Analysis of Cooperative Transmissions as an Enabling Technology for Smart Grid Data Aggregation: An Experimental Perspective

Muhammad Shahmeer Omar, Syed Ahsan Raza Naqvi, Shahroze Humayun Kabir and Syed Ali Hassan
School of Electrical Engineering & Computer Science (SEECS)
National University of Sciences & Technology (NUST), Islamabad, Pakistan 44000
Email: {11beemomar, 11beesraza, 10beeskabir, ali.hassan}@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. A possible technique for transmitting data to the aggregation point is the use of cooperative communication in the neighborhood area network. This paper presents an experimental comparison between cooperative networks located in disparate environments, in terms of range extension and energy consumption of the overall network. Transmissions have been achieved using universal software radio peripheral (USRP) platforms. The cooperative transmission (CT) takes place over a multiple hop network, and uses the binary phase shift keying (BPSK) scheme.**

***Index Terms*—Cooperative communication, GNU Radio, timing and synchronization, SDR, range, signal recombination, USRP, SISO**

I. Introduction

The fifth generation (5G) wireless systems have recently gained enormous attention because of many advantages they promise to offer. Whereas 5G is an amalgamation of a variety of techniques ranging from algorithmic designs to system level designs, a major challenge is to connect billions of devices around the globe. Among the many applications of internet of things (IoT), smart cities has recently captured the imagination of the research community. In literature, the concept of 'smartness' has been applied to various scenarios–from buildings [1] to the electric grid. However, this paper will focus on the advancements proposed in the electric grid using modern communication theory.

A *smart* grid is a self-healing network, which involves adding two-way digital communication technology to devices associated with the grid. With the precise framework of the smart grid currently under debate among the academia, a detailed information and communication technologies (ICT) architecture for smart grids has been presented in [2]. In addition, each device on the network can be given sensors to gather data, to be forwarded to the utility's network operations center [3]. One such device is the smart meter.

This paper posits a smart metering system that uses cooperative communication to relay data, in a multi-hop fashion, to distant aggregation points. The motivation behind user cooperation is resource sharing between multiple nodes in a given network. 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 range of the transmissions and reduce the radiated power from individual transmitters.

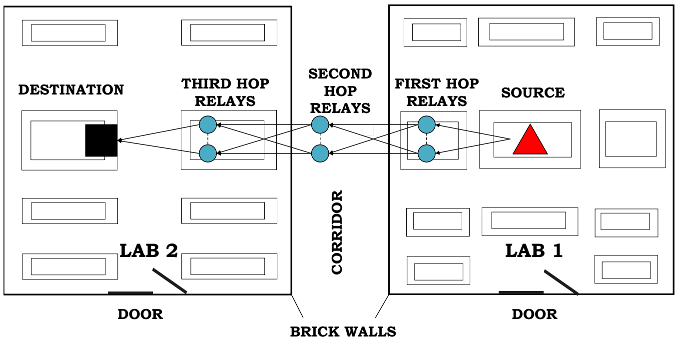
Despite the advantages of increased diversity and array gains, multi-relay cooperative networks demand synchronization in the reception and transmission of signals at the intermediate stage. It has been found that if timing errors are large enough, the setup would lose its efficacy in terms of diversity gain [4], resulting in performance degradation [5]. Similarly, the propagation environment plays its role, i.e., the line of sight (LoS) propagation differs from a general non line-of-sight (NLoS) propagation. The former is generally the case in outdoor environments whereas the latter is characterized for indoor propagations which are required when the networking area reduces to a home area network (HAN) [6] where smart devices in a home communicate with one another.

The authors present herein an empirical proof of the range extension and increased energy efficiency and network lifetime using cooperative networks. Communication using single-input single-output (SISO) topology acts as a control experiment, against which the performance of the multi-hop networks will be compared. Relay transmissions for cooperative networks have been achieved using a frequency division multiple access (FDMA) scheme. At the destination node for CT, the replicas of the signals transmitted by multiple relays are then combined using equal gain combining (EGC).

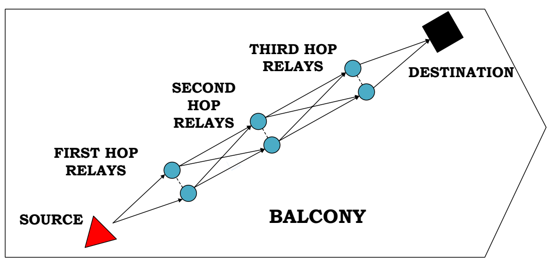
II. The System Model and Implementation

Fig. 1 shows the primary topologies used for the performance tests, which are explained in detail in the forthcoming sections. Basically, every tested experiment has a source and a destination node, in addition to intermediate relays between them. The relays utilize the decode-and-forward (DF) scheme, with BPSK modulation.

