Information Quality based Comparison of Transport Layer Protocols in Smart Grids

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Abstract—**One key difference in smart grid communication from other communication networks is the time criticality [1]. For certain types of exchange of dynamic information (e.g. protection, monitoring and control information etc.), the usefulness depends upon the arrival within a predefined frame of time, which in other cases does not serve the purpose and in worst case may not only de-stabilize the entire grid but lead to a less efficient controller performance. In this context, a connection-oriented protocol – TCP, guarantees the transport of messages between assets in smart grids, however, at the cost of high end-to-end delays due to the retransmission of, for instance, lost packets. This causes information to have changed/outdated for the receiver at the time of reception. Whereas UDP, a connectionless protocol, offers minimum end-to-end delays at the cost of unreliable, best-effort data transportation service. The research question raised in this paper is thus, which is preferred for the time critical applications of smart grids, and to what degree of packet losses and round trip times, TCP is preferable to UDP and vice versa. This paper addresses the issue by giving a performance comparison of both transport layer services in context of a smart grid scenario, using a quality metric called mismatch probability (mmPr). This quality metric considers the occurrence of events and the update strategy in one single metric which otherwise is not very intuitive and difficult to allow a similar useful comparison. The developed model will be used to predict and opt the best choice of transport layer protocol, and also tune the system to configure required time-out values, to meet the system requirements.**

Keywords—TCP; UDP; mismatch probability (mmPr); smart grids

I. INTRODUCTION

Today, the governments of several countries are envisioned not only to upgrade the entire power grid system to a smart grid but also to convert conventional fossil power plants into an entire renewable energy integrated system [2]. This goal will be attained by an active and reliable communication between various actors within the grid and a large scale installation of wind power and photo-voltaic (WP/PV) plants having a resilient communication infrastructure to coordinate their grid support services. Since communication plays a vital role in smart grids, further investigations strengthening system reliability are necessary regarding faster and reliable communication between WP/PV plants and system operators control centers. Smart grid applications can be supported by a number of communication technologies. However, new implementation of large scale communication infrastructure is not economically feasible. Therefore, existing communication infrastructure should be considered and further investigated for improved performance. On the other hand, it should be kept in mind that these existing communication and network infrastructures are heterogeneous, full of legacy systems and shared by many users – exposing data exchange to stochastic non-controllable delays and packet drops. This calls for a high consideration while designing systems like power grids that must provide high dependability [3].

In a smart grid scenario, the control decision made by the control-centers at any level (Transmission System Operator/Distribution System Operator) is exclusively dependent on the information provided by controllers located in WP/PV plants. Thus, it is very critical for the control-centers to be well aware of current status of their substations, as it keeps them from taking decisions based on the wrong/outdated information that can become a big risk for the entire power system. In the worst case scenario, this may result in an unstable power grid and/or a blackout.

Out of the seven OSI layer reference model it is the transport layer protocols, Transmission Control Protocol (TCP) and User Datagram Protocol (UDP), that offer different levels of end-to-end data transportation service quality to the application and determine either to guarantee data reception or not [4]. For instance, TCP provides a connection oriented [5] service that includes a mechanism to acknowledge the reception of data and a retransmission in case of lost data/acknowledgement. This allows a reliable/guaranteed transmission/reception of data packets in a causal order. TCP also provides congestion control, flow control and reliability by adding headers with the original message. However, due to the retransmissions and congestion control mechanisms, TCP generally suffers with relatively higher delays in case of dropped packets or time-outs. This, in particular, becomes serious in case of heterogeneous networks shared by many clients and can often get congested. UDP, on the other hand, provides connectionless, best effort service [6] with no guarantee of message delivery. It does not provide services like congestion control, flow control and reliability, therefore, faster than TCP. Due to the lack of such functionality, the application must accept that packets may very well be lost in the network or arrive in different order than it was sent from the source.

