SCTP-aware Link Layer Retransmission Mechanism for Smart-grid Communication Network

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Abstract—**The smart grid delivers electricity from suppliers to consumers and uses bidirectional communication to exchange real-time information between supply system and smart meters at the user end. With a combined communication infrastructure, smart grid manages the operation of all associated components to provide reliable and supportable electricity supply. The Neighborhood Area Network (NAN) of smart grid supports bi-directional data transfer between smart meters (installed at customer premises) and control center of the utility company through an aggregator. This communication suffers low throughput and excessive delays due to the Head of Line (HOL) blocking when the Transmission Control Protocol (TCP) is implemented for reliability. In this paper we propose SCTP-aware Link Layer Retransmission mechanism (SCTP-LLR) which augments the Stream Control Transmission Protocol (SCTP) with Link Layer Retransmissions at the aggregator. SCTP-LLR uses the multi-streaming feature offered by SCTP and implements link layer retransmissions at the aggregator to mitigate the effect of HOL blocking. We carried out simulations using Network Simulator and compared the performance of SCTP-LLR against TCP and SCTP. Our results show that SCTP-LLR outperforms both TCP and SCTP in terms of throughput and packet delays and is a promising protocol to be implemented in smart grid NAN for reliable and efficient communication.**

Keywords- Head of line blocking; Link layer retransmission; Neighborhood area network; Smart grid network; Stream Control Transmission Protocol

I. INTRODUCTION

Smart grid communication is the key concept of integrated information technology in modern power control system. The smart grid comprises of power delivery from generation system to electrical sub-stations, distribution system substations to the consumers and digital communication network for consumer's data collection from smart meters. In smart grid communications, transport layer plays an important role for data transfer between end users and the grid system. Conventionally in internet, the transport layer provides two types of services to the application layer namely connectionless service and connection-oriented service. The connectionless transport protocol User Datagram Protocol (UDP) provides high data rates but does not provide guaranteed data delivery. The connection-oriented service is provided by Transmission Control Protocol (TCP) which provides reliability in addition to congestion control and flow control. Although TCP is suitable for the typical wired internet, it does not meet the requirements of smart grid NAN communication. Some of the requirements for the transport protocol in smart grid NAN communication are security, ease of availability, reliability, scalability and real time response. An important challenge which limits the performance of transport protocols in NAN of smart grid communication network is Head of Line (HOL) blocking which occurs due to the large number of consumers connected to the grid.

In order to cope with the HOL blocking in NAN of smart grid communication network, we suggest augmenting the Stream Control Transmission Protocol (SCTP) with Link Layer Retransmissions (SCTP-LLR). SCTP is a reliable transport protocol with multi-streaming features which open multiple streams between end systems or peers. In our proposed SCTP-LLR mechanism, we use the multi-streaming feature at the end systems (smart meters and control center) and implement link layer retransmissions at the aggregator which connects wirelessly with the smart meters. Through simulations in Network Simulator (ns-allinone-2.35), we analyze SCTP-LLR mechanism in terms of throughput and delay for NAN in smart grid and compare it against TCP and SCTP. We find that SCTP-LLR outperforms both TCP and SCTP.

II. RELATED WORK

In [2] the TCP-aware link layer retransmission method for cellular networks called snoop was proposed and evaluated. In this scheme, the link-layer protocol takes advantage of the knowledge of the higher layer transport protocol. The snoop protocol introduces a module at the base station where the snoop agent monitors every packet which passes through the TCP connection in both directions, that is wired and wireless. It maintains a cache for the unacknowledged packets which are sent by the receiver across the link. A packet loss is detected by the arrival of a small number of duplicate ACKs from the receiver or by a local timeout. The main advantages of this approach are: 1) duplicate acknowledgments for TCP segments are suppressed and 2) local packet retransmission is carried out to avoid unnecessary fast retransmissions and congestion. The snoop approach suffers from not being able to completely shield the sender from wireless losses. Our protocol closely matches the snoop operation, however we select the access point of IEEE 802.11ah for link layer retransmissions and implement multiple streams of SCTP at the higher layer.