The setup determines the bit error rates at the destination node for a given range of transmit powers. The tested networks include those with one, two and three relays at the first, second, third and fourth hops. Each arrangement has been tested at varying distances between the source and the destination. It has been ensured that the length of each individual hop is the same.



(a) Indoor Topology



(b) Outdoor Topology

Fig. 1: Topologies tested

Fig. 2 shows the sequence of the signal processing steps taking place in the proposed transmitter and relay designs. The network with a single relay per hop represents a multi-hop SISO topology. By extension, multiple relays at the intermediate level form a cooperative network. The subsequent sub-sections provide further insight into the working of the network.

A. Transmitter Operations

The data source feeds integer, character or float raw data into the system. The output from the signal source then enters the encoder, where it is converted into a packet of a specified payload length along with an access code. Our design uses a packet payload of 736 bits, with 64 bits allocated for the access code. Access codes are used to detect the start of packets. Following modulation, the signal reaches the USRP sink, the RF front end for transmitting radio signals.

B. Relay Operations

Since the relay node uses the DF scheme, it both receives and transmits signals. Therefore, the portion of the relay block diagram in Fig. 2 up till the decoder may be termed a receiver.

The receiver operates at a higher sampling rate allowing it to 'listen' for signals over a wider bandwidth. Moreover, the receiver is designed to receive BPSK modulated signals. The USRP source serves as the RF front end for receiving signals. It digitizes signals and transmits them to the PC via the universal serial bus (USB) for processing. The frequency translating filter shifts each signal to the base-band, applies a low pass filter and decimates each stream such that the sampling rate for each stream matches with the transmission sampling rates.

The signal then proceeds to the frequency lock loop (FLL), where any carrier frequency offsets are eliminated. The timing recovery stage performs three operations. It ensures that symbols are sampled at the appropriate sampling points through a matched filtering operation using a root raised cosine (RRC) filter implemented in software. Additionally, it down samples the complex data stream from 4 samples per symbol to 1 sample per symbol. Finally, the channel phase distortions are removed by the Costas loop.

The signal replicas from each stream are then combined to achieve the advantages of frequency diversity. The network uses equal gain combining (EGC) for signal recombination.

C. Timing and Synchronization

Cooperative networks, such as those used during this research work, involve a single source and a destination node. Unlike SISO networks, however, the intermediate stage includes multiple radios, each receiving a signal from a different spatial path. Owing to the delays associated with PC scheduling and the subsequent data transfer from PC to USRP, however, it is improbable that the relays begin transmission at the same time. This loss in synchronization, in turn, results in a loss of diversity at the receiving nodes.

The synchronization scheme utilizes two different stream tags, each representing some unique information. These include

- rx–time: Generated once by the USRP Hardware Driver (UHD) block upon start of streaming.
- tx–time: The time-stamp that is compared with internal UHD clock for transmission.

The incoming messages are tagged once the signal reception begins (the *rx–time* tag). The resulting quantity has two components, indicating its integer and the fractional parts. A customized GNU Radio block reads this tag, extracts the timestamp and uses its value as a starting point for tagging in subsequent transmissions. The aforementioned block takes a single parameter, the delay, which should be greater than the random delays at each node.

The synchronization process may be divided into two stages. The samples are first tagged with timestamps, given by

$$\tau_{tx} = \frac{n}{R_{tx}} + d + \tau_{rx}, \tag{1}$$

where τ_{tx} is the value of the tx time tag, n is the sample offset, R_{tx} is the transmitter sampling rate, d is a numerical value expected to be greater than the maximum delay of the PC and τ_{rx} is the value of the rx–time tag. This tagging stage is performed by the PC.