A lot of work has been done in comparison of these transport layer protocols. For instance, [7] analyzes the performance of TCP, UDP and some improved protocols based on TCP in adhoc wireless networks based on throughput, packet loss, jitter, end-to-end delay and fairness. Reference [8] presents the same performance evaluation as [7] but on wired network environment. In [9], an analysis of both the transport layer protocols in a wireless LAN 802.11 test bed with different scenarios has been provided considering the flow fairness with a single access point and varying the number of mobile stations. Similarly, IEC-61850 is an important international standard for electrical substation automation systems [10]. It addresses the major concern of interoperability issue of integrated electronic devices at bay level. The abstracted models of communication defined by IEC-61850 can be mapped into a number of already existing protocols, e.g. MMS and GOOSE, which are mostly run over TCP/IP on public as well as private networks to ensure response times for certain services [4].

The scope of communication for certain information exchange being time critical in smart grids, as described in [1] [11] [12], is however, beyond just guarantying the reception of transmitted data. It is more of how fast (within the predefined time frame) and accurately the controllers update their status to the control center with any event that occurs within the system. Keeping in mind the pros and cons of both transport layer protocols, it necessitates a robust investigation before designing the complete network infrastructure for smart grids. For instance, the trade-off between using TCP and UDP, is in fact a trade-off between losing data in the network or accept much higher delays in data reception. Hence, this paper focuses on analyzing the trade-off between end-to-end delays and packet losses for the two transport layer protocols based on the information accuracy within the communication between actors in smart grids. In order to measure quantitatively the accuracy of information in a given scenario, we use an information quality metric known as mismatch probability (mmPr). This metric considers both the occurrence of events and the update strategy in one single metric which otherwise is not very intuitive and difficult to allow a similar useful comparison. Secondly, an analytical model has also been introduced to calculate mmPr and compared with the results obtained using experiential approach.

The remainder of this paper is organized as follows: Section II describes the case specific scenario adopted to get simulation results, Section III defines and explain the quality metric selected to compare performance of the two transport layer protocols, Section IV provides evaluation of simulation and analytical results and finally Section V summarizes the conclusion drawn and directions for future work.

II. SCENARIO DESCRIPTION

Fig. 1 presents the conceptual layout adopted in this paper. The control scenario is based on a smart grid communication scenario where the control-center (requester) has made a subscription to the controllers, e.g., voltage controller, in WP/PV plants, which will subsequently send status updates to the control-center in periodic intervals using the communication network shown in Fig. 1. This communication network can be a third party public communication network. As shown in Fig. 1, a number of renewable generation (ReGen) plant controllers located at different geographical locations, send update messages to a server in the control-center at different periodic intervals. One of the controllers is selected to extract end-to-end delay traces from information packets sent to the control-center using different propagation delays (D_L) and packet error rates (PER) with TCP as well as UDP. Other controllers have been added in the test scenario to produce cross traffic and to check the effect of increased propagation delay on end-to-end delay of each message. The end-to-end delay traces obtained from the controller are then used to calculate probability of mismatch of information between the controller and control-center using events generated at a specific mean interval.

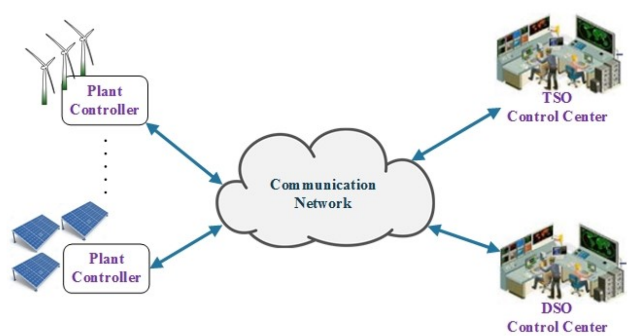

Fig. 1. Communication architecture where several plant controllers are shown communicating with control centers at different levels

The controller considered to extract end-to-end delay traces is proactive, meaning that it will keep on sending status updates to the control-center in periodic intervals. This periodic update of information can be well understood through the message sequence diagram in Fig. 2. Notation used for the message sequence diagrams in Fig. 2 and Fig. 3 is as follows: D_i denotes the time at which i^{th} message is sent to the controller, while d_i is the delay experienced by this message. R_i is the time at which control-center (requester) needs the status information from the controller. E_i is the event detected at any time interval by the controller. The case of information mismatch can be observed in Fig. 2 where R_1 results in a mismatch from E_1, while R_2 leads to a correct result as compared to E_2. The update process is assumed jointly independent to the event, delay, and request processes [13].

