields a throughput of 95kbps, exemplifying the inherent advantage of network cooperation.

A bar graph between the PER and increasing S-D distance for cooperative and SISO networks is shown in Fig. 8. As expected, increasing the end-to-end distance results in an increase in PER for both topologies, indicating a steadily deteriorating SNR in both cases. The error rates for SISO networks outstrip those for cooperative networks at all tested distances. The advantage afforded by cooperation may be seen from the fact that even at a S-D distance of 10m, the PER for the cooperative network is 60% of that of the SISO setup.

Fig. 9 shows the variation in throughput for increasing S-D distances at different transmit powers for SISO and cooperative links. The definition of throughput has already been defined in previous sections. If the number of correctly decoded packets is K, the number of bits per packet is N and the elapsed time is τ, then the throughput, η, may be written as,

$$\eta = \frac{KN}{\tau}. \quad (1)$$

In the plot, all cases demonstrate a decrease in throughput, although at different rates. The worst performance is shown by the SISO network at lower transmit power, whose transmissions suffer due to degrading SNR and a lack of correction through combining at the destination. Unsurprisingly, there is nearly 0kbps throughput for this situation at a S-D distance of 10m. At 10dBm, however, the SISO network's throughput improves to the extent that uptil a distance of 8.5m, it is superior to that of a cooperative network using a transmit power of 5dBm. Another observation is that the gap between the graphs for CT increases with increase in distance. In fact, at a distance of 10m, the throughput of the cooperative link at 10dBm is nearly twice that at 5dBm, further emphasizing the fact that the diversity gain becomes effective at higher node transmit powers.

As a final inspection, we observe the total network power consumption incurred by our algorithm. This may be calculated by,

$$\text{Power consumed} = P_{coop}\epsilon_{coop} + P_{siso}\epsilon_{siso}, \quad (2)$$

where P_{coop} is the probability of the occurrence of cooperative transmissions, shown in Fig. 10, ϵ_{coop} is the summation of all the node powers in a cooperative setup, P_{siso} is the probability of SISO transmissions being decoded correctly and ϵ_{siso} is the summation of all the node powers in a SISO link. Fig. 10 consists of two sub-plots. The plot on the left shows the dependence of the number of cooperative transmissions required against increasing node power, for given distances d. It clearly outlines that, at higher node powers, the network does not require cooperation among its nodes, as the high SNR allows for better signal fidelity in a SISO link. The other plot depicts the efficacy of our proposed algorithm, in terms of total network power, compared to fully cooperative and SISO networks. The abscissa is the individual node power. It may be noted that at lower SNRs, the total power in the network that uses our algorithm converges with that of the full cooperation case. However, its power requirement starts to fall at higher SNRs as SISO packet delivery becomes more efficient resulting in fewer cooperative transmissions, as seen earlier. Eventually, the network power of the proposed algorithm converges with that of a SISO network.

IV. Conclusion

This paper investigated the efficacy of using MAC-based transmissions in cooperative systems as compared to SISO networks. The cooperative network was seen to have a superior performance in terms of PER and throughput. In addition, the cooperative MAC algorithm used in this paper has been shown to strike a balance between the SNR advantage of CT and network energy efficiency. The existing work may be extended to include a network with more than two hops and the use of maximal ratio combining (MRC) instead of EGC. The scope of investigation may be widened to include overall system latency as well.

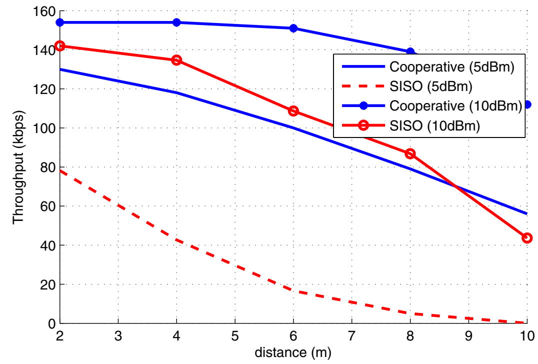

Fig. 9: Throughput versus S-D distance for SISO transmissions and CT.

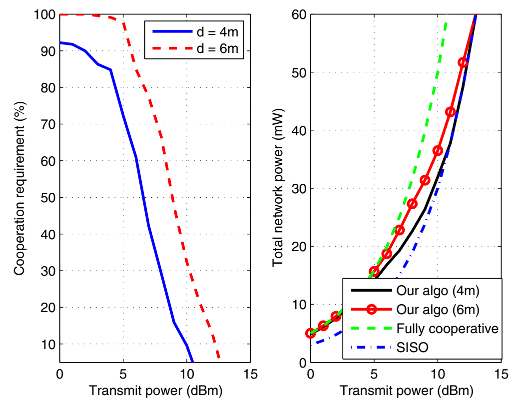

Fig. 10: Left: Percentage of cooperative transmissions against node transmit power. Right: Comparison of network energy efficiency for fully cooperative and SISO networks, with our proposed algorithm.

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