Smart-Metering-Oriented Routing Protocol Over Power Line Channel

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***Abstract*— This paper proposes an ad hoc routing algorithm to increase link reliability in power line communications over low-tension power grid. The algorithm assumes data concentrator (DC) located at the distribution transformer, which is polling meters connected to the power line and send information about energy consumption, loading profile and any other crucial data to the utility. The proposed algorithm is designed to keep the required processing complexity at the meter side to the minimum, while shifting the intelligence towards the DC. The protocol accounts for asymmetric characteristics of the power line channel, where some nodes could suffer very bad downlink quality due to noise at the meter side. These nodes couldn't receive data sent from DC and/or other nodes and are therefore classified as deaf nodes, although their transmission could be received properly by adjacent nodes. Furthermore, special packet structure is proposed to minimize algorithm overhead and packet routing mechanism. The protocol performance is compared against LOADng, LOADng-CTP and AODV in terms of protocol overhead, end-to-end delay, packet delivery ratio and memory requirements.**

Keywords–PLC, AODV, LOADng, LOADng-CTP, DC, smart metering, routing protocol

I. Introduction

Electrical power lines have been used as a communication medium extensively over the past two decades. Power Line Communication is an attractive alternative to utility companies as it provides low-investment medium for smart grid services including: smart metering, load survey, load shedding and profiling. Typical configuration comprises data concentrator (DC) located at the distribution transformer, which communicates with meters at households via low-tension distribution grid. However, as it has never been designed with communication aspects in mind, the power line channel introduces tough challenges to the communication system designer in order to achieve reliable link with acceptable availability, throughput and reachability. Factors like attenuation, narrow-band and impulsive noise, and impedance variability are among the issues that affects the link quality dramatically and therefore its impact should be mitigated. At the physical layer level, coding, interleaving and noise cancellation are commonly used to enhance the channel quality. At the network layer level, ad hoc routing protocols are used to achieve the same goal. In this arrangement, intermediate meters act like repeaters to regenerate packets from/to meters that couldn't be reached directly by the DC due to bad channel conditions. The routing algorithm should be designed to avoid network flooding at large number of nodes (meters), using a simple algorithm with small memory requirements to fit easily within the meter circuitry.

In this paper, a Low Complexity ad hoc routing protocol that is optimized for Smart Metering application (LCSM) is introduced, simulated, evaluated and compared to similar routing protocols, specifically: AODV, LOADng and LOADng-CTP protocols. LCSM protocol is designed to keep the required routing rules at the meter as simple as possible, while shifting the processing and memory requirements to the DC, where cost increase could be much more tolerated. Different Key Performance Indicators (KPIs) are evaluated including routing overhead, end-to-end delay, packet delivery ratio, topology discovery time and memory requirements. OPNET network simulator is used to evaluate the performance of LCSM protocol against AODV, LOADng and LOADng-CTP routing protocols.

The rest of the paper is organized as follows: Section II describes prior research efforts related to this work. Section III presents LCSM protocol specifications and its core operation. Section IV illustrates simulation results and comparison to LOADng, AODV and LOADng-CTP. Finally, Section V concludes and summarizes the main contributions of this paper.

II. Ad Hoc Protocols for Power Line Communications

Several attempts to customize ad hoc routing protocols for power line communications are found in the literature.

Shucheng et al. introduces an on-demand multipath routing algorithm that tries to find maximally disjoint routes in large-scale networks with Master-Slave structure [1]. The protocol is able to build multiple routes using request/reply cycles. When the master requires a route to a given slave before knowing any routing information, it floods the RREQ message to the entire network. Several duplicates that traversed through different routes reach the destination as a result of flooding. Finally, the destination node picks up multiple disjoint routes from received RREQ packets and sends ROUTE REPLY (RREP) packets back to the source via the chosen routes. This scenario results in large network overhead and end-to-end delay.

Wei et al. [2] demonstrates a routing protocol based on AODV routing protocol. they modify two modules of the AODV, RREQ broadcasting mechanism and neighbor table manage- ment. The aim of these modifications is to reduce the overhead by reducing the hello packets.

In [3], Sivaneasan et al. proposes a routing algorithm based on non-overlapping clustering. It uses two-states Markov model for simulating the channel state during communication with the meters. In this protocol all meters have the role of relaying the DC message.

