Cooperative Distributed Erasure Code Scheduling for Smart Grid Communications

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***Abstract*—The performance of smart grid applications such as advanced metering infrastructure (AMI) and demand response management (DRM) can be improved by exploiting wireless communication technologies. The communication data loading and data losses in smart grid impact the system. In this work, we propose the routing protocol which adopts the cooperative transmission architecture in smart grid communications. Our proposed scheme enables the cooperative nodes to encode and forward the packets through the distributed packet-level erasure coding. The experimental results indicate that our proposed erasure code embedded routing protocol can obtain the better throughput than the conventional routing protocols.**

I. Introduction

In smart grid communications, the data transmission may be conducted through heterogeneous networks. The heterogeneous networks (e.g., Wifi, 3G, LTE, WiMax, Ethernet, 5G, . . . , etc.) have different features [1]–[3]. Specifically, the cost of bandwidth, the price charged by service provider, the data rates are different in various networks. The wired networks can be regarded as a more robust infrastructure. However, much more investment and maintenance costs are needed for wired networks. Furthermore, wired devices decrease the network scalability in the new grid deployments. In contrast to wired networks, wireless networks often suffer from high loss rate, but provide a higher network scalability for the smart grid communications. In smart grid communications, sensors are deployed on the critical equipment of the smart machines (e.g., smart meters and smart appliances) to measure various parameters, such as conductor temperature, voltage and dynamic thermal rating line fault detection, and outage detection [4], [5]. These measured parameters will be transmitted to the smart meters via communication protocols including Wifi, Zigbee, bluetooth, . . . , etc.

Advanced Metering Infrastructure (AMI) for smart grid communications is the most sought after application to efficiently manage the supply and demand of electric power for country-wide or provider-scale areas [2]. Specifically, the AMI can provide the real-time data on natural gas or water consumption for utility system and allow customers to make informed choices in using energy based on the price. The AMI is created for the automated, two-way communication between a smart meter with an internet protocol (IP) address and a energy provider service. The estimation of the total throughput is required for the AMI applications. In smart grid communications, the data loss and data collision will influence the throughput of the AMI system. There has been much interest in the use of the forward error correction (FEC) codes [6] and the routing protocol design to reduce data loss and data collision.

The erasure code, one category of FEC codes, encodes a message of k symbols into a longer message with n symbols such that the original message can be recovered from a subset of the n symbols [6]. According to the operation methodology, the popular routing protocols can be categorized into two different classes. One class is proactive routing protocols (so-called "AODV") and the other is reactive routing protocols (so-called "DSDV"). In [7]–[10], the results indicated that the AODV yields a better performance than the DSDV. In AODV, each node periodically exchanges and updates the routing table information with one another. Certain AMI includes the mobile devices such as the electric vehicles and the smart cars. Thus the topology can change fast, and then the newest routing information can not be updated immediately. According to the old routing table, the data forwarded through a broken route will be lost.

In this work, we consider the AMI communication system which includes three s: 1) the customers, 2) the energy (e.g., electric and gas) providers, 3) the network service providers. In this AMI communication systems, we present a distributed erasure code based routing protocol for AMI communication systems. The main idea is to select a data transmission coordinator to employ distributed erasure coding mechanism to encode the received packets with the same destination. Then the coordinator forwards these encoded packets which are set to the same destination. These packets are uncorrelated due to the fact these packets are from different nodes, and the burst errors are less likely to occur by this un-correlation property. On the other hand, the customer always concerns about the selection of various networks based on the price. Thus we also consider the price in the routing protocol. The modified routing protocol firstly selects some potential route tables and then decides the lowest price of the route table from these potential route tables. The goal of this study is to propose a routing protocol with distributed erasure coding to improve the throughput of the AMI system.

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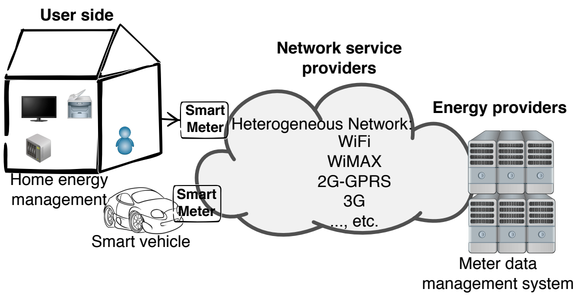

Fig. 1. The comparisons for various communication infrastructures.

