Design and experiment of testbed using network coding for power management *

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ABSTRACT

Energy optimization is an important problem in modern wireless embedded systems. In recent years, several techniques have been proposed to optimize power consumption at the computing and communication layers of these systems. Network coding is one of the promising techniques at the communication layer in which multiple messages are opportunistically encoded into a single message to reduce the number of transmissions. While network coding is a theoretically promising technique, its benefit in energy efficiency depends on the practical overheads associated with various computations such as encoding, decoding, and the coding opportunity algorithm itself. Analytical and simulation-based studies are often inadequate to sufficiently evaluate the effectiveness of network coding. In this paper, we present the design and implementation of a wireless testbed for the purpose of energy-aware resource management in networked embedded systems. We also evaluate the energy performance of network coding technique under a wide range of channel and traffic conditions. Our results show that the network coding is indeed beneficial under poor channel and heavy network traffic conditions even when all the encoding and decoding overheads are accounted.

Keywords

Opportunistic Network Coding, Wireless Testbed, Power Management.

1. INTRODUCTION

With the development of radio communication technologies and the Internet, wireless embedded systems has been connected each other. In order to improve the range of applications in the connected systems, they configure various networks and exchange data in the networks. However, with the limited battery capacity, the wireless embedded systems cannot be used for a long time. As a result, many kinds of power management methods has been devised, used, and researched.

As shown in the example of Figure 1, when the relay encodes required messages of two clients with exclusive OR (XOR) and sends it, total number of transmissions is reduced by network coding. The reduced transmission can decrease communication energy. Hence, network coding can be used as a power management technique in networked embedded systems. For the use of network coding in networks, the relay and clients require basic conditions. The relay needs to receive basic information (required messages and resource messages) of clients and to have their required messages. The relay must have a network coding algorithm, which searches network coding opportunities in given network conditions and encodes messages based on the found network coding opportunities. Lastly, the relay has to send encoded messages to clients by multicasting or broadcasting transmissions. This is because network coding cannot reduce total number of transmissions by unicasting transmission. In case of clients, they have to send the relay information of their required messages and resource messages. Clients also need a network coding algorithm, which matches their resource messages with their received encoded message and decodes the encoded message with the matched resources and XOR.

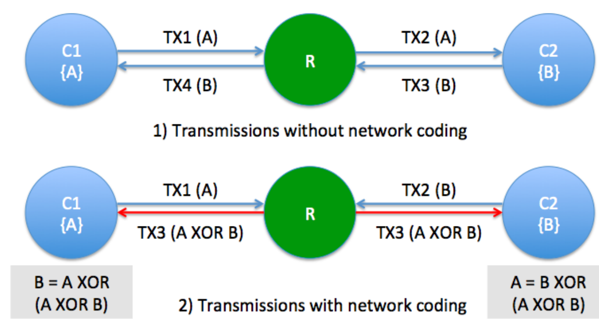

Figure 1: A simple example of network coding (C1: Client 1, C2: Client 2, R: Relay)

Network coding can be effectively used in the worse network environments. To be specific, if there is a complex network that consists of a lot of clients and relays and if the communication environments between them are very poor, total radio energy consumption will become huge. Network coding can be very useful in these bad communication conditions if network coding opportunities exist. In this paper, we study beneficial conditions for network coding with varying the number of clients, the transmission distance between clients and a relay, and the transmission range on the relay in our testbed network. Then, we discuss about the practical usage of network coding.

*This work was funded in part by the U.S. National Science Foundation under grant CNS # 1218819. The paper was presented at APRES 2015. Copyright retained by the authors.

There are several fundamental studies related to network coding (linear network coding [3], random network coding [4], and triangular network coding [5]). They were evaluated by theoretical evaluation metrics. Katti evaluated the network coding algorithm COPE by the wireless testbed in [6]. In order to study the energy value of network coding, we designed our testbed in wireless networks and implemented it by practical equipments. We also tested various cases according to test scenarios based on realistic variables. In particular, we discussed about the energy-efficient use of network coding in this paper.

The paper is organized as follows. In section II, we provide design of our testbed. Section III gives implementation of the testbed. We evaluate experimental results in section IV. Section V concludes the paper.