Zhenchao et al. [4] proposes a routing protocol based on overlapping clustering in order to establish different routes to reach the same meter which is useful at route failure condition. The DC selects cluster head that are responsible for delivering the data of neighboring meters to the DC.

Hong et al. [5] introduce a routing algorithm based on time slotted algorithm with random back off delay before transmission in order to reduce the collision.

In [6] Wenbing et al. proposes a routing protocol based on ant-colony algorithm which is described in [7]. There are two main tables that should be constructed; central routing table and pheromone routing table. Each child node can establish sub- routing table. Central node and child nodes need to establish their amplitude parameter list. Due to the response signal of child node, central node can set up sub-routing table one by one and update pheromone table. A greed stochastic adaptive searching method is also introduced in the ant colony optimization algorithm. One feature is that the establishment of the restricted candidate list (RCL) strategy. According to the amplitude parameters of the receiving signal among nodes, the RCL can be set up.

Clausen et al. [8] introduced LOADng routing protocol as a modified version of AODV protocol. LOADng outperforms AODV on packet delivery ratio and routing overhead. Jiazi et al. [9] improved the mechanism of RREQ compared to the basic LOADng in order to reduce the routing overhead. Furthermore, Jiazi et al. [10] introduce further modifications to LOADng and propose LOADng-CTP which is a class of collection-tree protocols and more suited to smart metering application. LOADng-CTP proves much better performance compared to LOADng and AODV.

Asymmetric characteristic of the power line channel has not been considered in the preceding protocols, where some nodes are subject to high line noise due to the household appliances [11]. Additionally, the preceding protocols assume that protocol algorithm will be programmed and executed at all nodes, whereas the majority of low-cost meters allow only for implementing very simple algorithms due to limited processing capability and on-board memory. LCSM takes the two aforementioned aspects into account. In the following section, specifications of LCSM is described.

III. LCSM Protocol Specification

The topology comprises Data Concentrator (DC) and several meters connected in a tree topology via low-tension power line grid. Figure 1 illustrates the topology of interest. The DC, as well as each meter, contains a power line modem that has a finite coverage range dependent on the maximum allowed transmitted power and receiver sensitivity. As shown, some meters could be accessed directly by the DC, while others are not reachable by the DC due to channel impairments, although they could be within the coverage range of intermediate meters.

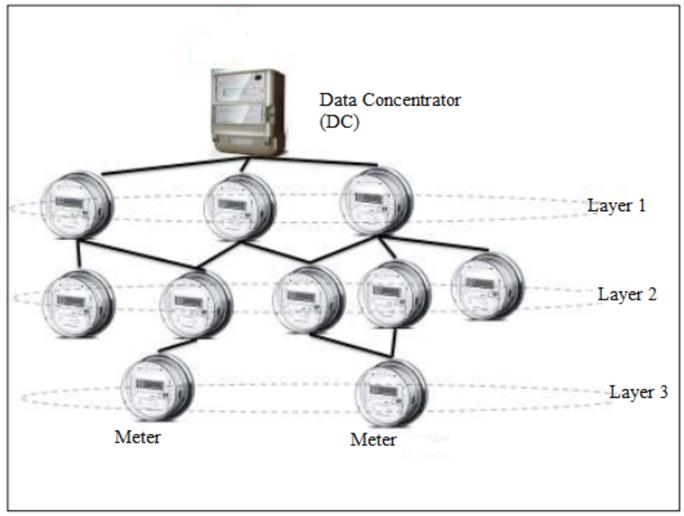

Fig. 1: Physical and Logical connection for smart metering system

A. Protocol Data Unit

LCSM utilizes two types of packets: Command packet and response packet. Command packets are the packets being sent from DC towards the meters and the response packets are those being sent from the meters towards the DC. Standard TLV (Type-Length-Value) packet format is used, as shown in Figure 2. The LCSM protocol utilizes source routing, so that the packet source-destination route is embedded within the packet body. Command packets are initiated from DC, while response packets are originated from meters. After topology discovery takes place, only the DC contains the complete visibility on network topology. Therefore, in command packets, the ID of each node along the route is included in order within the packet body. On the other hand, response packets contains only source, parent and final destination.