In [3] several schemes for enhancing TCP performance over different networks were evaluated. The schemes were organized into three wide categories: link-layer protocols that arrange local reliability, end-to-end TCP where loss retrieval is executed by the sender and split-connection protocols where the end-to-end link is divided into two portions at the base station. Wireless channels were categorized by the propagation phenomenon, along with fading, the reason of irregular high bit error rates causes packet loss in the wireless link. The throughput suffers due to packet loss through wireless link in the end-to-end connection. Their results support the idea of retransmissions in wireless domain for better results.

In [4] the performance of Session Initiation Protocol (SIP) over TCP was measured. SIP located in application layer, is a session initiation and signaling protocol used to create, maintain and close a connection between two end points. The analysis showed that SIP suffers from HOL blocking due to out of order delivery of TCP packets. It is concluded that SCTP gives encouraging results for SIP instead of other transport protocols like UDP or TCP. In [5], SCTP performance for the IPTV applications was investigated and found suitable. In [6], the IPTV technology invented to provide TV streaming for the end clients over Internet Protocol was described. IPTV offers several features in order to provide high degree of reliability of network resources to meet client's satisfaction. The authors proved that SCTP is a reliable transport protocol which has a mechanism to improve the performance of IPTV applications and give better results than UDP and TCP.

In [7] the benefits of SCTP over TCP and UDP were explained and it was stated that in TCP, the sender can send only one stream of bytes to the receiver whereas SCTP maintains multiple streams between sender and receiver within single association. This feature is known as SCTP multi-streaming. SCTP has a multi-streaming feature within an association to send data on multiple streams, these streams inside the association contains a unique number to send in-order data delivery. TCP includes a three way handshake mechanism to prevent the risk of Denial of Service (DOS) attacks. Whereas, SCTP establish a four way handshake mechanism to avoid DOS problem by using a cookie called INIT-ACK Chunk [8].

We enforce our choice of IEEE 802.11ah at the link layer by observing that this standard achieves higher throughput [9]. IEEE 802.11ah is a new global WLAN standard which uses Sub-1 GHz frequency band. This standard performs better than the other low-rate wireless standards in terms for Internet of Things (IoT) for the real time Machine-to-Machine (M2M) communication in smart grid.

III. SMART GRID COMMUNICATION NETWORK

The smart grid communication network provides bi-directional intelligent services, different from the conventional data communication services. From the architectural perspective, the smart grid communication network comprises of three layers:

- Communication layer: performs bi-directional interface functions between utilities, consumers, operators and grid components.
- Physical and Control layer: deals with the core functions such as power generation, transmission and distribution.
- Application layer: concerned with providing services to several applications to facilitate consumer or control systems.

The communication layer of the smart grid was designed to exchange data between smart meters and collection points. Smart grid communication requires high level of integration for multiple combinations among applications [10]. A well-engineered model is required to provide guarantee of data delivery among all smart grids. However, many smart grid communication architectures exchange information among smart grid tiers and also provide information to connect these tiers with the integrated smart grid networking architecture. The smart grid communication layer consists of the following parts as defined in [11]:

- Customer premises connect their devices with in the home network as an end user. In this manner, Home Area Network (HAN), Building Area Network (BAN), or Industrial Area Network (IAN) exists to connect groups of devices with smart grids.
- Advanced Metering Infrastructure (AMI) works separately with Neighborhood Area Network (NAN)/ Field Area Network (FAN).
- Control center observes smart meters for data storage and data analysis through WLAN Network of AMI enterprise.

NAN plays the role in information collection from multiple HANs and delivery of data to the utility company. The key communication parameters in smart gridw are network range, data rate and prospective technology. Power Line Communication is common for both HAN and NAN [12, 13]. Some of the important dynamic requirements for smart grid network design are listed below:

- IP Network
- Scalability for future deployment plans
- Real-time capability
- Robustness and reliability
- Broad coverage
- Security
- Cost Effectiveness

IV. SCTP-AWARE LINK LAYER RETRANSMISSION MECHANISM

A. SCTP Overview

Stream Control Transmission Protocol (SCTP) is a connection oriented transport protocol running over IP which is a connectionless network layer protocol. Internet Engineering Task Force (IETF) developed this protocol for transporting Public Switched Telephone Network (PSTN) signaling messages on top of IP networks. Further, it holds promise to support a variety of applications. SCTP is an end to end connection for exchanging information between two end points and uses multi-streaming feature for transmission of data. Each SCTP supports multiple independent streams which are unidirectional. Transmission Sequence Number (TSN) distinguishes between multiple streams in each SCTP. Each stream contains a sequence number known as Stream Identifier (SI). These two parameters are needed to provide uniqueness of each data chunk. Stream Sequence Number (SSN) discriminates data fragments into a stream. Stream Identifier is the most important number to differentiate one stream from other streams. When using multiple streams in multiple associations, the order of delivery is not considered. However, all streams within an association should be in-sequence. The HOL blocking can only affect messages inside a single stream, and other streams while other streams remain unaffected [1]. Any delay or retransmission in a stream does not affect other streams.

