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Transport layer performance analysis and optimization for smart metering infrastructure

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ABSTRACT

In a smart power grid, collecting data from a large number of smart meters and sensors over the conventional one-hop transmission control protocol (TCP) communication is prone to a high packet loss rate and degraded throughput due to the ineffectiveness of the TCP congestion control mechanism. The Split and Aggregated TCP (SA-TCP) proposes upgrading intermediate devices (known as regional collectors or RCs) to combine meters' TCP connections and forward data over a unified TCP connection to the utility server.

This paper provides a comprehensive performance analysis of the SA-TCP scheme. It studies the impact of varying various parameters on the scheme, including the impact of network link capacity, buffering capacity of RCs, propagation delay between the meters and the utility server, and finally the number of RCs utilized as SA-TCP aggregators. The performance results show that by adjusting those parameters, it is possible to tune throughput of a smart metering network to the desired amount while keeping the deployment cost minimal.

1. Introduction

Integrating the power grid with a communication infrastructure definitely enables a great deal of new and sophisticated services (Wang et al., 2010; Sarangi et al., 2012; Barbose et al., 2004). The collection of data from a large number of metering and sensing devices (Chandler, 2005; Fan et al., 2011; Shahraeini et al., 2012) enables utility companies to manage energy efficiently. This can be achieved by distributing power generation stations optimally, utilizing renewable energy sources, and quickly localizing and self-healing faulty spots. However, from a communication perspective, the large amount of data requires effective congestion control. The fact that a meter's data rate is low and that the large volume of data comes from a large number of sources renders Transmission Control Protocol (TCP) congestion control ineffective (Khalifa et al., 2010). The lack of an effective congestion control causes high loss rate and degrades throughput for metering data and similarly for any traffic that shares the smart metering communication network.

Our solution, *Split- and Aggregated-TCP (SA-TCP) scheme* (Khalifa et al., 2010) enhances TCP congestion control performance in a smart metering infrastructure (SMI). Instead of having the meters establish individual TCP connections with the utility server, they rather connect to intermediate devices (e.g., Regional Collectors or RCs), which we call *SA-TCP Aggregators*. Those devices forward meters' data over a unified TCP connection to the utility server. Since the SA-TCP aggregator node will have the data of a large collection of meters, maintaining the full range of congestion control becomes viable, making TCP congestion control effective. As a result, a packet loss rate is reduced, and so a better link utilization is achieved.

This paper comes as a continued study of the SA-TCP scheme, which was previously introduced in Khalifa et al. (2010). A mathematical model for the scheme was detailed in Khalifa et al. (2014). The model captures the SMI traffic behavior and draws conclusions about the network performance, including throughput, loss rate and delay. The model takes into account the characteristics of meters and the TCP congestion control mechanism (i.e., the dynamics of the congestions window size). It also takes into account the number of meters and number of SA-TCP aggregators, network setup parameters such as link capacities, buffering capacities and propagation delay. The modeling approach combines a Markovian model for the application

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layer and the TCP behavior of a single meter and then analyzes the superposition of several meters sharing a network by means of a queuing system. Based on the model, performance analysis and optimization of the SA-TCP architecture are performed and reported in this paper.

The contributions of this work are twofold:

- It provides performance analysis of the SA-TCP scheme in comparison with the conventional one-hop TCP protocol. The impact of various design and network parameters on the scheme is considered. Specifically, it shows the impact of SMI link capacity, propagation delay, number of SA-TCP aggregators and their buffering capacities. Such analysis is important for enhancing the SA-TCP scheme to achieve better TCP performance.
- It formulates an optimization framework, which ensures satisfactory performance results in terms of loss rate and end-to-end delay. It also considers minimizing the SA-TCP scheme deployment cost by balancing the number of SA-TCP aggregators and link bandwidth capacity while satisfying performance requirements.

In short, the SA-TCP scheme addresses the performance degradation caused by the TCP congestion control, which cannot adapt to a large number of low rate smart meters. The developed analytical model is a key component in our ability to analyze the performance and effectiveness of the proposed scheme under various design factors. Accordingly, the optimization formulation, which is based on the analytical model, further tunes the performance of SA-TCP as desired.

The rest of this paper is organized as follows. Section 2 reviews the related SMI TCP work. Section 3 presents the SA-TCP system model and summarizes our previous mathematical work developed to capture the SMI traffic behavior. Section 4 provides a comprehensive performance analysis for SMI traffic under SA-TCP and conventional one-hop TCP congestion control set-ups. Finally, Section 6 concludes the paper.