The PDUs used by LCSM are described as follows:

Neighbor Request (NREQ) - Neighbor Response (NRES): The purpose of NREQ packet is to explore who hears the DCs request. This is a broadcast packet. The response to this packet is NRES; the meter response with meter ID and the received SNR.

Layer/Parent Stamp (LPSTAMP) - Layer/Parent Acknowledgement (LPACK):LPSTAMP is used to inform the meter its parent-layer information. The response to this packet is LPACK.

Get Your Neighbors (GETN) - Neighbor List Reporting (NLREP):GETN packet is used to let certain parent reports its neighbors. The meter responds with NLREP packet that reports the list of which nodes are accessible by this specific parent.

Read Request (RREQ) - Read Response (RRES): After finishing the topology discovery cycle, the DC starts collecting the data (readings) using RREQ packet. The response to this packet is RRES packet.

Deaf Reading (DFREAD): DFREAD packet is used by the deaf node (the node that doesn't receive any request during certain pre-assigned time period is classified as DEAF) to broadcast its reading, which will be hopefully heard by adjacent node(s).

Source	Next Hop	...	Destination	EOR	Sender Layer	Type	Length In bytes	Value	C/R

Fig. 2: Standard TLV packet format.

```
Algorithm I   The Meter Algorithm
// EOR is the end of route
// D is the final destination
// C_packet is the command packet
// R_packet is the response packet
// N1 is the next hop 1
// SNR is the signal to noise ratio
// M is the meter
// DC is the Data Concentrator

for all M do
    if  received packet is  c_packet then
        if  sender layer < my layer  then
            if meter ID is N1 at the received packet then
                if EOR is existed then
                    respond_ to_ the_ packet_ accordingly();

                Else
                    //Remove mete's ID from the packet and
                        forward it to the destination;
                end if
            end if
        end if
    end if
  if received packet is  R_packet then
      if sender layer > my layer then
      // forward_packet_to_parent();
      end if
  end if
end for
```

Fig. 3: Meter Algorithm

B. Protocol Routing Mechanism

Figures 3 and 4 illustrate the pseudo codes of LCSM algorithms for both meters and DC, respectively.

```
Algorithm II   The DC Algorithm
// EOR is the end of route
// D is the final destination
// C_packet is the command packet
// R_packet is the response packet
// N1 is the next hop 1
// N2 is the next hop 2
// SNR is the signal to noise ratio
// M is the meter
// DC is the Data Concentrator
// DP Discovery Period
// CP Data Collection Period

for all DP do
    Broadcast_RREQ_Packet();
    // Wait for received packet
    if  received packet is  NRES then
        if SNR is higher than the threshold then
            // send LPSTAMP packet to these meters;
        else
            // save them as backup routes;
        end if
    end if
    if received packet is  LPACK then
        if all good nodes are stamped then
            send_GETN_to_Parents();
        else
            send_LPSTAMP_to_Next_Parent();
        end if
    end if
    if received packet is  NLREP then
        if SNR is higher than the threshold then
            // send indirect LPSTAMP;
        else
            // save them as backup routes;
        end if
    end if
end for

for all CP do
    send_RREQ_to required_Meter();
    // wait for RRES reception;
    // store the reading at a file;
    // send file to the server by GPRS connection;
end for
```

Fig. 4: DC Algorithm

Upon receiving a Command packet, the meter checks the node ID right after the source address. If it doesn't match the meter self ID, it ignores it. If it matches the meter ID, the meter checks whether it is the final node en-route (end of the route field - EOR), which represents the final packet destination. If it is, the meter responds according to packet type. If the meter ID doesn't lie at EOR field, this means that the meter lies within the source-destination route, and should act as a relaying node. Therefore, the meter relays the packet as it is after removing its ID field from the routing chain.

In Response packets, the meter checks the field representing parent ID, and if it matches self ID of the meter, it relays the packet to its parent by replacing the parent field with its own parent. (put Next Hop as P), and keep source and final destination the same. Whenever a meter receives a broadcast message from a deaf meter, it keeps the deaf meter ID, together with its reading. The meter reports deaf meter reading the next time its own reading is requested by the DC. According to this arrangement, the proper routing of packet only requires the knowledge of the node parent. Total routing matrix exists only at DC.