Communication Infrastructure	Range	Data rate	Price
GSM-GPRS	26 km	64-144 kbps	Expensive
3G	serval km	384 kbps (mobility)	Expensive
Wifi	30-50 m	54 Mbpx	Cheap
WiMax	6 km	100 Mbps	Cheap

Fig. 2. The comparisons for various communication infrastructures.

II. System Model

Figure 1 shows our system model. At the user side, the smart meter collects the various measured parameters which will be transmitted to the meter data management centers of the energy (e.g., electric and gas) providers. There are serval various communication infrastructures which can be applied to transmit various measured parameters. These communication infrastructures provide the different features which provide more options to the users and the energy providers. The comparisons for various communication infrastructures are summarized in Figure 2. As observed from Figure 2, the price of WiFi or WiMax is cheaper than the price of GSM-GPRS or 3G. The largest coverage of a single device is GSM-GPRS, while 3G has the smallest coverage. The data rate of GSM-GPRS is lower than the other communication infrastructures, while the data rate of WiMax is faster than the other communication infrastructures.

The AODV [11] routing protocol is now briefly described as follows. As the path discovery is started, a packet called route request (RREQ) is broadcasted by the source node to its neighbors. This kind of packet will be transmitted hop-by-hop until reaching a node which can reach the destination by a route. If the intermediate node may receive multiple duplicates of the same RREQ, the node will not broadcast the RREQ again. When the RREQ arrives at a node having an available link to the destination, this node will send a packet called route reply (RREP) back to the source node along the pre-constructed reverse path. Once receiving the RREP, the source node transmits the data. Any failed node will broadcast a special RREP to notify every active source node. The source node can then initiate another path discovery procedure if the source node still communicate with the destination. In this work, the price of the path which is provided by communication infrastructures is considered in constructing the route table through the AODV.

To realize the routing protocol with the distributed erasure coding mechanism, a data transmission coordinator should be properly selected to encode the packets via the distributed erasure coding. The smart meter will analyze the route table of the packets transmitted by nearby nodes (one-hop distance). If the smart meter is selected as a coordinator, the coordinator will adopt a code-and-forward scheme to cooperate the nearby nodes which will communicate with the same destination. The way to code-and-forward scheme is to encode the packets from these nearby nodes by Reed-Solomon (RS) coder [6], [12], and then forward the RS codeword to the same destination. The details can be found at the Section III in this paper. We assume that the coordinator with multiple antennas can receive at most M packets at the same time. Thus, the coordinator efficiently encodes the subset of these received packets by erasure coding in a shorter time than the mechanism that the source node erasure encodes the packets. Note that the packets in the subset of these received packets are uncorrelated due to that these packets are from different nodes, and this un-correlation property leads to the reduced burst errors.

III. Routing protocol mechanism with employing Distributed erasure code

In this paper, we apply the erasure code to the AMI system. The erasure code can be implemented by the RS code [6], [12], which take a codeword of k packets and generate $n - k$ additional check packets for the transmission of n packets over the network. Then the destination can recover all packets by any k received packets. Figure 3 shows an example for RS(7, 5) code. The lost packets, Packet 3 and Packet 5, can be reconstructed by RS decoding. However, two issues rise if erasure coding is applied to AMI applications. 1) The delay will be increased by using large n; and 2) it is inefficient to individually employ the erasure code at every smart meter.

The main idea of the proposed route mechanism is inspired by using the concept of the cooperative communications [1], [13] to properly select the coordinator from the smart meters which will perform the code-and-forward relay scheme. The proposed distributed erasure code embeded routing mechanism consists of the following two parts. The first part is to construct the route table by additionally considering the price as a metric in the AODV. The price often dynamically changes due to the different communication infrastructure services, and thus we simply use four scores, 1, 2, 3, 4, to represent “very cheap”, “cheap”, ”expensive”, and “very expensive”, respectively. Before the AMI system performs the AODV

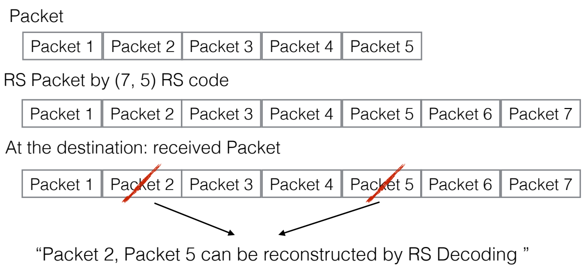

Fig. 3. A (7, 5) RS Code.

algorithm, every communication infrastructure is assigned a score in $\{1, 2, 3, 4\}$ according to their price. The route table for i-th smart meter is defined by a sequence

$$RT_i = \{RT_i(1), \dots, RT_i(\text{end})\},$$

where the $RT_i(1)$ represents i-th smart meter, and the $RT_i(\text{end})$ represents the destination. Figure 4 shows a simple example for the AMI communications with 10 smart meters. The route tables for the smart meters 1, 2, ..., and 10 are $\{RT_1, RT_2, \dots, RT_{10}\}$.