Next, these samples proceed to the USRP hardware, where they are stored in its buffer. Here, they wait for the local timer to reach the value specified by their corresponding timestamps, following which the transmission begins. This

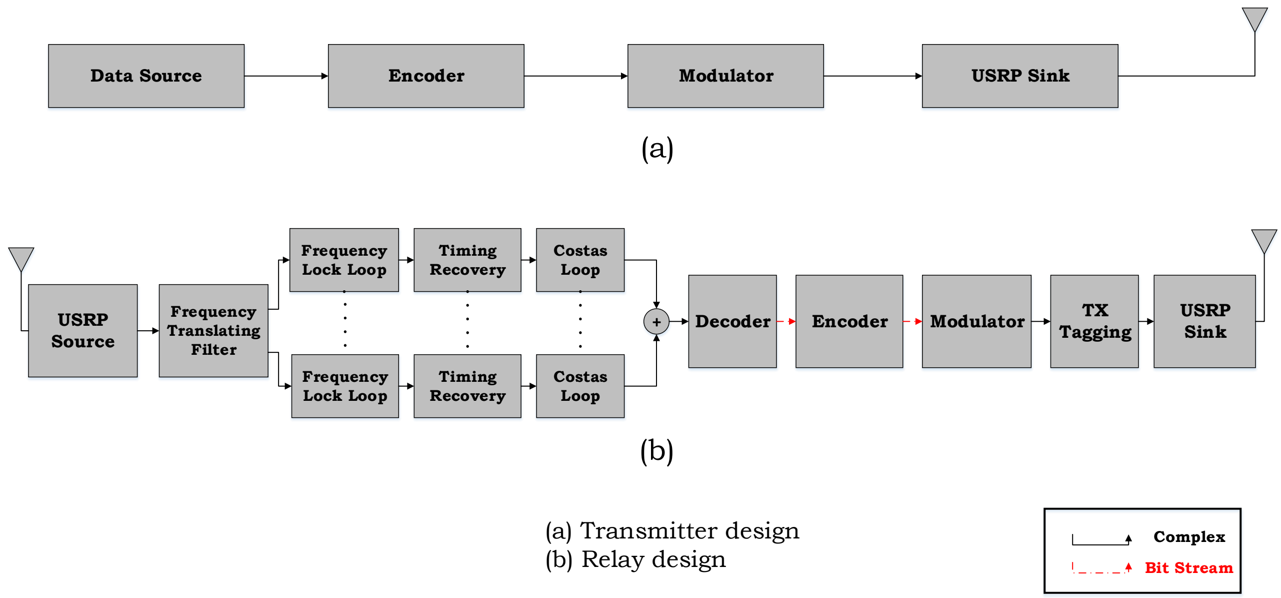


Fig. 2: Transceiver Design

TABLE I: System Parameters

Parameter	Description
Source frequency	2.6 GHz
1^{st} hop relay frequencies	2.8992-2.9008 GHz
2^{nd} hop relay frequencies	3.1992-3.2008 GHz
3^{rd} hop relay frequencies	2.9992-3.0008 GHz
Bit rate	50 kbps
Samples per symbol	4

scheme is implemented for all relay nodes and the delay is adjusted such that the transmitting node overcomes the random delays introduced by the PC, resulting in time-aligned transmissions.

It is worth noting, however, that in our synchronization algorithm we disregard any portion of the incoming signal that occurs before the start of packet marked by the access code. This extraneous segment at the start of reception is therefore 'sliced' off. In a 2-hop network, the entire procedure is performed at the destination, as it is the only node in the network that receives multiple streams. On the other hand, the relays in a multi-hop network that remove the start of a stream must compensate for this when calculating the transmit time. In order to overcome this problem, the system's relays first count the number of samples skipped in reception, and then add this number to n in (1). This maintains the synchronization.

III. Performance Evaluation

A. Experimental Setup

The proposed topology has been tested on USRP B200 and N200 nodes, which have an RF coverage from 700 MHz to 6 GHz. The setup uses VERT2450 antennas with 3 dBi gains. Each reading has been obtained after 3 minutes of continuous source transmission. This duration results in the reception of approximately 9 million bits at the destination. The relay nodes were connected to separate PCs, each of which were executing GNU Radio Companion (GRC) flow-graphs independently.

The indoor NLoS experiments have been laid out in the following manner,

- the source and the first hop relays have been placed in Lab 1, which offers a typical indoor office environment,
- the second hop relays have been placed in the adjoining corridor, where the brick wall imposes an NLoS channel and introduces wall penetration losses,
- the third hop relays and the destination are located in the nearby Lab 2, again with an NLoS channel.

Furthermore, the outdoor LoS experiments have been conducted in a similar configuration on the first floor balcony of the campus faculty block. Throughout this paper, *NLoS channel* or *environment* will be used to refer to indoor tests, whereas *LoS channel* or *environment* will be used to refer to outdoor experiments.

