Tailoring DDS to Smart Grids for Improved Communication and Control

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Abstract: Adopting new technologies in smart grid (SG) enables the improvement of reliable communication. A key factor for SG efficiency is reliable data exchange between different components and domains in the system. SG must allow remote and quick reaction for different events. This is not a trivial task especially with large scale power grids, which requires SG to have a reliable communication protocol. Data Distribution Service (DDS) is introduced as a data-centric middleware standard based on publish-subscribe protocol to address communication needs for distributed applications. DDS supports reliable data exchange between different components using various features such as quality-of-service (QoS). In this paper, we describe how DDS can be tailored to support SG to improve the communication of devices in SG. We first give an overview of DDS and discuss the benefits of applying it to the communication system in SG. We then describe communication requirements and constraints in SG. and discuss how DDS can be tailored to SG with respect to the requirements and constraints.

1 INTRODUCTION

The traditional power grid uses the simple power generation and consumption paradigm which involves little management for efficiency, and thus has significant power loss. According to the report by The World Bank (World-Bank, 2015), the U.S loses 6% from its total power in transmission and distribution process, the U.K loses 8%, China loses 12%, some other countries even lose a significant amount, such as Iraq which loses about 35% of its produced power. Furthermore, traditional power generation systems create a large amount of carbon dioxide (CO2) contaminating the environment.

Smart grid (SG) has emerged as the next generation for improved efficiency of power production and consumption. Unlike the traditional power grid which is not designed for device communication, SG aims at facilitating communication and data exchange between various equipment and devices across the power domain. It enables bidirectional data exchange between power suppliers and consumers for improved power management (Fang et al., 2012). As an example, in SG, smart meters measuring power consumption are able to communicate their data to utilities which are in turn able to send real-time pricing back to smart meters.

Communication management in SG is a challenge due to the heterogeneity of the infrastructure. SG components involve significant data exchanges requiring efficient communication. A given approach to enhance SG communication has to consider concerns such as time constraints and devices requirements. Some protocols such as the Distributed Network Protocol (DNP3) (NIST, 2010) and Modbus (Modbus-IDA, 2006) have been tried to overcome the communication challenges in SG. However, they introduce significant overheads and latency which make them unsuitable for SG (discussed more in Section 2).

DDS has emerged as a potential model to address the challenges in SG. Based on a simple publish/subscribe protocol and QoS policies, it is designed to support high-performance, scalable, dependable and real-time data exchange between different components with little overheads. In this paper, we describe how DDS can be tailored to SG. We first identify communication requirements for different components in SG and discuss how DDS should be tailored to satisfy those requirements.

The remainder of the paper is organized as follows. Section 2 gives an overview of the DDS model and describes the advantages of applying it to SG. Section 3 outlines the related research and describes how the work in this paper is different. In section 4, we describe the SG communication requirements for different domains in the system. In section 5, we describe how to tailor DDS to SG to achieve improved communication and control. Finally, Section 6 concludes the paper and outlines the future research.

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2 OVERVIEW OF DDS

Data Distribution Service (DDS) (Object-Managment-Group, 2015) is a data-centric middleware standard by the Object Management Group (OMG). It came in 2004 as a Publish/Subscribe protocol to address the data sharing needs for a wide variety of computing environments, ranging from small local networks to large scale systems. DDS provides a scalable platform and location-independent infrastructure to connect publishers and subscribers. DDS also supports a wide variety of quality-of-service (QoS) properties including time sensitivity, reliability, and many others (Corsaro, 2014).

The DDS specification is described as two-level interfaces. The first level is Data-Centric Publish-Subscribe (DCPS) which is a lower layer API that allows DDS-enabled applications to communicate with each other. The second interface is Data Local Reconstruction Layer (DLRL) which is an upper layer specification that outlines how an application can interface with DCPS. DLRL is defined as optional.

DCPS is the core of the DDS model which allows heterogeneous components to interact through reading and writing the data form/to the global data space. Components interact by declaring their intent to publish or subscribe data. Figure 1 shows the interaction (through a global data space) between different entities in the model. DDS entities that are involved in DCPS-based applications include:

- **Domain:** This is a conceptual container in the system. Components in a domain can only communicate within the same domain, which allows for data isolation and optimized communication.
- **Domain Participant:** This represents the participation of a given application in the domain. Each process has one domain participant for each data domain.
- **Data Writers and Publishers:** An application uses a writer to write the data. It is also an interface (access point) to publishers. A publisher is an entity that is responsible for data issuance to the data domain. A publisher can be used by an application to group multiple writers.
- **Data Reader and Subscriber:** A reader is utilized by an application to receive the data. It is also the access point to subscribers. Similar to publishers, a subscriber can be used as a container to group multiple readers.
- **Topic:** This is a basic data object to be published/received. A given topic must match in order to establish a connection between a publisher and a subscriber. A topic is defined in terms of name, data type, and QoS.