The second part is to decide the coordinator according to the routing tables of adjacent smart meters. Once a coordinator is selected as the cooperative node, the coordinator will immediately notice the nearby smart meters which communicate with the same destination. Then a cooperative communication is built for the AMI communication. An example for constructing a cooperative communication is shown in Figure 4. The smart meter 4 observes the routing tables of the smart meters with on-hop distance and finds the route table of the smart meters 1, 2, and 3 have the same destination. Specifically, we obtain a cooperative condition "$RT_1(2) = RT_2(2) = RT_3(2) =$ smart meter 4, and $RT_1(\text{end}) = RT_2(\text{end}) = RT_3(\text{end})$". Then the smart meter 4 encodes 3 packets received from smart meters 1, 2, and 3 to generate 5 FEC packets through RS(5,3) code. Note that the smart meter 4 plays the role as a coordinator for smart meter 1, 2, and 3 until the cooperative condition vanishes (e.g., the packets received from nearby smart meters have different destinations). The route table of smart meter 5 will communicate with the D_2. Therefore, the smart meter 4 observes that only one packet will transmit to D_2, and thus the smart meter 4 does not cooperate this packet by code-and-forward coding scheme.

IV. Simulation Results

The simulation environment is described as follows. There are Q_f fixed smart meters and Q_m mobile smart devices with the maximum speed of 20 km/hr in a simulation area whose boundary is defined as 10 km x 10 km. During one simulation, five nodes are randomly selected to form one pair of links with the same destination to transmit the packets produced from the collected parameters. Each transmitter sends the packet with 253 bytes every 10^{-3} seconds. Ten nodes are randomly selected to form a communication with different destinations. The network congestion conditions are simulated

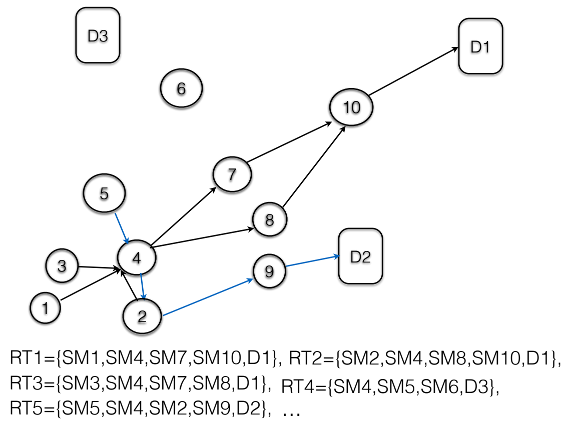

Fig. 4. The communication topology for 10 smart meters.

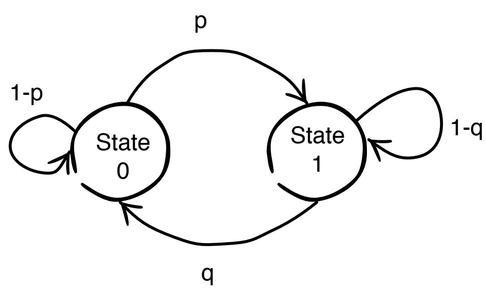

Fig. 5. Gilbert channel model.

by selecting other nodes with constant bit rate (CBR) streams. These congestive nodes randomly transmit the packets to the destinations. The CBR stream has the packet size of 256 bytes. The starting time of each CBR stream is randomly chosen between 0 and 3 seconds for one simulation. We run 300 simulations and in each simulation the mobile devices move randomly and freely by the random waypoint model to generate 30 different scenarios.

Packet losses in the network usually appear in bursts and can be approximated by a 2-state Markov process known as a Gilbert channel model [14]. Figure 5 shows the Gilbert channel model with its transition probabilities p, q. The state 0 and 1 represent the packet is being received and lost, respectively. The probability p represents that the next packet is lost given that the current one is received; q is the probability that the next packet is received given that the current one is lost. The packet loss rate (PLR) which equals to the probability of being in the state 1 can be computed by $PLR = \frac{p}{(p+q)}$.