2. Related work

The TCP layer issues in smart power grid have been addressed in a number of recent publications, addressing congestion control, delay and security. Allalouf et al. (2011) propose hop-by-hop traffic reduction assuming that meters' data samples are required at certain intermediate devices, but not at the utility center, and assuming that the intermediate devices are sophisticated enough in terms of hardware and software capabilities to process and analyze data packets at the application layer. Therefore, they propose to route traffic through devices where more reduction can be applied to such data. Kim and Thottan (2011) propose a new transmission control protocol that targets mainly delay-sensitive smart grid applications. However, congestion control is not studied. Kim et al. (2011) also aim at making TCP faster. Their focus, however, is on the security aspect of TCP. They design a secure transport protocol for a smart grid data collection protocol that avoids the need to support TCP with Transport Layer Security (TLS) (Dierks and Rescorla, 2008). In the same line, Dan et al. (2013) develop a secure collection protocol that allows an intermediate concentrator to be an untrustworthy device. As such, the protocol is applicable to SA-TCP allowing the TCP session to be split at a device such as the aggregator while stay secure.

At a first glance, SA-TCP seems to have resemblance with Indirect-TCP (I-TCP) (Bakre and Badrinath, 1995) in splitting TCP connections and with Chakravorty et al. (2003) in aggregating TCP connections. However, I-TCP, which was introduced to support Internet Protocol (IP) mobility, does not change the number of TCP connections between the end systems. Aggregation of TCP connections in Chakravorty et al. (2003) is in the form of sharing TCP state information (e.g., round trip time and congestion window size) among a set of TCP connections that a single mobile device initiates, so the number of connections does not change. The idea of splitting TCP has appeared in other areas too. Amir et al. (2000) develop a transport protocol that connects a group of devices over a wide area network, in which if packets get lost, they are retransmitted from an intermediate device. In wireless sensor networks (Halder and Bit, 2014), spitting TCP over multiple hops is also common (Dunkels et al., 2004; Wang et al., 2005). The purpose of splitting in both cases is to achieve low latency.

3. Overview of SA-TCP scheme

3.1. SA-TCP system model

Smart Metering Infrastructure is composed of a large number of smart meters and smart sensors forming regions of local area networks. By means of wireless communication technology (or possibly Power Line Carrier (PLC)), the meters communicate over multiple hops with intermediate devices known as Regional Collectors (RCs) (also called concentrators) (Relich, 2008). These RCs are installed at pre-selected locations in every region and act as gateways to route the meters' data packets through a wide area network to the utility server, in which data is collected for processing (Niyato et al., 2011; Leeds, 2009).

The scheme, SA-TCP, enhances TCP performance (Khalifa et al., 2010) by introducing the concept of aggregation at the transport layer. The RCs implement the added service of splitting and aggregating TCP connections as depicted in Fig. 1. Hence, we refer to RCs as SA-TCP aggregators. Every set of n meters establish n TCP connections with an SA-TCP aggregator. Thereby, the meters' data packets are received at the application layer of the SA-TCP aggregator and are forwarded by the aggregation application over a single TCP connection to the utility server. In other words, the TCP connections between the meters and the utility server are no longer one-hop, but rather, two-hop connections. As for the TCP Protocol mechanisms, there is no change in all the end points (i.e., meters, SA-TCP aggregators and the utility server).

The aggregation application can implement various scheduling policies depending on the nature of traffic and desired performance. For example, a priority-based or time-based scheduling can be applied to enable urgent data (e.g., alerts) to be delivered sufficiently fast. The work of this paper, however, does not address such policies; rather the focus is on the performance of TCP as a result of its congestion control mechanism.

Our model assumes that the RCs are reliable devices. Given the importance of such devices, other publications, such as Niyato

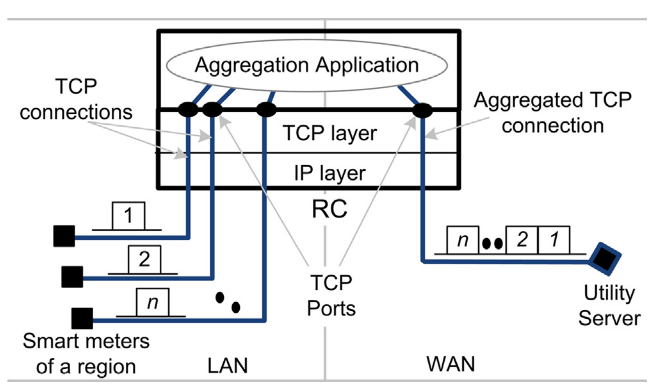

Fig. 1. Layered architecture of SA-TCP aggregator.