IV. Simulation Results and Performance Analysis

A. Simulation Environment

The LCSM protocol is simulated and evaluated by means of OPNET14.5 network simulator. Simulations are performed using number of nodes ranging from 50 to 500. The network is subject to multipoint-to-point (MP2P) traffic with all nodes generating traffic towards the Data Concentrator. Models of physical and Medium Access Control (MAC) layers of power-line modems are modeled using bus topology and an adaptive connectivity matrix. The purpose of the connectivity matrix, which is N x N (N is the number of nodes connected to power line) is to simulate whether a specific logical link between two nodes exist or not. In this way, PHY and MAC layers of the power line channel are modeled to allow for the application of LCSM at the network layer.

B. Simulation Parameters

The simulation parameters are summarized in Table I. The power line channel could be considered physically as bus and logically as tree topology. Layer 1, 2 and 3 represent the tier at which the meters are located with respect to the Data Concentrator.

TABLE I: Simulation Parameters.

Parameter	Value
Number of Nodes	50-500
Simulation Time	100 seconds
Topology	Physically Bus, Logically Tree
MAC type	CSMA-CD
Slot time	0.214 second
Data rate	2400 bps
Preamble length	0 (no preamble)
Channel propagation delay	5.5 e^{-6} second
Type of service	Bursty traffic source
Burst duration	80 seconds
Burst period	5 seconds
Traffic type	Multi-Point-to-Point (MP2P)

C. Simulation Results

Comparison to AODV and LOADng

First, LCSM routing protocol is compared with LOADng [12] and AODV [13]. Although both protocols are originally designed for mesh network topology, the rationale behind comparing their performance to LCSM, which is a collection-tree protocol, is to highlight the expected enhancement resulting from using customized protocol for the smart metering case, which is by nature a tree topology. The results of LOADng and AODV are extracted from [12]. Figures 5, 6 and 7 show the simulation results for LOADng, AODV and LCSM routing protocols.

It is observed from Figure 5 that the overhead of LCSM is much lower than that of LOADng and AODV. The difference in overhead bytes is considerably higher at higher number of nodes. This is due to the large number of RREQ, RREP and RREP-ACK packets used in AODV for discovering the topology [13], [14]. At LCSM protocol, the parents are responsible for a lot of children which leads to reducing the overhead.

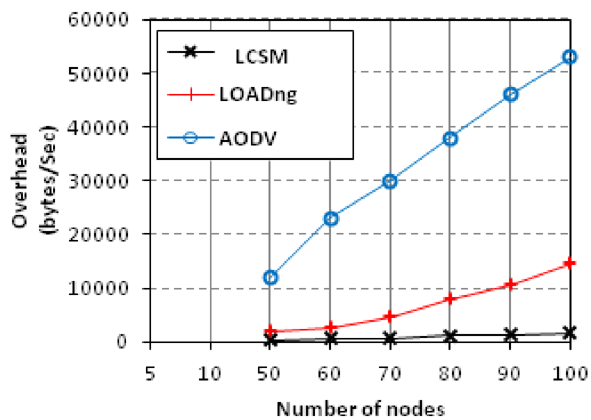

Fig. 5: Routing Overhead

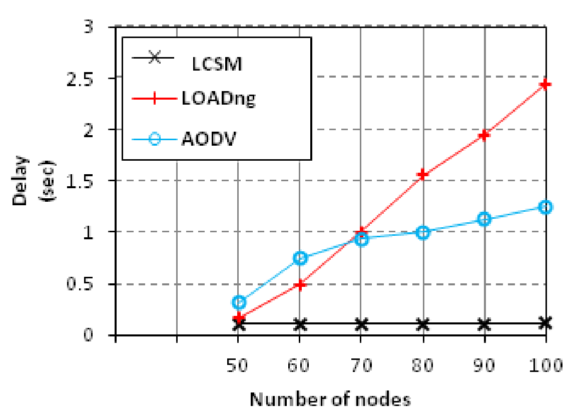

Fig. 6: End-to-End delay

It is important to study the end-to-end delay as only one (DC) is responsible for collecting data from around 400 meters. So, it is required to have a routing protocol with a controlled end-to-end delay, especially when dealing with time-critical events like load disconnect and fault isolation. As shown Figure 6, LCSM routing protocol provides much lower end-to-end delay than LOADng and AODV. The variation of end-to-end delay at LCSM protocol is very small at large number of nodes.

