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Area Limitations on Smart Grid Computer Networks

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Abstract

Smart grid implementations rely on the real-time monitoring and controlling of the electric power grid. To achieve real time there is need for a messaging system with minimum delays. After mentioning latest implementations and their delays we analyze the role of the different communication protocols needed within smart grids and we describe key factors to a message's delay. Taking into consideration a packet's speed constraints we then calculate a radius, within which, the ETSI communication requirements for smart grids are satisfied.

Index Terms: Smart Grid, Electrical Substation Automation, IEC61850, Real-Time Communication, Electric Power Grid.

1. Introduction

Smart grid became possible through the electricity's ability to change its properties when consumption is different than production. To be exact, electricity is produced with certain frequency value. When consumption is greater than production frequency drops and when the opposite happens frequency rises [1]. Based on that, we can measure the frequency at the consumer's side and increase or decrease production accordingly in order to balance production-consumption. A smart grid utilizes a computer network to pass the electricity's measurements and achieve real-time monitoring and controlling of the electric power grid. Current state-of-the-art includes the encapsulation of the electricity measurements from the consumer, inside a Transport layer packet and its transfer to a control center over a computer network. Results from such implementations including mainly time delays can encourage the development of smart grids. Various important implementations have been reported so far, such as the use of UDP with time delay of 4~8ms [2], a comparison between UDP and TCP with time delays of 33 and 41ms, respectively [3] and the suggestion that using application layer protocols as CoAP or WebSocket can meet the smart grid requirements [4].

The packets exchanged for distributed monitor and control have transmission delay that can, in some cases,

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be no more than 10 milliseconds [5]. In consequence, due to the strict time constraint, reliability has to be guaranteed even in cases when the network has a lot of traffic. For this reason the IEC 61850 GOOSE protocol is usually employed whose publish/subscribe mechanism can ensure fast reliable communication. IEC 61850 [6] is a standard for electrical substation automation and provides data models for all the devices inside substations in order to achieve interoperability. Utilizing a protocol from IEC 61850 means complete compatibility with electrical substations, which lowers complexity when the interaction with a substation is needed.

The following section mentions and analyses related studies. Section 3 describes the network's architecture and the use of different protocols on smart grid networks and section 4 provides information about transmission delays, requirements of smart grids and area constraints of successful implementations. Finally, section V provides general information and conclusions.

2. Related Work

In [2] the authors state that TCP which is usually used for reliable communication cannot guarantee low time latency. GOOSE on the other hand can be efficient enough especially if priority settings are implemented in the data link layer. For this reason, they implement an encapsulation of the GOOSE message into the UDP transport protocol. This way the transmission over a local area network is possible as shown in fig. 1 and using the priority settings of IP and MAC layers low latency is guaranteed among various messages.

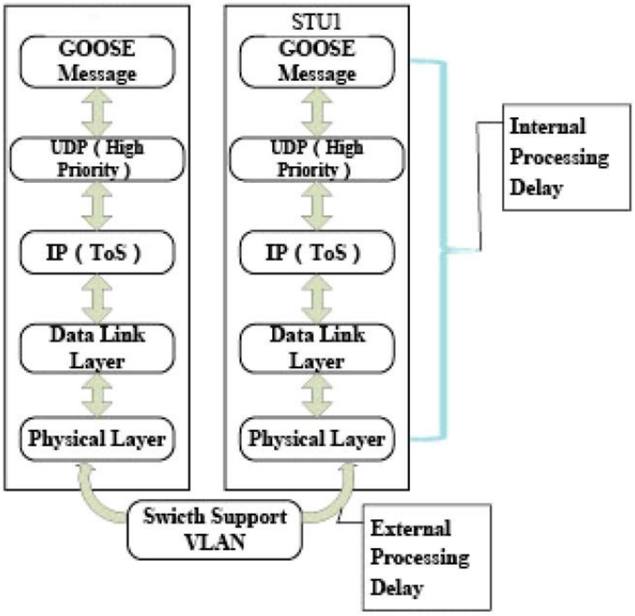

Fig.1. Transmission Mechanism of IEC61850 GOOSE over UDP

UDP though, does not ensure reliable communication and moreover, the messages can arrive out of order. With that in mind, in [2] utilizing the GOOSE retransmission mechanism is proposed. This way, reliable communication over UDP is achieved. Additionally to avoid overloading the network in case of too many retransmissions, the packet retransmission intervals are gradually increased as shown in fig. 2.

