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Comparative Analysis of TCP, UDP and SCTP in Smart Meter Data Transfer

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ABSTRACT

The ever-increasing demand for electricity has caused a lot of problems to utility companies all over the world. One challenge has been that the old metering system hasn't been readily configured to rapidly match the current demand patterns as it suffers from many short comings like poor and insufficient interaction between consumers and utility companies. This has prompted utility companies to implement smart meters in their distribution networks. TCP is one common protocol in smart meters but as we know one big challenge with sending data using TCP is that it Introduces data overheads, hence, there's possibility that TCP introduces some form of delay in smart meter response time. This research aimed at comparing the data transfer rates for different transport layer protocols and recommending the best protocol based on their delay as we shall see from the simulation. OPNET was used to simulate and develop a smart meter network by deploying an ethernet network of smart meters. Since the OPNET platform has no specific smart meters available, a smart meter was developed using an advanced workstation (node) in OPNET and configure it with typical characteristics of a smart meter within the TCP/IP application protocol One big challenge in this experiment was that SCTP is a new protocol and has not been integrated fully in OPNET. The lack of smart meter nodes also meant that results did not actually reflect a true scenario of how a true smart meter would perform in reality.

Keywords: Smart meter, OPNET, Protocol, Simulate, TCP=Transmission Control Protocol, SCTP=Stream Control Transmission Control, IP=Internet Protocol.

INTRODUCTION

The ever-increasing demand for electricity has caused a lot of problems to utility companies all over the world. The energy system has expanded rapidly over the years in many countries especially Europe and the United States especially in the areas of distributed generation (DG).

The biggest challenge has been that the old metering system hasn't been readily configured to rapidly match the current demand patterns as it suffers from many short comings like poor efficiency, high cost of energy consumption, low fault detection speed as well as insufficient interaction between consumers and utility companies. Most distribution equipment is outdated and need replacement, while most governments are under pressure to reduce cost of electricity by enforcing laws that bring about competition in electricity generation, transmission and distribution.

Ongoing research and developments in power systems have contributed in developing of reliable and efficient grid systems which support distributed generation, security, reliability as well as interaction between consumers and utility companies. These systems have been called smart grid because they make use of intelligent electricity delivery system which combine modern digital and information technology to provide reliable, secure and many more benefits for both utility companies and consumers. Smart grid intends on modernizing the existing grid system for better efficiency and interaction. The most integral component in the smart grid system is the use of smart meters at the consumers premises. Smart meters measure electricity digitally and sends such data to the utility company through an inbuilt communication module. The old electromechanical and electronic meters could not send notifications to consumers, detect outage at meter side or provide multiple tariff schemes as with smart meters.

Smart meters can provide energy saving through Time of Use rates. This means that utility companies can set different tariffs at different day times to reflect true cost of generating electricity. Consumers can be serviced with warning alarms before peak rates can be applied e.g., consumers can avoid using high power equipment like pressing iron at high tariff times or peak demands. If consumers are able to maintain their electricity usage low but system senses more demand for electricity on the grid the power management system at the utility end can switch on peak plants like solar mini grids or standby generators to compensate the grid. The smart metering system aims to make the real-time changes during load unbalancing, switching of loads, and/or any failure conditions that occurred in the distribution system without operator intervention. Smart meters with communication protocol TCP/IP will play an essential role in this technique's operation. The smart meters send data via a secure communication protocol TCP/IP to the Local Data Concentrator (LDC) or Local Control Device (LCD). The local controller takes the necessary actions.

Several researches have evaluated the performance of smart grid networks, mostly using TCP/IP and other communication protocols. Communication protocols have been used to send data from simulation and receive it back. [1] Proposed two-level control architecture where the model has been designed using MATLAB/SIMULINK. To attain it, the model consists of two LV distribution networks falling under one substation. Thus, two local controllers and one master controller have been modelled. The simulation suggests use of TCP communicational protocol which is slower than UDP or SCTP and uses way too many overhead data. [2] compares two major measurements which are delay and throughput for both SCTP and TCP of smart grid communications and shows a moderate benefit from using SCTP due to superiority evidence of SCTP over TCP. [3] argues that smart grids are a driver towards a future low-carbon electricity system. In [4], authors made a summary of wired and wireless communication methods for smart metering. According to the authors power line communication is an ideal low-cost method for smart meters. They've also presented an Orthogonal Frequency-Division Multiplexing (OFDM) scheme based on the PLC system.