As shown in Figure 7, LCSM routing protocol introduces a delivery ratio which is very close to 100% regardless of the number of nodes.LOADng initiates route discovery for every router (network-wide broadcast) leads to a high number of collisions on the media, and thus a lower data delivery ratio, especially for larger number of nodes [10]. This is also applicable to AODV.

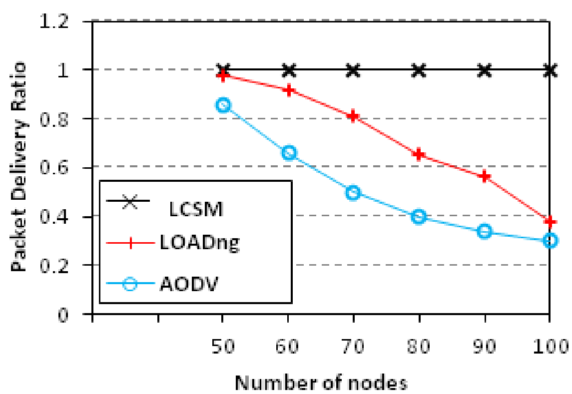

Fig. 7: Packet Delivery Ratio

Figure 8 shows the topology discovery time against the number of nodes. It shows a considerable increase in discovery time after 200 nodes

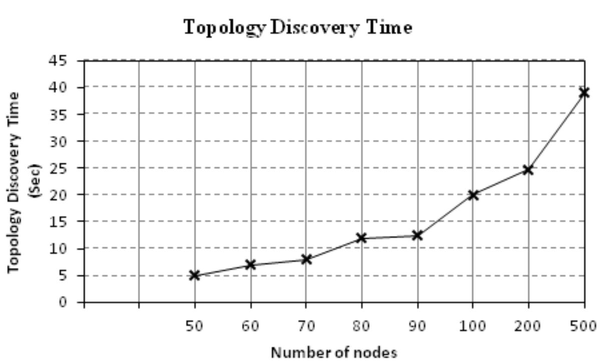

Fig. 8: Topology Discovery Time at data rate 2400 bps.

Memory requirements for LCSM, AODV and LOADng:

For LOADng and AODV the memory requirements to store the routing table depends on the size of the network, the network topology and the number of traffic flows in the network. The contents of the routing table for LOADng protocol are:

(R_dest_addr, R_next_addr, R_metric, R_metric_type, R_hop_count,R_seq_num, R_bidirectional, R_local_iface_addr, R_valid_time) [8].

In LCSM protocol the only required entry to be stored at the meter is the parent address. The other routing information is contained at the message body. The overall matrix describing the topology is only stored at the DC.

Comparison to LOADng-CTP

Second, LCSM routing protocol is compared with LOADng-CTP [10]. Both protocols are collection-tree oriented, so both are optimized for smart metering application. As shown in Figure 9, the number of bytes sent during the topology discovery process in both protocols are almost the same till reaching 200 nodes. At increased number of meters, the difference become larger and LOADng-CTP offers lower overhead. This is clear at 500 nodes. This performance is justified by the fact that the number of packets used for the topology discovery process in LOADng-CTP is less than the number of packets required by LCSM protocol, while the LCSM packet size is less than LOADng-CTP packet size. For this reason, the difference becomes obvious at higher number of nodes.

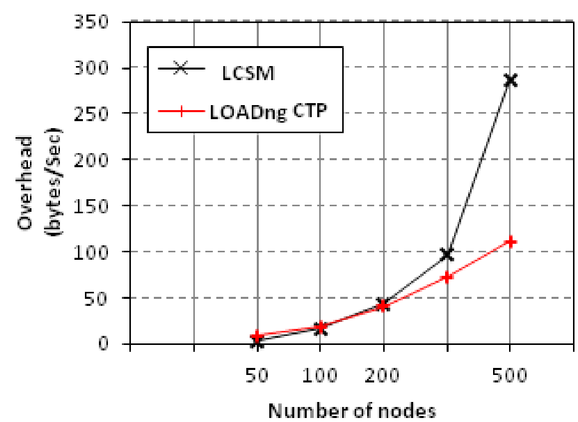

Fig. 9: Routing Overhead for LCSM and LOADng-CTP(in bytes).