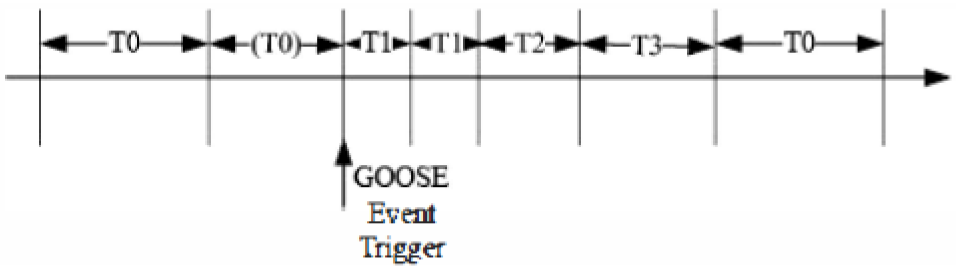

Fig.2. Retransmission mechanism of GOOSE packet

The implementation [2] using GOOSE over UDP with priority settings, which is based on IP addresses, is tested on a cascaded system with three switches. According to the results the time latency is as low as 4 ~ 8 milliseconds which points to the conclusion that this implementation can fully satisfy the demands of a real-time messaging system.

In [3] the authors develop three communication systems and argue their suitability based on the time delays. Their study includes:

- TCP/IP communication mode.
- UDP communication mode.
- IEC61850 GOOSE communication mode.

First case scenario is the TCP/IP mode. The network topology is shown in fig. 3. There are Data Terminal Units (DUT) connected with each other and every DUT has server sockets for each of the other DUTs and one client socket. Servers can initiate transmissions to the clients and respectively, the clients can request server data.

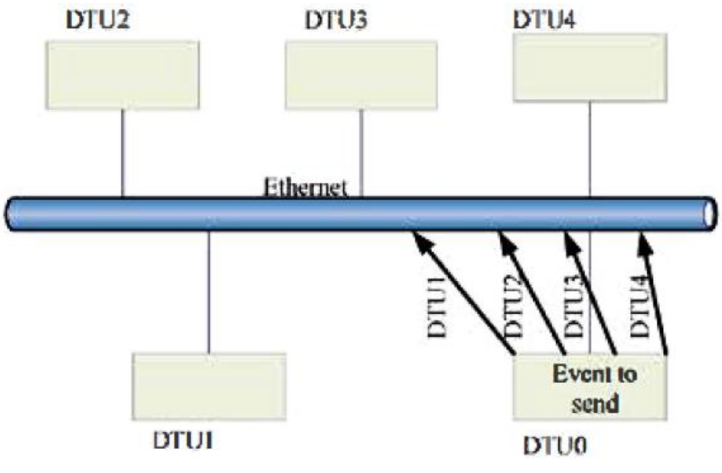

Fig.3. TCP/IP communication

Second case is the UDP communication mode, in which there are no response mechanisms. There is only address filtering through the destination IP. The network topology is shown in fig. 4.

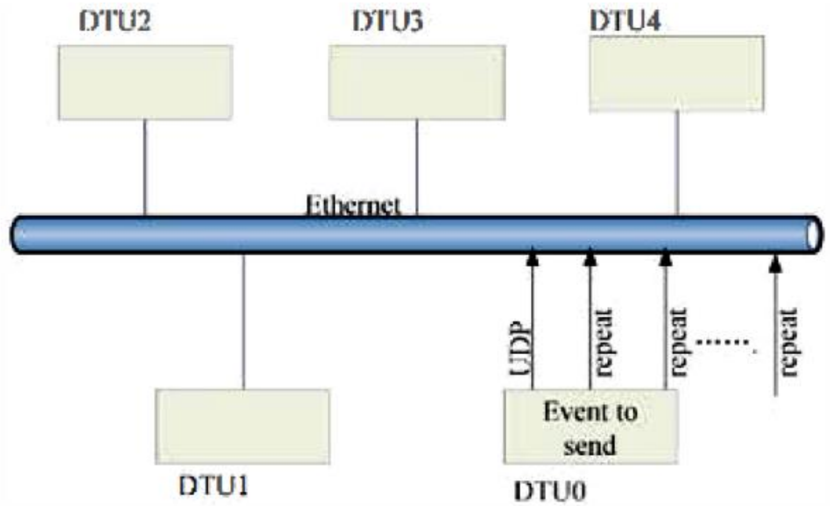

Fig.4. UDP communication

Third case, using the IEC61850 GOOSE they design a system where alarms are triggered when certain events happen. This way the system provides a mechanism for fault isolation that can be used in various scenarios including the self-healing ability of a smart grid. The topology is as shown in fig. 5. R1 to R6 are automatic circuit breakers and R0 is a contact switch. When the connection between R2 and R3 is breached by a fault, QF1, R1 and R2 detect it at the same time. After that based on the GOOSE messages that are published, the source of the fault is identified.