B. Range Extension Experiments

The first phase of testing involved increasing the source-destination (S-D) distance from 10m to 14m, for a four hop cooperative network, in fixed steps for a given number of relays. Particular care was taken to ensure that the total transmit power at each hop and the net power transmission for the entire network were constant. This measure was aimed to keep all variables, except hop distance, constant thus allowing a fair assessment of the coverage range for multi-hop SISO and multi-hop cooperative networks. The relative coverage ranges

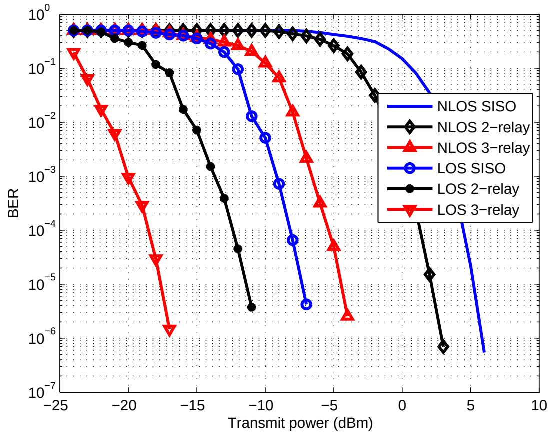


Fig. 3: Comparison of BERs between multi-hop SISO and CT topologies at a fixed coverage distance of 12m.

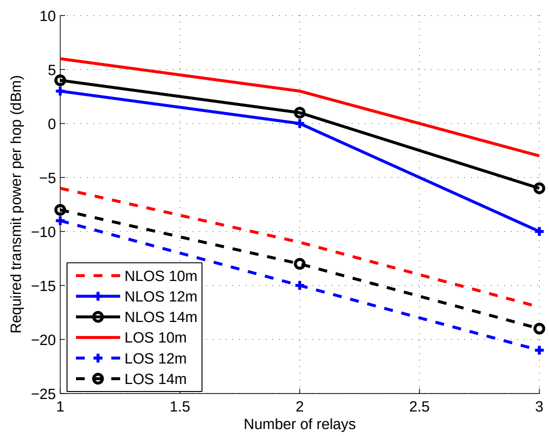


Fig. 4: Range extension experiment to determine the hop power required to maintain a BER of 10^{-4} at the destination.

for various network topologies were deduced by the transmit powers required to achieve a certain quality-of-service (QoS) at a given S-D distance.

C. Performance Analysis

Fig. 3 demonstrates the SNR advantage of transmissions in a LoS environment. For instance, SISO transmissions in this channel show approximately a 12dB advantage over transmissions in the NLoS environment at high transmit powers. We can also observe an increase in diversity order in both environments as we increase the number of relays, per hop.

Fig. 4 shows a graph of the transmit powers required to maintain a BER of 10^{-4} at the destination versus the number of relays employed at each hop, for different distances and in disparate environments, namely LoS and NLoS channels. The first thing to note from the graph is the difference in powers required for each channel type. The LoS channel requires far less power for equivalent number of relays and distances than NLoS, e.g. a SISO multi-hop network with coverage distance of 14m requires -6dBm power per hop in a LoS environment as compared to the 6dBm requirement in NLoS environment for achieving the same BER. Moreover, it can be seen that the power requirement, for different number of relays, falls off more rapidly in the NLoS channel when moving from 2 to 3 relays per hop at the coverage distance of 10m as compared to coverage distances of 12m and 14m, respectively. This difference can be attributed to the penetration losses that occur in the NLoS channel. In a LoS channel, diversity is achieved sooner, hence a linear trend is seen in the graphs of transmit power vs. number of relays per cluster. It can be noted from the plot that a 3-relay network in an NLOS channel at a coverage distance of 12m requires almost the same transmit power per hop as a SISO network in a LoS channel at a coverage distance of 14m. In this experiment the total hop power is kept constant. This is because the individual transmit powers of each relay in an NLoS setup is -11dBm whereas it is -6dBm in a SISO network. This increase in lifetime, however, comes at the price of decreased coverage distance (12m) in the NLoS channel as compared to that in the LoS channel (14m).

IV. Conclusion

This paper demonstrated, experimentally, the trade-offs between the range, energy efficiency and network lifetime of multi-hop cooperative networks in different operating environments. The paper illustrated how varying the number of relays per hop can cause networks in different environments (LoS and NLoS) to show similar performances in terms of different parameters. Since the multi-hop cooperative networks in an NLoS environment performed similar to the multi-hop SISO networks in a LoS environment, it may be concluded that CT can overcome the limitations enforced by the channel and, hence, indoor sensor networks can greatly benefit from this technique.

As a future extension to this work, we plan to test a wider array of network topologies in different settings. Furthermore, the authors plan to compute the K factor for a better characterization of the testing environments.

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