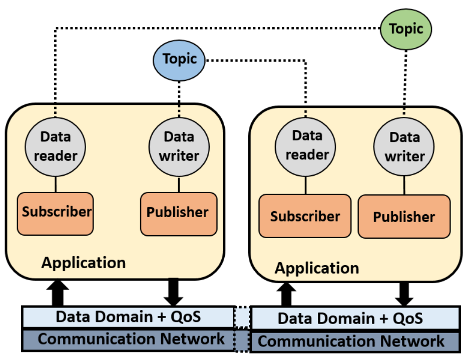

Figure 1: DDS architecture and components.

DDS has many advantages over other publish/subscribe protocols such as DNP3 and Modbus. First, DDS is simple and flexible, while supporting complex messaging scenarios as opposed to Modbus. Second, unlike DNP3 which induces 50%-80% of the processing delay in embedded power devices (Lu et al., 2011), DDS does not introduce any overheads. DDS also enables high-performance data exchange and QoS on a component base, while supports different types of communication such as one-to-one, one-to-many, many-to-many, and many-to-one (Object-Managment-Group, 2015). These features make DDS as a potential solution for addressing the communication challenges in future grid.

3 RELATED WORK

Smart grid is still in its infancy stage. Organizations and researchers have been trying to use and integrate different protocols to improve the communication system in SG. Some works in the literature (Bakken et al., 2009; A. Alkhawaja, ; Twin Oaks Computing, 2011) have considered use of middleware solutions such as DDS or message-oriented middleware for communication and data exchange in SG.

The work by Bakken *et al.* (Bakken et al., 2009) argues that middleware solutions (e.g., DDS framework) are better approaches to address interoperability and data exchange in SG. They justify the advantages of middleware standards over other protocols on achieving reliable end-to-end communication. Carrying over their study, in this work, we address what needs to be done in order to adopt DDS to SG.

Alkhawaja and Ferreira (A. Alkhawaja,) also considered the integration of DDS with the SG domain. Their work discusses use of existing middleware solutions to support distributed large-scale applications with QoS requirements. In the same light as Bakken *et al.*'s work, their work also emphasizes the bene-

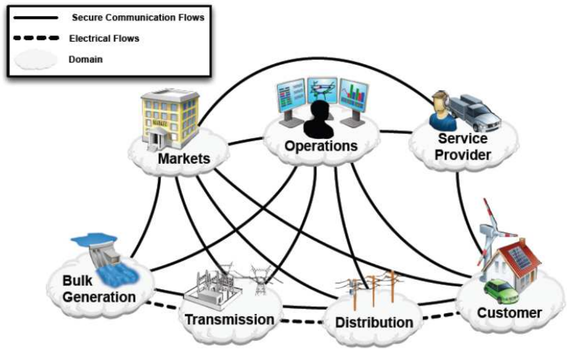

Figure 2: Smart Grid Communication.

fits of applying DDS to the SG. They show that the lightweight architecture of DDS ensures high performance and predictability by its capabilities to reserve resources and enforcing QoS. However, the scope of their work does not considers SG requirements and tailoring DDS to SG. In our work, we address how DDS should be tailored to satisfy SG requirements.

The report by Twin Oak Computing (Twin Oaks Computing, 2011) describes the capabilities of DDS in general. It describes how the DDS architecture can improve communication in large scale systems such as power grid systems. The report argues that DDS can be used for safety critical systems such as renewable energy systems. It also describes the importance of DDS in achieving communication interoperability. However, there is little discussion as to use of DDS in SG.

4 SG COMMUNICATION REQUIREMENTS

Smart grid involves four main domains (NIST, 2010) – i) power generation, producing power on high voltage levels, ii) power transmission, transmitting generated power to substations, iii) power distribution, distributing power to end users, and iv) power consumption, ultimately consuming the power. Each one of these domains has its own components and requirements. Figure 2 depicts the communication involved in the domains (NIST, 2010). In this paper, we use the term component interchangeably with device.