2. DESIGN OF THE TESTBED

Most wireless testbeds are composed of network, hardware, and software. The **network** in testbed is required to support an open communication protocol and diverse routing schemes. Network coding is positioned in the communication protocol. Therefore, the testbed network should allow to program the protocol. For realistic network environments, the network needs to support multicasting as well as unicasting and broadcasting. In order to implement these traffic, at least four **hardware** devices are required in testbed. That is, there is one relay and three clients. As the relay widens the transmission range to clients by **software**, there will be unicasting, multicasting, and broadcasting in order. Hardware and software are required to support encoding a message and decoding an encoded message with exclusive OR (XOR).

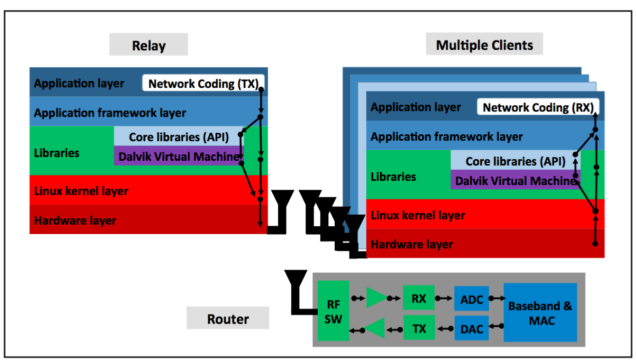

Figure 2: Block diagram of architecture of our testbed

Fig. 2 shows an architecture of our testbed using Android platform. It describes specific procedures from network encoding to network decoding by layers and blocks. The encoded message in the relay is transmitted to the multiple clients by the router. Fig. 3 expresses internal operations and interfaces between the relay and the client. In section III, we present implementation of our testbed.

3. IMPLEMENTATION OF TESTBED

3.1 General implementation

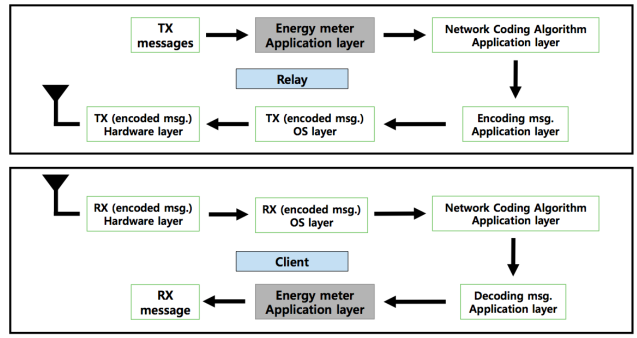

Figure 3: Internal operations & interfaces of relay and client in testbed

Our testbed was implemented by the Android platform with IEEE 802.11 network. This is because the IEEE 802.11 network allows to program various types of transmissions (unicasting, multicasting, and broadcasting), and XOR encoding and decoding. We considered to program these operations at OS layer programming and at application layer programming (see Table I). In order to minimize the disadvantages of programming at the application layer, and to maximize the benefits of this layer programming, we uninstalled all unnecessary pre-installed applications and programmed XOR encoding and decoding at the application layer.

Attributes	OS kernel	Application
Resource optimization	High (entire system)	Low (application-specific system)
Operation	Fast and Stable (by entire optimization)	Slow and Unstable (with other applications)
Algorithm implementation	Difficult	Very convenient (compatible with any Java code)
Maintenance	Hard (to update drivers & patches for new version)	Easy (to be compatible with any system condition)

Table 1: Pros. & Cons of network coding programming at OS kernel and Application layers

3.2 Network model

As shown in Fig. 4, we designed that our testbed consists of one relay and multiple clients in a single-hop radio network. In the testbed network, we assumed that the relay operates as a base station to all clients and that each client has one different message and needs the other clients' messages. Thus, all clients had to exchange their messages through the relay in the network. Lastly, we assumed that an encoded message in all test scenarios was sent by broadcasting transmission for benefit of network coding.

The test scenarios were mainly designed how the relay sends messages to clients in our testbed network with consideration of network coding. In particular, all test scenarios were initiated by sending the message **A** from client 1 to a relay. Then, a scenario determined the next task. For example of unicasting TX in Fig. 4, if the transmission range on the relay is one client, the relay transmitted the message **A** to the other three clients individually. After client 2, 3, and 4 sent their own message (B, C, D) like client 1, all clients received the other clients' all messages from the relay. When each client received the last message, the test scenario in the unicasting network was completed.