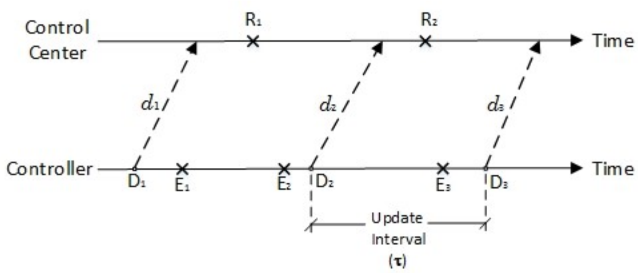

Fig. 2. Message sequence diagram showing proactive, periodic update of information with a mismatch case scenario

The case of information mismatch in TCP and UDP can be observed in Fig. 3(a) and (b), respectively. For the case of TCP in Fig. 3(a), it has been assumed that the communication connection is already established, i.e. there is no three-way handshake involved. Now, during the transmission of information messages, as soon as some message is dropped due to any reason, for instance congestion

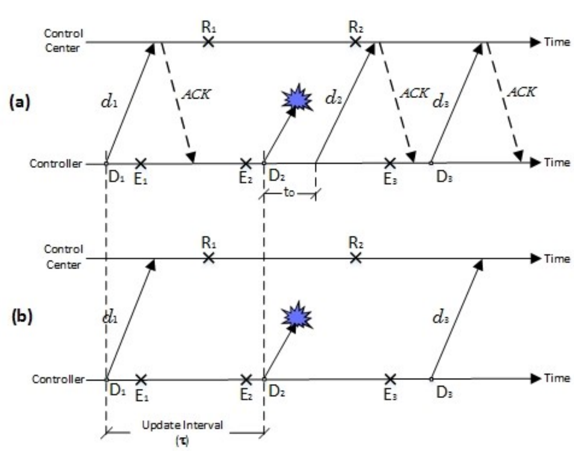

Fig. 3. Message sequence diagram showing proactive, periodic update of information with an information mismatch case scenario for (a) TCP and (b) UDP

TABLE 1. PARAMETERS USED TO OBTAIN SIMULATION RESULTS

Parameter	Value	Unit
Simulation Iterations for delay traces	100	Per Prop. delay
Simulation Iteration for mmPr calculation	100	.
Link data rate	10	Mbps
Message size for TCP/UDP	500	bytes
Mean interval of Events	30	s
Default rate of periodic updates (τ)	0.1	s^{-1}
Link packet error rate (PER) range	[0, 10]	.
Link propagation delay range (D_L)	[0, 5]	s

in the network, it is resent after a transmission timeout period. In case the congestion in network is too high and the message is dropped many times, it will be sent several times depending on the retransmission algorithm used. Although this mechanism ensures/guarantees transmission of message at the control-center but at the cost of increased end-to-end delay which may become a cause of a mismatch of information between the two electric devices. The suspected impact would be a wrong decision that leads to a wrong action, which ultimately may not only de-stabilize the system but lead to a less efficient controller.

Contrary to the case in TCP, a loss of information in UDP is not compensated with a retransmission. This may also, however, become a cause of mismatch of information depending on the events occurring in the controller side. The case of information mismatch in UDP is shown in Fig. 3(b).

III. INFORMATION QUALITY METRIC

As mentioned in section II, it is critically important for the control-center to receive correct information at correct times to take correct actions. In this context, it is a kind of challenging the reliability of TCP and other similar kinds of protocols that, although, ensure the reception of information at the other end but with extra end-to-end delays added. This necessitates a deep insight while designing and selecting a transport layer protocol for the communication networks in systems like smart grids, where several applications are time critical. Therefore, a measure of the probability of receiving correct information at different network conditions will serve to provide future directions for optimizing the network.

A. *Defining the Probability of Mismatch (mmPr)*

The probability of correctness of information received is taken in the opposite form as probability of mismatch of information (mmPr) [13] and thus, used as a quality metric in this paper. In order to model mmPr, communication between a controller at some asset (WP/PV plant) and a control-center has been considered, as shown in Fig. 1. These are considered to be located at different geographical and network locations, where the control-center at certain control period needs to be aware of the dynamically changing controller's status information. This information access occurs over a shared network and thus offers stochastic end-to-end delays. Here, mmPr can be defined as:

$$mmPr := \Pr(I_{cc}(t_c) \neq I_{ct}(t_c)) \quad (1)$$

Here, I_{cc} and I_{ct} are the information available at control-center and the controller respectively, while t_c is the control time where the two sets of information are compared. Out of the three basic information access schemes, as elaborated and analyzed in [13] (i.e. reactive access, proactive-periodic and proactive event-driven access), this paper uses the proactive periodic access scheme for the controller to send its status updates.