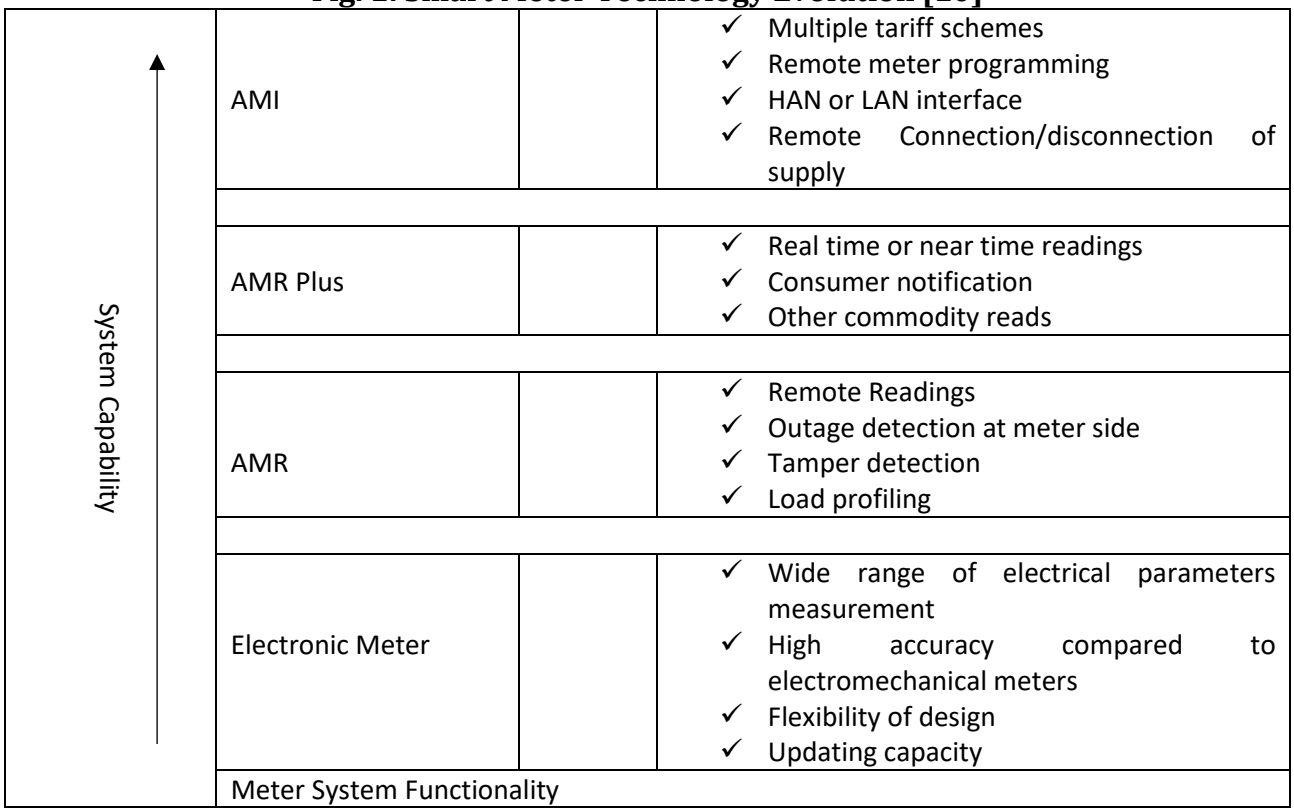
The work did not explain the different power outage problems that occur in power systems. [3] Introduced Global System for Mobile Communication (GSM) and ZigBee-based smart meters, which calculate the energy and send the results to the Telco company, who then puts these results together and acquaint the consumer through SMS messages or the internet. [4] Studied