Another approach for evaluating the network overhead is based on the number of packets required to fully explore the topology. Figure 10 illustrates the value of this parameter against the number of nodes for both LCSM and LOADng-CTP. The similarity between the two protocols in terms of the number of packets required for topology exploration is obvious. However, as LCSM uses source routing,it is expected that with increasing number of nodes, the network depth (the maximum number of hops required to reach all nodes) increases, and therefore the average packet length will increase. This explains the fast increase in overhead bytes at LCSM compared to LOADng-CTP with increasing number of nodes, as illustrated in Figure 10.

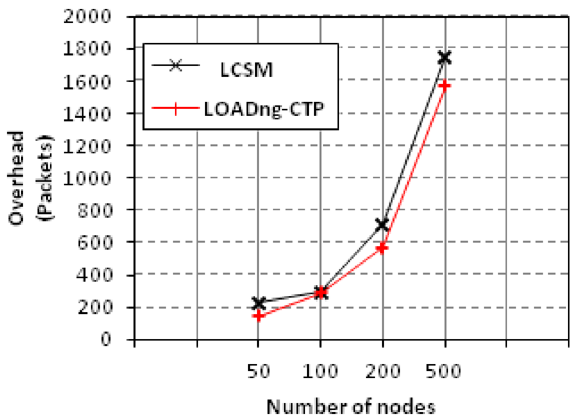

Fig. 10: Routing Overhead for LCSM and LOADng-CTP(in packets).

As mentioned previously, the data rate affects directly the end-to-end delay. Thus, it is predicted that the end-to-end delay for the packets sent at 2.4 kbps will be much greater than the packets sent at 11 Mbps as shown in Figures 11. However, as the simulation results in [10] was performed at 11 Mbps data rate, it is required to evaluate the end-to-end delay of LCSM at the same data rate. Figure 12 illustrates the delay of both protocols when both are operating at 11 Mbps. It is clear that LCSM introduces smaller delay than LOADng-CTP at the range of nodes considered.

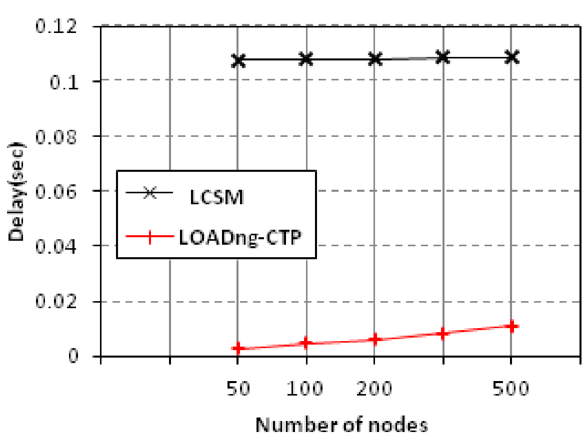

Fig. 11: End-To-End delay for LCSM (at data rate=2.4 kbps) and LOADng-CTP(at data rate=11 Mbps).

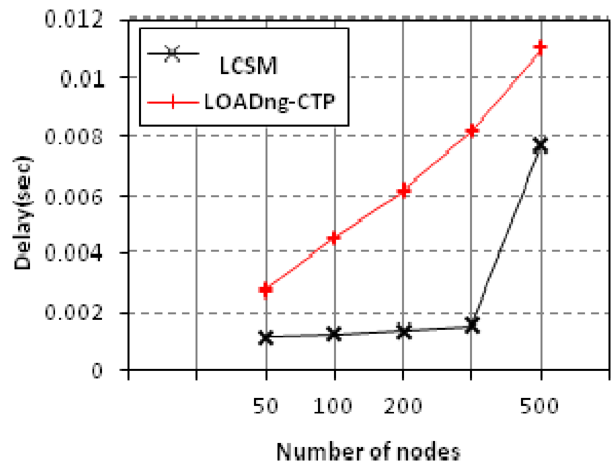

Fig. 12: End-To-End delay for LCSM (at data rate=11 Mbps) and LOADng-CTP(at data rate=11 Mbps).