A scenario of in-order data delivery in multiple streams of an SCTP is further described in [1]. Each stream is allocated a buffer at the transport layer of receiver. Stream Identifiers are unique in order to direct fragments with the same Stream Sequence Number to the proper stream. Stream Sequence Numbers are used to ensure in-order data delivery within a stream. In case fragment with SSN-22 is lost and does not reach the receiver while fragment with SSN-23 reaches the receiver, SSM-23 is buffered till SSN-22 is retransmitted and received thus delivering in –order data to the upper layer.

B. IEEE 802.11ah

IEEE 802.11ah standard provides higher throughput for Internet of things (IoT) and Machine to Machine (M2M) applications. The goal of this standard is to develop a global Wireless LAN (WLAN) standard that can perform functions in Sub-1 GHz frequency in ISM band to send burst-data between low energy devices. It can cover up to one kilometer of area. The operating technology contains one or more bands as follows: 917-923.5SMz (Korea), 950.8-957.6SMz (Japan), 863-868.6SMz (Europe), 902-928SMz (USA) and 314-316SMz, 430-432SMz, 433.0-434.8SMz (China) [14]. This standard increases the coverage area for the IoT and improves the efficiency for the M2M communicating devices. It is possible to achieve low costs by using simplified hardware-structure for the IoT device components. Overall these characteristics make this standard suitable for use in smart grid communication networks.

Some of the notable features of IEEE 802.11ah standard are:

- Compatible with the 802.11 WLAN legacies.
- Coverage range up to 1000m much higher than Bluetooth and ZigBee.
- Supports data rate of 100 kbps and more.

C. Design of SCTP-LLR

Our proposed protocol SCTP-LLR is designed for smart grid communication networks, for end to end bi-directional communication between smart meters and control center through data-concentrator or aggregator. Figure 1 shows the network model for SCTP-LLR. SCTP is implemented at the smart meters and control center at the transport layer while link layer retransmissions are carried out by the aggregator through a link layer module. SCTP-LLR design includes details of operation both at the transport layer and the link layer though the main emphasis is on the link layer module implemented at the aggregator. Each packet is temporarily cached at the Data-Concentrator (aggregator) which performs local retransmissions across the link in case of packet loss. Typically, the cache size is proportional to the propagation window size.

SCTP has the same congestion control mechanism as TCP with some small changes. One of the differences between the two is that in SCTP the initial window size is equal to 2 times the link MTU, the congestion window increases based on the acknowledgment of bytes and SCTP does not have the fast recovery mechanism. Since we are implementing SCTP as the transport layer protocol, we support multi-homing and multi-streaming features of SCTP as discussed in earlier sections. During SCTP handshaking process, the link layer module at the aggregator saves sender and receiver information. Also instead of caching packets, actually chunks are cached at the aggregator.

1) Data transfer from control center to smart meters

After SCTP handshaking between the control center and smart meters, data from control center is sent to smart meters through the aggregator. When the aggregator receives a new data chunk from the control center, it caches it and then forwards it to the smart meter. When it receives acknowledgment from the smart meter, it removes the chunk from its cache. However, in case of a loss, the aggregator retransmits the lost chunk through an alternate path and does not allow the duplicate acknowledgment to reach the control center. This way data is recovered from the aggregator instead of recovering it from the control center. The aggregator keeps track of all data and acknowledgements which pass through it.

When a new chunk arrives from the control center to the aggregator, it is cached and forwarded to the smart meter. A timestamp is added for estimation of round trip time. When an out-of-sequence chunk is received from the control center is discarded. When a new acknowledgment is received, the aggregator clears its cache and updates the round trip time for the wireless link. This acknowledgment is forwarded to the control center. If the aggregator receives acknowledgment which is less than the last acknowledgment (that situation rarely happens), it discards that acknowledgment and continue packet processing. When a duplicate acknowledgment is received, if it is for a packet which is not in the aggregator cache, it is forced to be retransmitted by the control center through congestion control. If it is an ordinary duplicate acknowledgment, the aggregator retransmits the lost packet, is repeated duplicate acknowledgment is received, it is discarded.