B. Delay and Information Modelling

Analytical modeling of TCP throughput delay in [14] provides a mathematical model to compute delay for bulk TCP data. However, using the model in [14] and other such models for a small size of packets (in the order of few hundred bytes) and periodic interval of 10 seconds do not serve the purpose. This is because the sender congestion window for such settings does not exceed a certain limit. Normally, a packet would take half the duration of RTT to be received (at the receiver) if successful and would take duration of Timeout if packet is lost. Considering such settings, a network simulator can provide a mechanism to measure the delay that a packet of few bytes experiences to get across from sender to the receiver.

As shown in Fig. 4, OMNeT++ has been used as a network simulator to obtain end-to-end delay traces using a link data rate of 10 Mbps. This rate has been considered as a base case, which of course can be replaced by the data rates of any of the available communication technologies depending upon the system requirements. The delay traces are obtained with different pairs of linearly distributed link propagation delays and packet error rates for TCP as well as UDP, using identical network environment. For each pair of D_L and PER, a set of 100 messages, each of 500 bytes in length at an exponentially distributed period of 10 seconds, was sent from controller to control-center to capture end-to-end delay traces. A set of 100 messages has been considered, specifically, to take the CDF of the end-to-end delays instead of one single delay for each group of network parameters. In case of TCP, this set of 100 messages are sent under a single three-way handshake, where the time taken to establish a connection is considered to be zero seconds. This assumption is made because the purpose here is not to get the exact model of TCP, but to get the potential solution of the impact that the additional delays have on the mismatch probability.

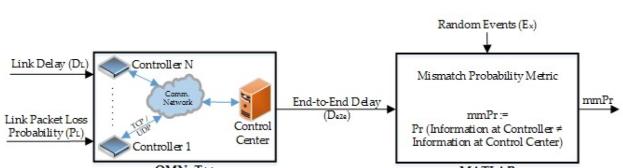

Fig. 4. Simulation layout

The end-to-end delay traces were then used to determine mmPr by comparing the time of reception of information with the exponentially distributed random events generated at a specific mean interval. Based on the results of mmPr, a comparison has been made to see which of the two protocols provide better performance in terms of probability of mismatch of information at different propagation delays and packet loss probabilities. Table 1 summarizes all parameters used in the analysis of results.

IV. Performance study of TCP versus UDP

A. Analysis by simulation

This section presents the results of simulations performed showing the impact of TCP and UDP on mismatch probability at two different packet loss probabilities. The results obtained via delay traces are also compared with those obtained through the analytical model. A trade-off between the packet losses and added delays to the information will be presented in the end that would help designing/selecting a protocol for the time critical message types in smart grids.

We estimate the mismatch probability by comparing at time instances of information access with the actual value. The average of mismatches yields the mmPr estimate:

$$\widehat{mmPr} = \frac{1}{N}\sum_{i=0}^{N} I(I_{cc}(t_c) \neq I_{ct}(t_c)) \quad (2)$$

Fig. 5 shows the impact of increasing propagation delay on mismatch probability (mmPr) considering perfect conditions for the network with no loss of information (i.e. PER = 0). It can be observed that under this condition TCP and UDP show the same performance approximately around 2.5 seconds of the propagation delay. However, above this delay the increase in mmPr for TCP is abrupt as compared to UDP. As the network is loss-less, this difference is because of the transmission timeout of TCP. Analytical results for UDP's mmPr have also been added in Fig. 5 which clearly indicate that for low propagation delays it gives the same results as obtained from the simulation model, but then deviates a little. This deviation is due to the fact that simulation results are gained from a combination of delay traces, and we expect the delay distribution to be slightly different from exponential distribution. This, nevertheless, matches the conclusions drawn in [13] i.e. more deterministic the distribution, higher the mismatch probability.