Figure 13 illustrates the packet delivery ratio of both protocols, and indicates that both protocols are identical and have a packet delivery ratio very close to 100%. This result is reasonable as the initiation of route discovery is made only for single destination, thus resulting in minimum number of collisions.

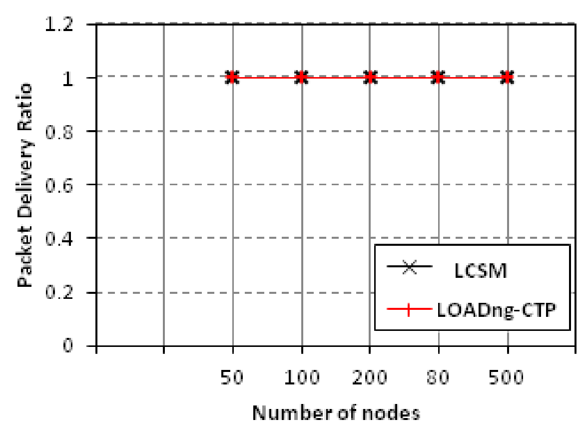

Fig. 13: Packet Delivery Ratio for LCSM and LOADng-CTP.

Memory requirement for LOADng-CTP:

For LOADng-CTP, only the route to the root is needed, and therefore one routing entry to the DC is required. This entry is defined by: (R_dest_addr, R_next_addr, R_metric, R_metric_type, R_hop_count,R_seq_num, R_bidirectional, R_local_iface_addr, R_valid_time) [8]

The routing table entry for LOADng-CTP is much smaller than LOADng but it is higher than LCSM.
Figure 14 illustrates the topology discovery time for LCSM protocol with data rate 11 Mbps.

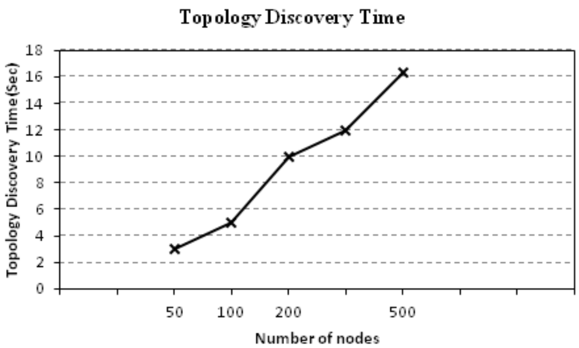

Fig. 14: Topology Discovery Time for LCSM at 11 Mbps.

V. Conclusion

A low-complexity ad hoc routing protocol for smart metering over power line (LCSM) is proposed. A comparative analysis between the proposed protocol and AODV, LOADng and LOADng-CTP routing protocols is demonstrated. The simulation results show that LCSM routing protocol has considerably lower routing overhead compared to AODV and LOADng, especially at high number of nodes. It is also shown that the End-To-End delay of LCSM is lower than both LOADng and AODV, as the later are designed for mesh networks, while LCSM is a collection-tree oriented protocol. Comparison between LCSM and LOADng-CTP shows that the routing overhead is almost similar (LOADng-CTP is slightly better), the packet delivery ratio are almost the same (very close to 100%) and LCSM offers considerable lower end-to-end delay when running the simulation with the same data rate (11Mbps). Furthermore, algorithm complexity at the meter side when using LCSM is considerably reduced.

Table II summarizes the comparison between LCSM, LOADng-CTP, LOADng-CTP and AODV.

TABLE II: Comparison between LCSM, LOADng-CTP, LOADng and AODV protocols.

Comparison parameter	LCSM	LOADng-CTP	LOADng	AODV
Routing Overhead	Low	Low	High	High
End-to-End Delay	Low	Medium	High	High
Packet Delivery Ratio	High	High	Medium	Medium
Packet Format	Ethernet Format	AODV Format	AODV Format	AODV Format
Memory Requirement	Only parent should be saved	Complete routing table should be saved	Complete routing table should be saved	Complete routing table should be saved

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