the possibility of using wireless sensor networks (WSN) in a smart grid network especially in seaport location but studies don't really show the protocol to be used at the transport layer. [5] The power line communication modem is used to send and receive the data between the server and the energy meter. Results are presented to validate the hardware implementation of the protocol (OSI) but does little work in evaluating throughput efficiency on the suggested protocols. [6] Discusses several transmission media for smart grid networks but does not show by means of experiment how these technologies can be of use or even to show their robustness in smart grid communication. [8] Introduced the energy theft detector that tracks suspicious customers based on their regular and malicious consumption patterns. [9] States that the European Commission has been working on the definition of the policies that will address future transport protocol requirements. Having reviewed so much work on smart meters, it seems that little work has been done to compare transport layer protocols to ascertain the best option for smart meter data transfer especially in comparing the three main candidate protocols which are TCP, UDP and SCTP. This article will compare the three protocols to understand their strengths and weaknesses as far as their use are concerned in smart meter data transfer.

ELECTRICITY METERING TECHNOLOGY AND HARDWARE STRUCTURE

Smart meters are different from conventional electrotechnical and electronic meters because of their additional functionalities and features.

Fig. 1: Smart Meter Technology Evolution [10]



Electromechanical meters were the first type of energy/electricity metering system [11]. They could only measure active power which is typically displayed on a mechanical counter in kWh. It was designed with four major systems i.e., driving system, moving system, braking system and the registering system. Two electromagnets make up the driving system while the moving system had an aluminum disc. [12] Breaking system was made up of a permanent magnet while the gear train acted as the registering system. The electromagnetic force would then be produced by a combination of voltage and current coils. Voltage coil was always connected across the supply then the current coil connected in series with the load. [12] Voltage coil would then produce a magnetic flux in proportion to the voltage then the current coil produces a magnetic flux proportional to the current. Aluminum disc was mounted on a rigid disc. The mechanical force would then be exerted on the disc by the Eddy currents produced. The register movement would then integrate the speed of the disk over the time by counting the number of revolutions [12].

Current coil produced the alternating flux which was proportional and in phase with the load current. Voltage coil carried a current proportional to the supply voltage. The flux that was produced by the voltage coil was not in phase with the voltage because it was lagging by 90°. However, some electromechanical meters used winding with the series connected lag adjusting resistor to perform this task [13].

As seen in fig. 1 electronic meters were more flexible in operation compared to the electromechanical meters as they were capable of measuring electricity usage with digital technology as well as other electrical parameters like phase voltages, current, frequency, power factor, active/reactive power as well as power quality measurements. Apart from these measurements, they're also capable of sending data through a communication link.

Typically, electronic meters consist of power supply, microcontroller chip, Real Time Clock (RTC), LCD display and communication ports. They have voltage and current inputs with a reference voltage. Voltage and current signals are processed to measure and display electrical parameters. They provide timely data, high accuracy in measuring a wide range of loads. They do not get influenced by external magnets, therefore, they're more reliable than electromechanical meters [14].

With the advent of time, designers added more functionalities to improve performance of electricity transmission and distribution. Therefore, apart from Automatic Meter Reading (AMR) a function which was present in electronic meters, smart meters brought about two-way communication between the meter and the utility company. All this is achievable through a feature called Automatic Metering Interface (AMI). Things like load profiling, pre-payment, remote disconnection and multi tariffing are also possible with smart meters [15].