2) Data Transfer from Smart Meter to Control Center

The smart meter monitors Negative Acknowledgment (NACKs) from the aggregator for selective retransmission of lost packets. A modification is required at the smart meter to enable Selective Acknowledgment (SACK) processing. No change is required at the control center. The LLR module has the ability to generate SACKs at the aggregator and process them at the smart meter retransmit lost chunks

V. RESULTS

A. Simulation Scenario

We simulate the smart grid network model of Figure 1 with smart meters connected to aggregator wirelessly and control center connected through wired connection. IEEE 802.11ah standard is implemented for wireless connections and LLR mechanism is implemented through the addition of a module at the aggregator which caches packets and retransmits in case of packet loss. We increase the number of smart meters connected to the NAN and observe throughput and delay when TCP, TCP-LLR, SCTP and SCTP-LLR are implemented. The transport protocols work at the control center and the smart meters while LLR mechanism is implemented at the link layer in aggregator. We implement FTP at the application layer for file transfer. The focus of our data transfer is from smart meters to control center through aggregator such that as the number of smart meters increase, the chances of HOL blocking also increases, affecting the throughput and delay.

B. Simulation Parameters

Table I lists the simulation parameters which are almost constant throughout simulations. The simulations were performed by increasing the number of smart meters and throughput and delay were observed in case of TCP, TCP-LLR, SCTP and SCTP-LLR.

TABLE I. SIMULATION PARAMETERS

Parameter	Value
Simulation time	25 seconds
Buffer size	Equal to window size
Application layer protocol	FTP
Network layer protocol	DSDV
MAC protocol	IEEE802.11ah (wireless links)
Queue type	Droptail
Queue size	50
Bit rate	250 kbps
Antenna model	Omnidirectional
Packet size	160 bytes

C. Simulation Results

1) Average packet delay

Average packet delay is the average time taken by a packet to reach from sender to receiver. It is given by Equation 1 where D_{avg} is the average packet delay, D_{agg} is the aggregate delay of all the received packets and k is the total number of packets received.

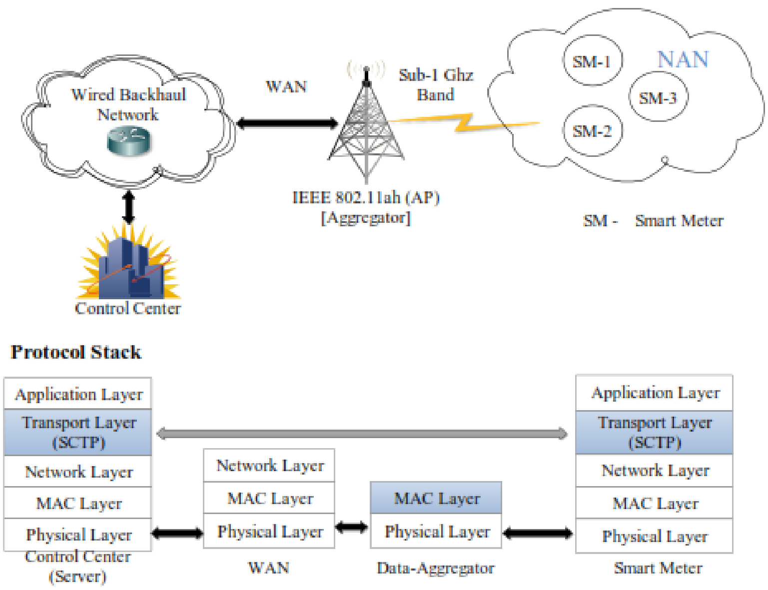

Fig. 1. Network model for SCTP-LLR mechanism

$$D_{avg}=(D_{agg}/k) \quad (1)$$

Equation 2 gives expression for D_{agg} where d_j is the delay of the *jth* packet.

$$D_{agg} = \sum_{j=1}^{n} d_j \quad (2)$$

Figure 2 shows average packet delay comparison of TCP, TCP-LLR, SCTP and SCTP-LLR for 25% and 50% network error rate respectively when transmission rate is low (500 kbps). Figure 3 shows same comparison but when transmission rate is high (2 Mbps). In both cases, the number of smart meters is increased progressively to observe the impact of increasing number of users getting connected with the NAN of smart grid. Our results show that average packet delays in TCP and TCP-LLR is high and increases as number of smart meters increase while it is low in SCTP and SCTP-LLR and does not get affected much as number of smart meters increase. The most promising performance is given by SCTP-LLR which outperforms all other transport layer protocols.