Figure 6 shows the throughputs of the modified AODV, the modified AODV with RS(10,7)-code (MAODVRS(10,7)) and the proposed distributed erasure code embedded routing protocol, denoted by DECAODV, for $(Q_f = 15, Q_m = 5)$ and the various PLRs. From Figure 6, the throughput obtained by using MAODVRS(10,7) is lower than the throughputs obtained by using MAODV and DECAODV. Under a lower PLR = 5%,

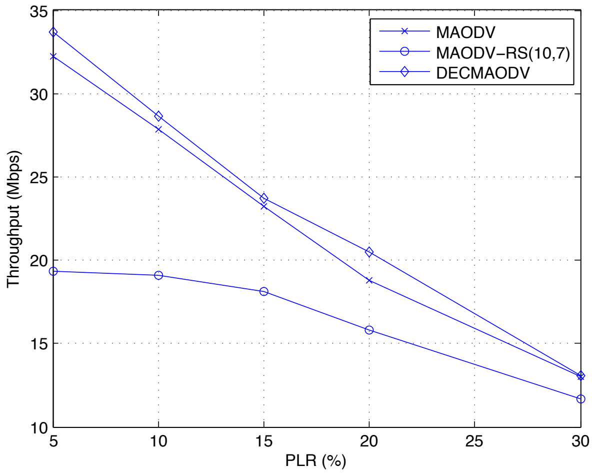

Fig. 6. The throughputs of the modified AODV (MAODV) and the proposed distributed erasure code embedded routing protocol, denoted by DECAODV, for $(Q_f = 20, Q_m = 20)$ and the various PLRs.

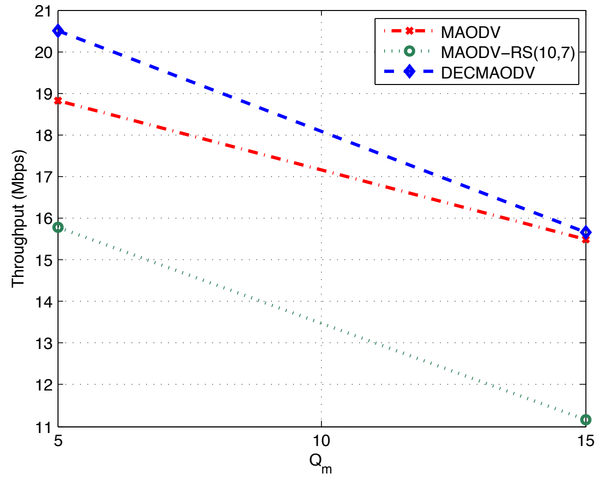

Fig. 7. The throughputs of the modified AODV and the proposed distributed erasure code based protocol for $(Q_f = 15, Q_m = 5)$ and $(Q_f = 15, Q_m = 15)$. The network condition PLR = 20 %.

due to more redundant packets issued by RS(10,7)-code, the throughput obtained by using MAODVRS(10,7) is only 19.32 Mbps which is lower than MAODV and DECAODV. Under the PLR = 20 %, the throughput of the DECAODV is higher than MAODV due to the lower error-correcting ability of the MAODV.

Figure 7 plots the throughputs of the MAODV and the MAODVRS, and proposed DECAODV, for $(Q_f = 15, Q_m = 5)$, and $(Q_f = 15, Q_m = 15)$. The network condition is setup as PLR = 20 %. From Figure 7, the throughput obtained by using MAODVRS(10,7) is lowest for $Q_m = 5, 15$. When Q_m increases to 15, there are more smart meters to share the bandwidth, and thus the MAODV and the MAODVRS, and proposed DECAODV obtained a lower throughput than the case of $Q_m = 5$. Compared with the MAODV scheme, DECAODV can efficiently recover the lost packets due to the packet collision.

V. Conclusion

In this paper we investigate the cooperative transmission architecture for smart grid applications. The AODV with considering prices and the erasure coding mechanism are employed to reduce the data loading and data loss in the smart grid systems. Inspired by the concept of the cooperative communication, we develop a distributed erasure coding embedded routing protocol scheme by exploiting the benefit of the relay diversity. By analyzing the route tables of the nearby nodes, a coordinator can be selected to cooperate the packet transmissions via the code-and-forward scheme. The coordinator encodes the packets by using RS code and then forwards these RS codewords to the destination. The simulation results indicate that our proposed erasure code embedded routing protocol scheme can obtain the better throughput than the conventional routing protocol scheme.

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