Hardware Structure of a Modern Smart Meter

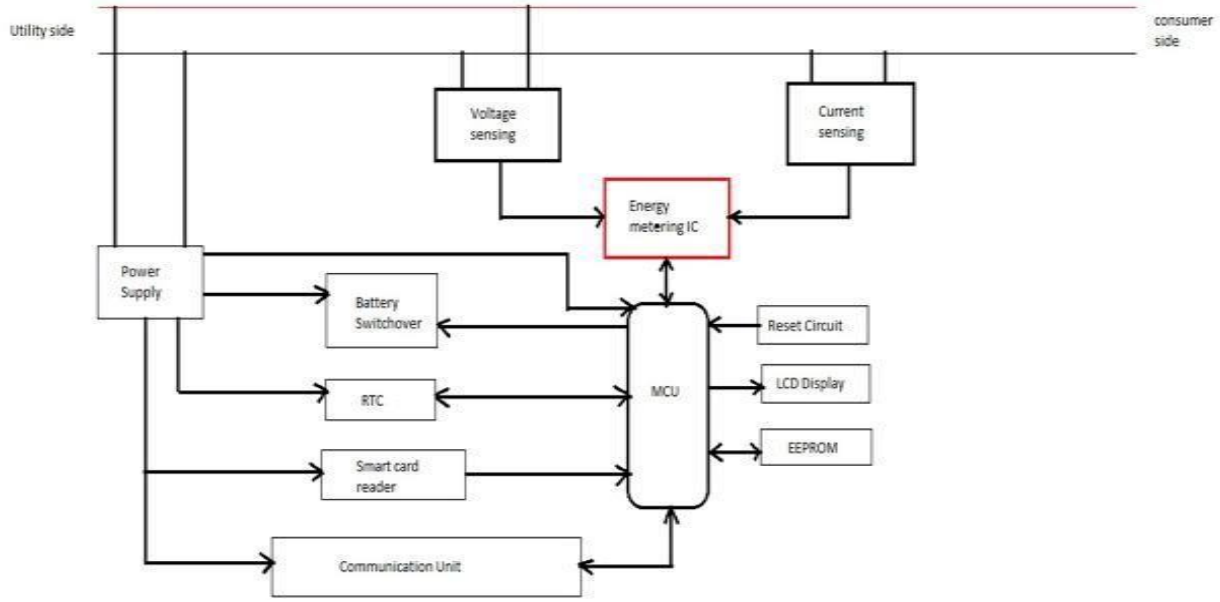


Fig. 2: Hardware Structure of a modern electricity smart meter [16]

A modern smart meter consists of the following hardware components;

- Voltage and Current sensing unit
- Power Supply
- Energy measurement unit
- Microntroller chip
- Real Time Clock
- Communicating System

In a typical smart meter, voltage and current sensors are connected to the microcontroller unit through the signal conditioner which does the ADC i.e., analogue to digital conversion. Resistor dividers are mostly used as voltage sensors because they're cheap [17].

The current sensors can make use of current transformers to produce a secondary current which is proportional to the primary current. Magnetic properties of the current transformers are highly linear over a wide range of primary current and temperature. Although current transformers are inexpensive as compared to other forms of current sensors like shunt resistors, they have nonlinear phase response at low currents and large power factors [17].

The power supply unit mostly varies from one smart meter designer to another. In essence the smart meter is a 230/12 volts step down transformer with a maximum current of 1A which is used to provide the required power. Basically, a total of three DC voltage levels of 5V, 3.8V and 3.3V are used to power the microcontroller which operates at 5V, the GSM module which operates at 3.8V and the Real Time Clock which operates at 3.3V. The circuit charges a 12V rechargeable battery when power is present. When power is off the battery can handle all components in the smart meter for 24hours. Therefore, the microcontroller goes into the sleep

mode when power is off in the main supply. The microcontroller writes the last data obtained from the energy chip to its EEPROM before it goes into sleep mode [17].

The energy measurement unit converts analogue to digital signals and computations which are later passed on to the microcontroller.

The microcontroller practically controllers all functions of the inside smart meter and for that it's considered the core of the smart meter. Some of the notable functions include;

- Communication with the measurement chip
- Tamper detection
- Calculations based on received data
- Communication with the energy measurement chip
- Smart card and sim card reading
- Power management as well as communication with other devices

The real time clock keeps track of the current clock. It provides time as well as date information and is mostly built-in to the energy measurement chip which communicates with the internal microchip [18].

COMMUNICATION SYSTEM IN MODERN SMART METERS

The communications system in smart meters consist of capabilities such as communication gateway, intelligent control and management. All these make up the Advanced Metering Infrastructure of smart meters which distinguishes smart meters from electronic meters (AMI). AMI consists of several communication protocols such as Home Area Network (HAN) which is used to establish communication link between smart meters and smart appliances or the in-home display units. The Neighborhood Area Network (NAN) is used to transfer data between smart meters within the same neighborhood. Zigbee communication has been the widely used communication protocol. Smart meters connect to remote servers of the utility companies, this is done through the Wide Area Network (WAN). The communication between remote servers and smart meters is facilitated by the data concentrator. GSM, GPRS, 3G and other available telecommunication technologies such as WiMAX are used to connect the meter to the Wide Area Network. Our main interest at the moment is communication at the transport layer, so we shall delve a little bit deeper to understand how communication is done at the transport layer to understand the application of TCP, UDP and SCTP in a smart meter [19].