In order to find out network conditions for the maximum energy gain of network coding ($E_{NC\,gain}$), our test scenarios considered three network variables (transmission distance between clients and a relay, number of clients in testbed network, and transmission range on the relay). This is because we assumed that network coding's energy gain based on this equation ($E_{NC\,gain} = E_{unit\,TX}{}^{*}\ TX_{gain\,(NC)}$). Especially, $E_{unit\,TX}$ (unit transmission energy) can be varied by transmission distance. $TX_{gain\,(NC)}$ (transmission gain by network coding) can be depend on network conditions such as the number of clients, and the transmission range on the relay in the test network.

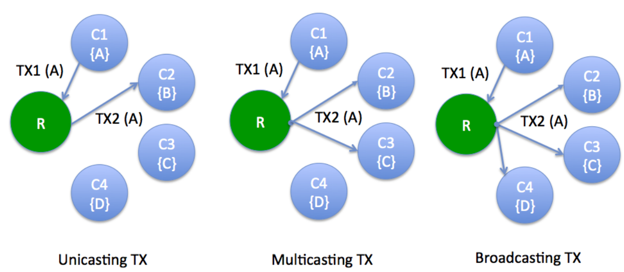

Figure 4: Examples of network model in 4-client network

3.3 Transmission range implementation

TCP (Transmission Control Protocol) supports only unicasting in our testbed network. On the other hand, UDP (User Datagram Protocol) allows to program unicasting, multicasting, and broadcasting transmissions. Thus, we had implemented the three different transmissions by UDP. The problem was that UDP does not guarantee the success of transmission. To prevent this issue, we programmed some additional codes. That is, if a client does not received a message from the relay within a predetermined time, the client will request a retransmission to the relay. We also programmed that the relay has a certain delay after sending a message for the clients to prepare enough for the next message after receiving a message. As a result of these extra codes, we had implemented UDP communication with less than 3% transmission error rate.

4. EVALUATION

4.1 Transmission distance (unit transmission energy)

We started to test two networks in Fig. 1. To be specific, we iterated two sequential transmission sets (from TX1 to TX4 and from TX1 to TX3) several times. The relay with network coding had one transmission reduction by network coding. Hence, we measured energy consumption of two different relays in Fig. 1 and calculated the energy difference between two results to obtain the energy gain by network coding. In addition, for considering the effect of transmission distance, we tested the two networks in Fig. 1 with eight-feet-long (short) and 35-feet-long (long) transmission distance between the clients and the relay.

We expected the network coding (NC) saves the relay's energy consumption up to 50% because NC reduced one transmission on relay among two transmissions. However, the experimental results showed that network coding saved 3.3mJ (31.3%) in the short transmission distance and 5.9mJ (39.1%) in the long transmission distance (see Fig. 5). For the discrepancies, we started to consider overhead for network ($E_{NC\,loss}$). To be specific, we assumed that energy balance by network coding was described by the expression ($E_{NC\,gain}$ - $E_{NC\,loss}$). This is because energy loss for network coding operations ($E_{NC\,loss}$) lowered energy gain of network coding ($E_{NC\,gain}$). As a result of the energy loss, both improvement rate in Fig. 5 could not reach to 50%. Furthermore, $E_{NC\,loss}$ was not changed by transmission distance. But, the long distance transmission increased $E_{unit\,TX}$. The increased $E_{unit\,TX}$ enlarged $E_{NC\,gain}$. Therefore, network coding is more beneficial in a network with a long transmission distance.

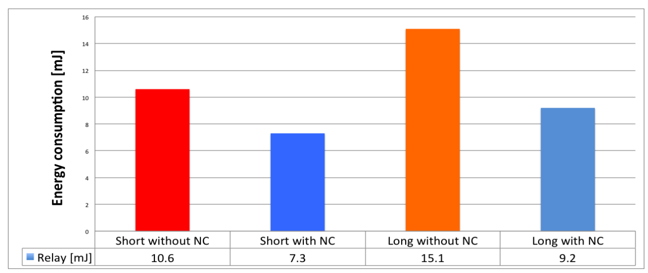

Figure 5: Energy consumption of the relay (short & long distance, without & with network coding)

4.2 Number of clients (TX gain)

In order to change the transmission gain in the previous 2-client network, we added two more clients as shown in unicasting example in Fig. 4. Network coding in this four-client network saved three transmissions. In particular, without network coding, the relay spent three transmissions for each client message because the relay forwarded each message from one client to the other three clients by unicasting transmissions. There were four clients. Thus, total number of transmissions on the relay was 12 (=3*4, #1 in TABLE II). On the other hand, the relay with network coding used two transmissions for each client message. As a result, each client had one different missed message. For the missed messages, the relay sent the last message encoded by all client messages (A, B, C, D) to all clients. Then, they had their missed message by decoding the last message. Therefore, total number of transmissions with network coding was nine (=2*4+1, #2).