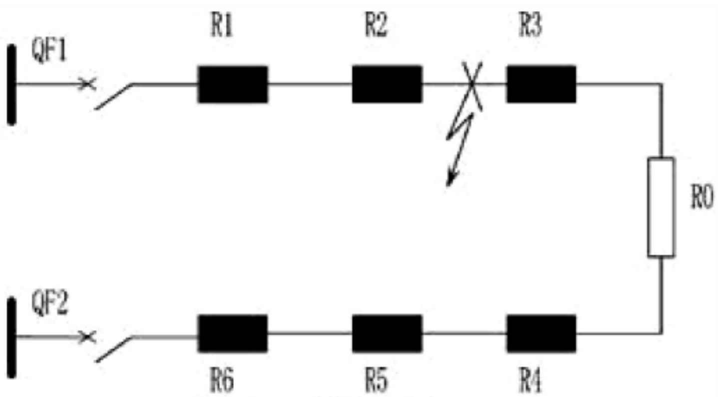

Fig.5. Fault happens between R2 and R3

The test results from the aforementioned implementations are shown in fig. 6

Node num	Communicate mode	technical requirements	Measure value
4	TCP	<50ms	41ms
	UDP	<50ms	33ms
	GOOSE	<50ms	30ms
5	TCP	<55ms	49ms
	UDP	<55ms	36ms
	GOOSE	<55ms	32ms
6	TCP	<60ms	59ms
	UDP	<60ms	39ms
	GOOSE	<60ms	34ms

Fig.6. Test results

A comparison between [2] and [3] indicates that in [3] the GOOSE's publish/subscribe mechanism is used for fast message exchange in devices connected via Ethernet (without IP) inside substations. In addition it is emphasized that using GOOSE can offer great compatibility advantages due to interoperability with IEC61850 devices. On the other hand in [2] GOOSE messages are sent over UDP which allows GOOSE messages to be transmitted using IP which is not integrated in the GOOSE protocol. Moreover, in [2] reliability over UDP is achieved by using the retransmission mechanisms of the encapsulated GOOSE message.

Another study [4] argues the suitability of application layer protocols [7] for message exchanging within smart grids. Specifically the use of protocols that are commonly found in Machine to Machine communications such as:

- Websocket
- HTTP long polling
- CoAP

The comparison among the three produces the following results as shown in fig. 7. The conclusions are that the Machine to Machine protocols can be utilized efficiently in smart grids depending on the messages' function [4].

	Header overhead	Network latency	TCP Acknowledgements
HTTP	$\simeq$ 100 bytes	est. 5 ms (RTT)	2 per each update
CoAP	6 bytes	est. 2.5 ms	N/A
WS	6 bytes	est. 2.5 ms	1 per each update
savings	94%	50%	100% (CoAP) 50% (WS)

Fig.7. Comparison among M2M protocols

3. Various Architectures

IEC 61850 [6] which is a standard for electrical substation automation design, maps the electricity data to the MMS (Manufacturing Message Specification), SV (Sampled Values) or GOOSE (Generic Object Oriented Substation Events) protocol. MMS is implemented on top of the TCP stack which means that it can travel reliably though a computer network. GOOSE and SV are implemented on top of Ethernet's Data Link layer which means that they do not adopt any Network layer features.

All the above protocols need to be implemented over a transport layer protocol in order to transfer the data to a distant computer over a WAN (Wide Area Network) and achieve remote automation of electrical substations.

The transfer protocol that will enable such communication depends on the message's function. TCP is typically used for reliable communication since it has built-in acknowledgment and retransmission mechanisms while UDP only moves the packets to the carrier and has no concern whatsoever if they are being delivered.

For the purpose of monitoring and controlling the power grid in real time the common choice would be TCP since it provides reliability which is something that UDP lacks. However considering that the goal is to achieve real time, if a packet gets lost and has to be retransmitted it will arrive a considerable amount of time later. During that time the information ceases to be useful since it no longer corresponds to the electrical grid's current state. Moreover, instead of a retransmission, the sender could have sent a newer updated value that suffers delay because of the retransmission that took its place. Taking everything into account, when it comes to real-time monitoring of the power grid, retransmissions are not just useless but might also become harmful. For this reason UDP is considered more suitable.

The MMS protocol runs on top of TCP which means that it cannot be used since it is by its nature a reliable protocol. GOOSE and SV however can be encapsulated within a UDP packet. At this point there are some options that define the network's architecture.

All the messages with the electricity's information (e.g. GOOSE) will be received from a local server. This server has the option to either encapsulate the GOOSE message to a UDP packet or to strip the GOOSE headers and add only the payload to a UDP packet. Accordingly, at the receiver's side, the first case requires a UDP server to accept the UDP packet, strip the headers and forward the encapsulated (GOOSE) packet to a (GOOSE) server. The second case requires a UDP server to receive the packet, read the information and act accordingly. Second case needs less computational time because of fewer headers and has bigger payload in each packet. Both advantages create trivial difference though. First case on the other hand, has the advantage that it reduces complexity greatly since the GOOSE message is received by a GOOSE server. As mentioned before, GOOSE is defined in the IEC61850 standard which means that all the tools that have been implemented for the standard are fully compatible and can be used. This simplifies considerably the implementation.