The TCP/IP Protocol Suite

The Internet protocol suite, commonly known as TCP/IP, is a framework for organizing the set of communication protocols used in the Internet and similar computer networks according to functional criteria.

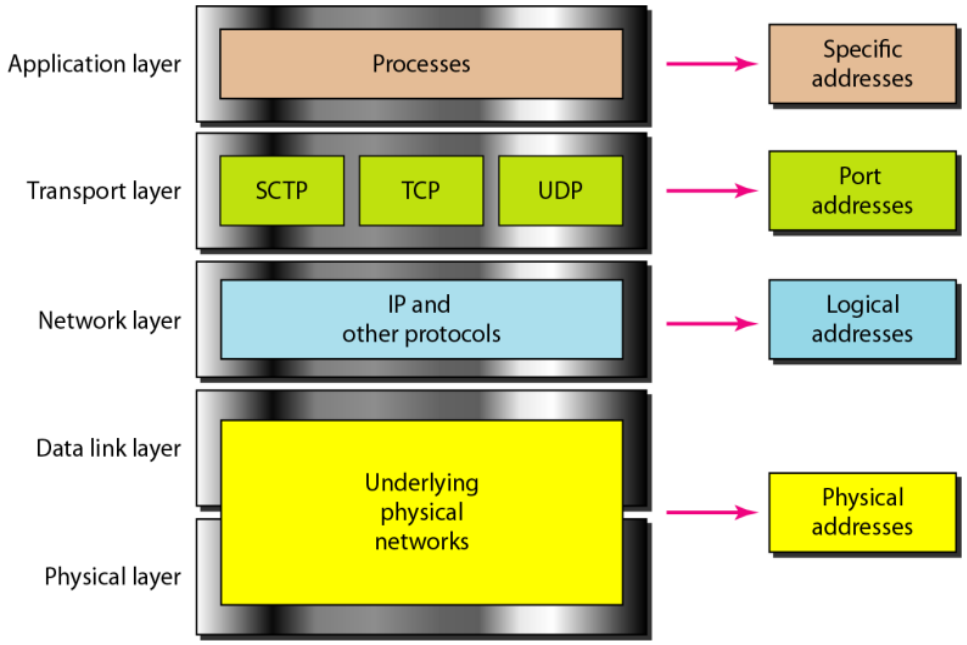


Fig. 3: TCP/IP Protocol Suite [20]

The host-to-network layer is the lowest layer of the TCP/IP model. It is concerned with the physical transmission of data and can be seen as a combination of the Data Link and Physical layers of the OSI model. The protocols it supports include Ethernet, Frame Relay, Token Ring and ATM [21] The Network layer is responsible for logical transmission of data over the internet and routes each of the data packets independently from the source to the destination, using the optimal route. The protocols it supports include Internet Protocol IP, Address Resolution Protocol ARP, Reverse Address Resolution Protocol RARP, Internet Control Message Protocol ICMP and Internet Group Message Protocol IGMP [21].

The transport layer is responsible for error-free and end-to-end delivery of data from source host to the destination host. It corresponds to the transport layer of the OSI model. We shall come back to the transport layer after we're done with introduction of the TCP/IP model [21]. The application layer is the highest layer of the TCP/IP model and it provides the interfaces and protocols needed by users. It combines the functionalities of the session layer, presentation layer and the application layer of the OSI model. The protocols it supports includes Hyper Text Transfer Protocol HTTP, File Transfer Protocol FTP, Simple Mail Transfer Protocol SMTP, Domain Name System DNS, TELNET and Simple Network Management Protocol SNMP [22]. Let's look at the Transport layer a bit further to understand its working, protocols used and how they apply to data transmission.

Transport Layer in TCP/IP Model

As alluded to earlier the transport layer is responsible for error-free and end-to-end delivery of data from source host to the destination host. The transport layer in TCP/IP differs from transport layer in OSI model in that the transport layer in OSI model is always connection oriented while that in TCP/IP can either be connection or connectionless. For the sake of this research, we shall concentrate on TCP/IP [22].

How the Transport Layer Works

The transport layer mainly supports 3 protocols to provide end to end connection; Transmission Control Protocol TCP which is connection oriented, User Datagram Protocol UDP which is connectionless as well as Stream Control Transmission Protocol SCTP which combines some of the features of TCP and UDP [23] Let's closely look at the three protocols in detail.