Fig. 2. Average packet delay comparison of TCP, TCP-LLR, SCTP and SCTP-LLR for 25% and 50% error rates when transmission rate is 550 kbps

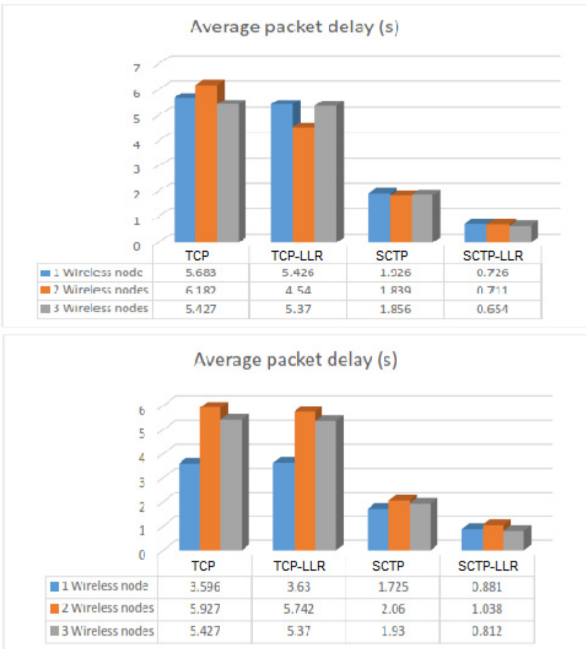

Fig. 3. Average packet delay comparison of TCP, TCP-LLR, SCTP and SCTP-LLR for 25% and 50% error rates when transmission rate is 2 Mbps

2) Average throughput

Throughput is defined as the fraction of time used by the network to successfully deliver one packet payload. Throughput provides the ratio of channel capacity used for successful transmission and it is one of the most important and useful network metrics. Throughput is calculated using:

$$T = \frac{\sum_{i=1}^{n} P_i \cdot \delta}{D_{agg}} \quad (3)$$

Where throughput is represented by T, δ is the packet size, P_i is the *ith* packet and D_{agg} is the aggregate packet delay.

Some of the parameter values defined in Table I have been used in these simulations. Throughput is compared when TCP, TCP-LLR, SCTP and SCTP-LLR are implemented in the network model of Figure 1 and number of smart meters is increased. We first carry out simulations with 25% error rate and the results are shown in Figure 4. We observe that the best results are shown when SCTP-LLR is implemented. In this case, throughput is high from the start and either increases or keeps constant while in all other protocols, throughput either remains low or suffers as time follows. Also in SCTP-LLR, throughput is not affected much by the increasing number of smart meters. Figure 5 shows throughput comparison when error rate is set to 50%. The same results are observed and we conclude that SCTP-LLR outperforms other protocols in terms of throughput.

Fig. 4. Throughput comparison of TCP, TCP-LLR, SCTP and SCTP-LLR for 25% error rate as number of smart meters increases

Fig. 5. Throughput comparison of TCP, TCP-LLR, SCTP and SCTP-LLR for 25% error rate as number of smart meters increases

VI. CONCLUSION

In this paper, SCTP aware Link Layer Retransmission (SCTP-LLR) mechanism is presented to deal with wireless link losses in NAN of smart grid communication network. The basic idea is to implement a link layer module at the aggregator which connects wirelessly with smart meters and wired with the back end control center. This link layer module enables retransmissions of chunks from smart meters thus suppressing end to end retransmissions between control center and smart meters. We tested this mechanism through simulations in Network Simulator which show that SCTP-LLR mechanism shields the sender from duplicate acknowledgments arising from wireless losses resulting in throughput improvement and delay reduction. The results demonstrate that the SCTP-LLR mechanism outperforms other transport protocols like TCP, TCP-LLR and SCTP in terms of throughput and packet delay.

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