Another feature that needs to be implemented inside the architecture is priority settings. There are many kinds of packets being exchanged within a smart grid and not all of them serve the same function. That is why they have different priorities. Preferential treatment can be implemented on UDP packets (on the IP address) but needs to be configured on all the network devices as well (switches, hubs, routers etc.).

4. Area Constraints

The messaging system that is being used by smart grids has to be able to provide real-time monitoring and controlling. In order to achieve real-time, a packet's speed is crucial. The delivery time for each transmission depends on the transmission delay, the queuing delay and the propagation delay. The first two, are computation times directly related to the hardware that is used. The propagation delay though depends on the distance between sender and receiver. A packet's transmission speed depends on the speed of light on the specific carrier and is typically around 2/3 of the speed of light.

According to the European Telecommunications Standards Institute (ETSI), the requirements within a smart grid depend on the packet's function and its delay has to comply with the following values [5]:

Table 1. Typical Response Time according to Function

Function	Typical Response Time
Protection	1 – 10 millisecond
Control	100 millisecond
Monitoring	1 second
Metering/Billing	1 hour – 1 day
Reporting	1 day – 1 year

Protection and control, are functions that have to be performed in real time and thus, their implementation poses a challenge.

The delivery time of a packet can be calculated as the summary of the propagation delay plus the packet's transmission delay.

$$\text{Packet Delivery Time} = \text{Transmission Delay} + \text{Propagation Delay} \quad (1)$$

The Propagation Delay is calculated as the distance between sender–receiver divided by the propagation speed which is the speed of light on the carrier.

$$\text{Propagation Delay} = \text{Distance} / \text{Propagation Speed} \quad (2)$$

Packet transmission delay is calculated as the packet's size divided by the carrier's bit rate.

$$\text{Packet Transmission Delay} = \text{Packet size} / \text{Bit Rate} \quad (3)$$

The transmission delay depends on the packet size but can be counted in the scale of a few micro seconds (e.g. a 1624 byte packet being transmitted via Ethernet which has bit rate of 100 Mb/s would need approximately 116 μs). This means that the packet delivery time depends mainly on the propagation delay. Propagation speed is approximately 2/3 the speed of light and it cannot be assumed greater than the speed of light in any case. This means that the only parameter that can be changed is the distance. Considering that we already know that the packet delivery time cannot exceed 10ms for protection and 100ms for control, we can calculate a radius, within which we can achieve messaging that meets the ETSI communication requirements for smart grids.

Using (1) we can replace the packet delivery time with 10ms and 100ms respectively, in order to find the maximum distance. The transmission time along with computation time of all the devices contained in the network topology (microprocessors, switches, hubs) are considered trivial since they are counted in micro seconds. Taking everything into account, we reach the conclusion that protection can be implemented within a 2.000km radius and control can be implemented within a 20.000km radius from production. These values assume that the control center is physically located within the power production. In different case, packets have to travel from the control center to the power production which means that these packets' delivery time have to be added to the original packet delivery time.

$$\text{Delivery Time} = \text{Delivery Time A} + \text{Delivery Time B} \quad (4)$$

Where *Delivery Time A* is the time needed for a packet to travel from consumption to the Control Center and *Delivery Time B* is the time need for a packet to travel from the Control Center to the Production. Additionally, packets do not travel in straight lines within a network. Distance depends on the network's topology so the radiuses are actually smaller. Furthermore, if the packets are intended for remote control, the time needed for altering the power production has to be included as well.

5. Conclusions

Smart grids require an underlying messaging system which is able to balance production-consumption in real time. For this reason, each message has to reach its destination with minimum delay. In this paper, we present the use of key protocols and how they form a functional architecture for smart grids. Moreover, considering the propagation speed constraints for each packet, we calculate the limits of an area, within which, smart grid can be implemented according to the ETSI communication requirements for smart grids.

In addition we provide a literature review on already implemented communication systems and mention different architectures and their time delays respectively. Finally we highlight the importance of the distance among the devices within smart grids, since it is the main source of delay in the pursuit of real time. With that in mind, the propagation delay and the distance among the devices are considered essential and should be included along with the other information of power grids being monitored and controlled through high-speed computer networks.

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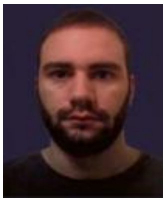
Authors' Profiles



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