Transmission Control Protocol:

Transmission Control Protocol (TCP) is a transport protocol used to ensure reliable transmission of packets. It includes mechanisms that solve many of the problems arising from packet-based messaging such as lost packets, out of order packets, duplicate packets, and corrupt packets [22]. It is the underlying communication protocol for a wide range of applications such as web servers, websites, email applications, FTP and peer-to-peer apps. TCP operates with the internet protocol (IP) to specify how data will be exchanged online. IP is responsible for sending data packets to their destination, while TCP guarantees that bytes are transmitted in the order they were sent with no errors or omissions. Together, the two protocols are referred to as TCP/IP [23]

Three-way handshake - Establishment of the TCP connection requires that both the client and the server participate in what is known as a three-way handshake [23]. The process can be broken down as follows:

1. A client sends the SYN packet to the server—a connection request from its source port to a server's destination port.
2. The server then responds with a SYN/ACK packet, acknowledging the receipt of the connection request.
3. The client then receives the SYN/ACK packet and responds with an ACK packet of its own.

When the connection has been established, TCP breaks down data packets into segments, each of which is packaged into a datagram and sent to its destination [24].

User Datagram Protocol (UDP):

User Datagram Protocol (UDP) is a connectionless transport layer protocol of the Internet Protocol (IP) suite. It is mostly contrasted with Transmission Control Protocol (TCP) which is a connection-oriented protocol. UDP is known for its low overhead making it suitable for applications where low latency and real-time data delivery are more critical than guaranteed delivery and error recovery [23-25]. Here's a detailed account of how UDP works, especially in the context of smart meter data transfer:

Connectionless Nature:

As mentioned earlier UDP is connectionless meaning that there is no establishment of a connection before data transfer begins. Each packet is treated independently, and there is no ongoing relationship or state between the sender and the receiver [25]

Header Structure:
UDP packets consist of a simple header that includes a source port, a destination port, a length field, and a checksum field. The source and destination port numbers identify the applications or services on the sending and receiving devices [25-26]

Port Numbers:
Port numbers help in identifying the specific process or application on the sender and receiver sides. For example, in the context of smart meter data transfer, the UDP ports might be assigned for communication between the smart meter and the data collection server [26]

Low Overhead:
UDP has a lower overhead compared to TCP. It does not involve the complex handshaking and error recovery mechanisms that TCP employs. This makes UDP more suitable for applications where speed and efficiency are more critical than guaranteed delivery.

Real-Time Applications:
UDP is often preferred in real-time applications such as video streaming, VoIP (Voice over Internet Protocol), and smart meter data transfer. In the context of smart meters, where timely data transmission is crucial, UDP can be used to quickly send meter readings and status updates without the overhead of establishing and maintaining a connection [26].

Application Layer Responsibility:
Since UDP doesn't guarantee delivery, reliability is always implemented at the application layer if required. For smart meter data transfer, applications may include mechanisms to confirm receipt or may tolerate occasional data loss [26]. In the context of smart meters, UDP may be chosen for its efficiency and low latency, especially when dealing with real-time data updates. However, it's essential to consider the potential trade-offs, such as the lack of guaranteed delivery and the need for additional error-handling mechanisms at the application layer.

Stream Control Transmission Protocol (SCTP):
Stream Control Transmission Protocol (SCTP) is a transport layer protocol designed to provide reliable, connection-oriented communication between two endpoints. Unlike User Datagram Protocol (UDP) and Transmission Control Protocol (TCP), SCTP offers features like multi-streaming, multi-homing, and improved reliability. In the context of smart meter data transfer, SCTP can be a suitable choice for applications that require reliable and efficient communication[28]. Below are some of the characteristics of SCTP;

Connection Establishment:
SCTP establishes a connection between two endpoints before data transfer begins. This involves a four-way handshake where both endpoints exchange initialization parameters to establish the connection. This process ensures that both parties are aware of the communication parameters before data exchange starts [28].

Multi-Stream Support:
One of the distinctive features of SCTP is its support for multiple streams within a single connection. Each stream operates independently, allowing for parallel data transmission. This can be particularly useful in smart meter data transfer scenarios where different types of data (e.g., meter readings, status updates) can be sent concurrently over separate streams [28].