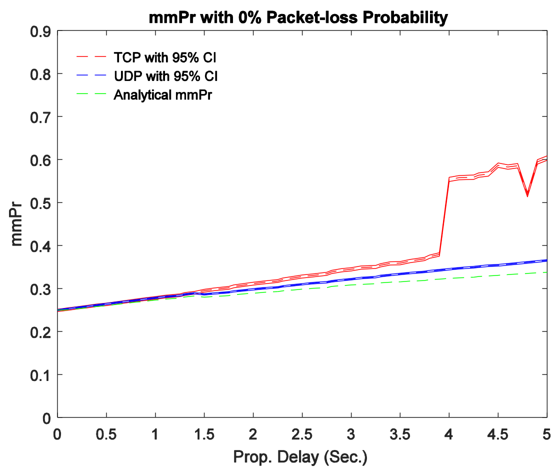

Fig. 5. Mismatch probability versus propagation delay with 95% confidence interval PER of 0%

The difference of mmPr becomes more prominent as PER in the network is increased. This is shown in Fig. 6 where the rate of packet loss in the network is increased to 10%. The huge variation (jumpiness) in the results is basically due to the variation in the mean end-to-end delays that depends upon the time a packet is lost during transmission as well as the cross traffic involved. It is observed that higher packet loss probabilities cause TCP performance to degrade faster than UDP.

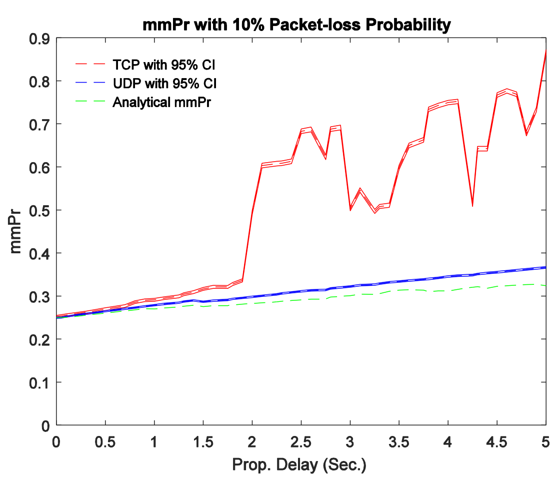

Fig. 6. Mismatch probability versus propagation delay with 95% confidence interval at PER of 10%

B. *Trade-off between packet loss and delay*

To support our analysis of TCP versus UDP, we now make use of existing mmPr models that are compared considering raw packet losses (UDP) versus the prolonged delay caused by packet losses (TCP) in the given model. In the periodic access scheme, controller sends the state of the information (current value) to the control-center with a specific time period (update rate). This update rate is important in the sense that it can be used to determine the entire traffic generated. The model for probability of mismatch used in this paper, as mentioned in [13], is given in (3):

$$mmPr = \int_0^{\infty} \exp\left(-\int_0^t \tau F_D(s)ds\right) A_E(dt) \qquad (3)$$

Where τ is the status update rate, F_D is the CDF of delay and A_E is the CDF of backward recurrence time for an event process that is a stationary renewal process [13]. Packet losses for UDP in this model can be regarded as a thinning of the update process, i.e. a reduction of the rate τ with the factor $(1-P_{LOSS})$ such that $\tau_{eff} = \tau(1-P_{LOSS})$, whereas, as mentioned earlier, packet losses for TCP lead to a higher delay and in particular delay CDF. From the model shown it is neither clear nor intuitive as to which change has the most severe impact on mismatch probability, and this is what is assessed in the following.

Considering a simple case with delay and event, inter arrival processes are exponentially distributed with rates λ (event) and ν (delay), the following expression of the mismatch probability can be derived from (3) (see [9]):

$$mmPr = \varphi e^{\psi} \frac{\Gamma(\varphi+\psi)}{\psi^{\varphi+\psi}} F_{\Gamma(\varphi+\psi,\psi)}(1) \qquad (4)$$

With $\varphi = \lambda/\nu$ and $\psi = \tau_{eff}/\nu$, $F_{\Gamma(a,b)}$ the CDF of a gamma distribution with parameters a and b. The important aspect to notice here is that the mmPr is in reality a complex function of ratios between the update rate, event rate and the delay rate respectively. We use this simplified model in the following to elaborate the trade-off between delay and packet losses reducing the effective update rate, which later we map into a comparison between UDP and TCP performance, since as (3) shows, the distribution of the delays (and events) are also important and for TCP these are certainly not exponentially distributed as we assume in the simple analysis.