The transmission gain (three) by network coding in the four-client network was greater than the transmission gain (one) in the two-client network. Hence, we expected that network coding has more energy gain in a network with more number of clients. As shown in Fig. 6, the results presented that the energy gain of network coding in the four-client network (6.4mJ) was larger than the gain in the two-client network (3.3mJ). As the number of clients in a network grows, total number of transmissions in the network is also increased. At the same time, the increased number of transmissions can provide more network coding opportunities. Therefore, network coding can save more transmissions (radio energy consumption) in a network with a large number of clients.

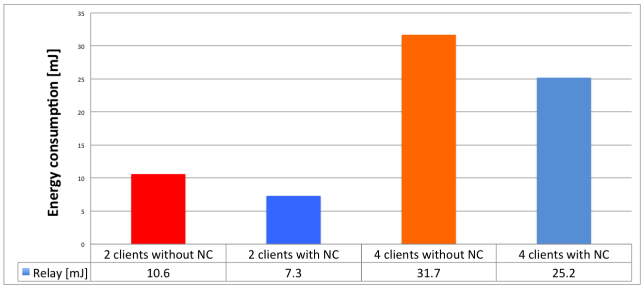

Figure 6: Energy consumption of the relay (two & four clients, without & with network coding)

4.3 Transmission range on the relay (TX gain)

As the transmission range on the relay in the four-client network was increased from unicasting to multicasting and broadcasting (see Fig. 4), total number of transmissions was decreased dramatically. For instance, the relay in the multicasting network (#3 in TABLE II), which covers two clients per one transmission, required total eight transmissions (=2*4) because the relay spent two transmissions for each client message in the four-client network. By increasing transmission range on the relay, its transmission gain was enlarged from four (#1 to #3) to eight (#1 to #5). On the other hand, transmission gain by network coding was constant to three (#1 to #2 and #3 to #4). Therefore, without consideration of overhead, network coding is more profitable in a network with a wide transmission range.

No.	Transmission range	Total no. of transmissions
1	Unicasting network without NC	12
2	Unicasting network with NC	9
3	Multicasting network (2) without NC	8
4	Multicasting network (2) with NC	5
5	Broadcasting network without NC	4

Table 2: total number of transmissions on the relay (*NC: network coding)

However, network coding could be more practical in a network with a narrow transmission range. As you shown in TABLE III, the expected improvement rates by network coding were not significantly different between the unicasting network (#1 and #2, 25%) and multicasting network (#3 and #4, 37.5%). But, the multicasting network consumed more $E_{NC\,loss}$. To be specific, unicasting transmissions were delivered from the relay to a client directly. On the other hand, multicasting transmissions were sent from the relay to multiple clients via IEEE 802.11 router. This is because the multicasting network was made by the router. In addition, when one of clients in the multicasting network missed a message, the relay retransmitted the message to all clients in the multicasting network. As a result of the large overhead, the energy gain in the multicasting network (37.5% to 3.7%) was more deteriorated by the energy loss for operations than the gain in the unicasting network (25% to 20.5%).

No.	Energy [mJ]	Imprv rate in tests	Imprv rate in assumptions
1	31.7		
2	25.2	20.5% (6.5mJ)	25%
3	24.7		
4	23.8	3.7% (0.9mJ)	37.5%
5	20.5		

Table 3: Energy consumption of the relay & improvement rates (*Imprv: Improvement)

5. CONCLUSION

In this paper, we present a practical design of testbed using opportunistic network coding. The energy gain of network coding ($E_{NC\,gain}$) is determined by unit transmission energy and TX gain. For the experimental scenarios considered, our evaluation shows that energy savings due to network coding is significant in the following cases: long-distance transmission, more number of clients, narrow transmission range. Furthermore, it requires to consider the energy loss for network coding operations ($E_{NC\,loss}$). This is because we can decide the use of network coding only if the energy balance by network coding is positive ($E_{NC\,gain}$ - $E_{NC\,loss}$ > 0).

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