Reliability with Acknowledgments:
SCTP ensures reliable data delivery by employing a selective acknowledgment mechanism. The receiver acknowledges the receipt of individual messages, allowing the sender to retransmit only the necessary data in case of packet loss. This selective acknowledgment contributes to efficient use of network resources [28].

Error Detection and Correction:
SCTP includes a checksum mechanism to detect errors in the transmitted data. If an error is detected, the erroneous segment is discarded and the receiver can request retransmission if necessary. This contributes to the reliability of data transfer [28].

Flow Control:
SCTP incorporates a flow control mechanism to prevent overwhelming the receiver. This helps in adapting the rate of data transmission based on the receiver's ability to process the data, ensuring efficient and fair utilization of network resources.

Multi-Homing:
SCTP supports multi-homing, allowing a single endpoint to have multiple IP addresses. This can enhance fault tolerance and resilience in smart meter networks, where devices may have multiple network interfaces or paths to communicate with a central server [28].

In summary, SCTP provides a reliable and feature-rich alternative to TCP for applications like smart meter data transfer. Its support for multi-streaming, multi-homing, and efficient error recovery makes it well-suited for scenarios where reliable and flexible communication is crucial.

SIMPLE SMART METER NETWORK SIMULATION

A simple smart meter network simulation was designed to compare the three protocols using OPNET.

Development of Smart Meter Network Using OPNET

A smart meter network allows for data access between smart meters and the server. The communication with smart meters requires the creation of a topology for connecting them to the server. To develop an appropriate model of a smart meter network, a model was developed within OPNET environment to analyze data transfer delay amongst the three protocols.

Limitations

Because OPNET does not have smart meter nodes, advanced workstations were used and configured with characteristics of a smart meter. The three workstations were configured with

the three protocols i.e. first smart meter configured with TCP; the second smart meter configured with UDP. As for the third smart meter there was another challenge of locating SCTP in OPNET. As stated earlier in my introduction SCTP seems to be a new protocol which has not yet been implemented in OPNET, therefore, the closest I could get to simulating SCTP was to use a combination of TCP + UDP which is available in OPNET. As we know from its characteristics SCTP seems to bear the qualities of both TCP and UDP, therefore, it was assumed that simulating a combination of the two protocols might get us closer to what would look like SCTP when in fact not.

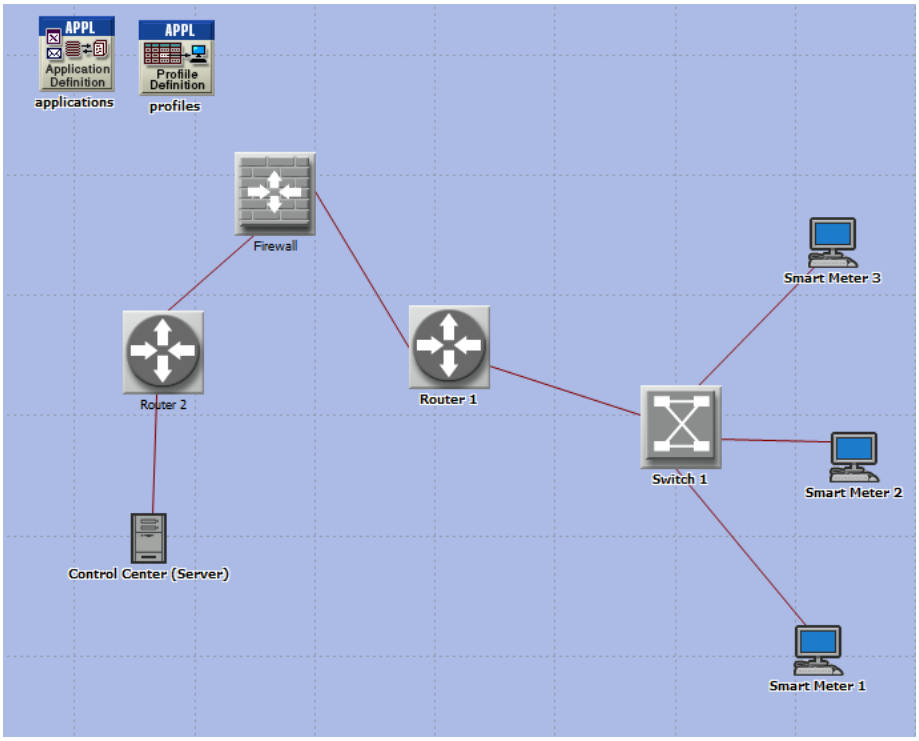


Fig. 4: Smart Meter Network Design Using OPNET.