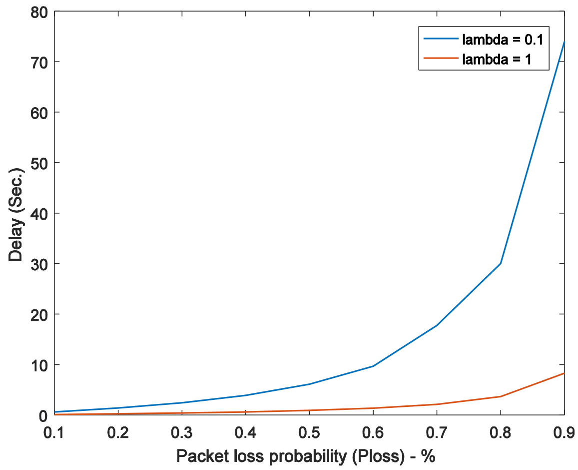

Fig. 7. Trade-off between packet-loss and end-to-end delay for a given propagation delay at minimum and maximum event rates (lambda).

The results shown in Fig. 7 illustrate the trade-off between packet loss probability and the delay it takes to achieve same level of mismatch probability. The point we make here is that for a given packet loss using UDP, this leads to an effective reduction of update rate, reducing the mismatch probability. If for the same protocol using TCP, the packet loss is reduced to zero, the plots in Fig. 7 show the mean delay that TCP should attain if the same mmPr should be achieved. If the reliable protocol (TCP) can do this faster, then this protocol outperforms the UDP, and if it is slower, then UDP performs best. Comparing this to the results from previous sections (Fig. 5 and 6) it seems that in general the TCP is above the timely threshold shown in Fig. 7, indicating that the TCP assessed is in general performing poorly in the situation of sending dynamic data over network. However, as the plots in Fig. 7 also indicate, there is room for adjusting e.g. timeout values to accommodate for the losses for slow dynamic information (lambda = 0.1 events/sec), where a significant amount of time can be spent on retransmission before it no longer pays off. For faster information dynamics, here 1 event/sec in average, there is so little time in overhead that it is very unlikely to be possible. The TCP timeouts in relation to this trade-off will be focused in our future research. On the other hand, other protocols may also be designed, e.g. multiple transmission of same information via UDP which reduces packet losses to nearly zero at the cost of a potential added delay, as long as the complete message transfer delay (end-to-end delay) is kept below the shown graphs, or else a simple UDP based protocol suffices.

V. CONCLUSION AND FUTURE WORK

Timely transmission and reception of information is critical in many applications of smart grids. This criticality can be addressed by a clever selection of transport layer protocol that provides different levels of data transportation service quality to the application. However, in standards, for instance, IEC-61850, the abstracted models of communication that can be mapped into a number of already existing protocols are often based on TCP/IP. This paper, therefore, evaluates the performance of TCP and UDP, based on mismatch probability considering a scenario that can be mapped to a smart grid communication case. The evaluation shows how the selection of transport layer protocols effects the quality of information received. It also shows how the selection of UDP or TCP is a trade-off between loosing data in the network or accepting much higher delays in reception of data, respectively. It has been shown that the trend in mmPr for UDP remains approximately the same for all cases of packet loss probabilities from which it can be concluded that UDP should be preferred for time critical message transmissions in smart grids compared to the standard TCP model assessed. On the other hand, the second aspect of our analysis shows that there may be room to adapt TCP e.g. by adjusting timeout values to achieve better performance, however, most suitable for information which changes slowly.

The information access scheme used in this paper was proactive with periodic updates. This, however, leads to the direction of studies in future e.g. performance evaluation of transport layer protocols based on other two information access schemes i.e. reactive (request-response based) and proactive with event driven updates, implementation and evaluation of simulation results in a Real-Time Hardware-in-the-Loop environment where the effects of different parameters are safely examined and finally based on the results from a real time scenario developing an adaptive algorithm for transport layer protocols to be used in smart grid scenario.

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