Results

The main focus of this experiment was to compare delay in the three protocols so that from an experimental position we can ascertain which protocol would offer better transfer speeds as applied to smart meters, therefore, whilst the set up of this experiment could offer other results like received traffic, throughput etc only one result (delay) was captured to make the comparison.

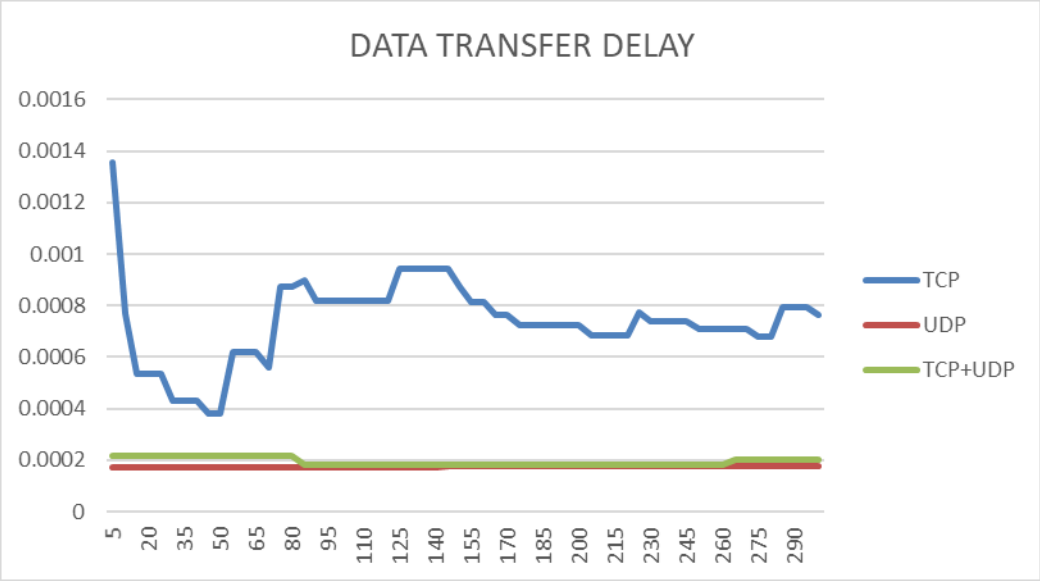


Fig. 5: Comparison of Data Transfer Delay Amongst TCP, UDP and SCTP

As seen from the graph, TCP (blue line) shows a high delay at start of simulation almost reaching a delay of 0.0014 seconds but suddenly drops and almost maintains a uniform delay. A combination of TCP + UDP which offers similar attributes as SCTP shows a slight delay (purple line), much better than TCP but not better than UDP a connectionless protocol.
UDP (Orange line) almost shows negligible delay.

CONCLUSION AND RECOMMENDATIONS

Choice of transport protocol for data transfer in smart meters should be based on the specific requirements and constraints of the application. TCP, UDP, and SCTP each have their own strengths and weaknesses, and the decision should take into account factors like data integrity, real-time requirements, network conditions, and security. In the context of smart meter data transmission, the choice of protocol is critical for balancing reliability, efficiency, and suitability for real-time applications. TCP offers high reliability but at the cost of efficiency, making it less suitable for real-time applications. UDP excels in efficiency but sacrifices reliability. SCTP provides a balance by offering reliability, efficiency, and suitability for real-time data transmission, making it a promising choice for smart metering applications. Seeing that each of the available protocols has benefits not found in the next protocol, it would be ideal to develop hybrid transport protocol solutions that dynamically adapt to different network conditionse e.g. TCP+UDP as the case of SCTP based on specific data transfer requirements as well as development of intelligent algorithms that can automatically select the most ideal transport protocol.

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