Before adopting DDS to SG, the requirements of SG communication should be identified, which provides a base for implementing DDS. As discussed in Section 3, there are some works that discusses possible implementation of DDS in SG. However, to the best of our knowledge, there is no work addressing communication requirements and how DDS should be tailored to SG to satisfy the requirements. In this work, we study different types of devices involved in SG communication in the above four domains and identify communication requirements and constraints imposed by the devices. In the rest of this section, we discuss the four domains in terms of involved devices and related requirements on latency, reliability, and dynamism.

4.1 Devices in Power Generation

Power generation consists of large generation plants (e.g., nuclear plants, fossil fuel plants) which are capable of generating high voltage power. Those plants work as systems that involve many components such as generators, transformers, compressors, and turbines. They are critical in power generation and should be continuously monitored and reported on their status. Beside those physical components, there are also software components that are used for remote control such as remote management system (RMS). RMS controls a power grid with restrictive time requirements in communication. For example, data related to Breaker must be transmitted no longer than 2 seconds after the event has occurred (Ericsson, 2010).

Another important component in power generation is wireless sensors which are used for monitoring the health of the generation devices. They communicate with each other to send data to detect any fault in the generation process. Thus, reliable communication is critical. However, sensors are vulnerable to harsh environmental conditions such as wind and rain (US.DOE, 2004), which increases communication dynamism. Such a dynamism should be considered in designing the communication system in SG.

4.2 Devices in Power Transmission

Supervisory control and data acquisition (SCADA) systems are widely used in power transmission for remote monitor and control. A SCADA system consists of different types of Intelligent Electronic Devices (IEDs) which work to control different parts in the system. An IED has the capability of sending data and interacting with other IEDs and with the control center. An IED may have restrictive time constraints on communication. For example, IEDs responsible for substation protection and control have to transmit their data within 12-20 ms (Ericsson, 2010). In order to satisfy such a requirement, a reliable communication protocol is required. Another example is protection relays which are responsible for detecting and overcoming failures in power devices. Protection relays also have a restrictive time requirement that the response must be within 3 ms to avoid faults that may lead to blackouts (IEEE-Power-Engineering-Society, 2004; Schwarz, 2004).

Substations are another core components in power grid. A substation has a microcomputer for remote control and to communicate with other systems in the grid, which require reliable data transmission in a timely manner.

Phasor measurement unit (PMU) is a device for measuring the health of the grid. PMU has the capability of processing and communicating data with other devices in SG (Ek, 2014). PMU is required to provide data to the control center at the rate of 6 – 60 samples per second (Rihan et al., 2011), which is critical for safety control.

4.3 Devices in Power Distribution

The distribution domain in SG introduces the notion of distributed energy resources (DER) such as solar panel and wind turbines. Those systems contain different components to generate power and communicate with other devices. Communication between DERs and other components is a challenge due to unreliable environments where a large number of DERs are envisioned to communicate via wireless connection and such a connection is vulnerable to interference and harsh weather conditions (Yu et al., 2011).

DERs have a set of communication constraints to be satisfied to guarantee the grid reliability. An example is that the reading interval of meters has to be 5-15 minute (DNV.GL, 2014). This requires any DER device to issue its data with respect to the specified interval and any violation of the constraint may result in unreliable data.

4.4 Devices in Power Consumption

The power consumption domain involves devices such as smart meters and wireless energy monitors. Smart meters communicate with power utilities to send and receive data such as the total cost of the electric power and pricing information in real-time (DNV.GL, 2014), which requires continuous and accurate updates on a regular basis.

5 TAILORING DDS

In this section, we describe how the DDS framework can be tailored to satisfy the communication requirements identified in Section 4. We explain how the reliable and restrictive time constraints can be addressed by QoS in DDS. We also describe how to tailor the discovery mechanism in DDS to satisfy the dynamism requirements in SG communication.

The devices studied in Section 4 can be categorized into publisher-related, subscriber-related, and system-related in the context of DDS, depending on their functionalities. Figure 3 shows the categorized devices. In the figure, the rectangle shape represents the components that can work as a system (with multiple components inside them) in the domain. The oval shape represents publishers and the dashed rectangle represents the components that can work as both publisher/subscriber. Sensors are categorized as publishers as they are used to sense and report on the health of the devices in power generation. Smart meters in the power consumption domain are categorized as publishers/ subscribers as they are used to send usage readings to utilities and receive from utilities the total cost of the electric power corresponding to the readings. On the other hand, SCADA systems in the power transmission domain are categorized as systems as they consist of multiple devices with data sending and receiving functionalities (i.e., publishers/ subscribers).

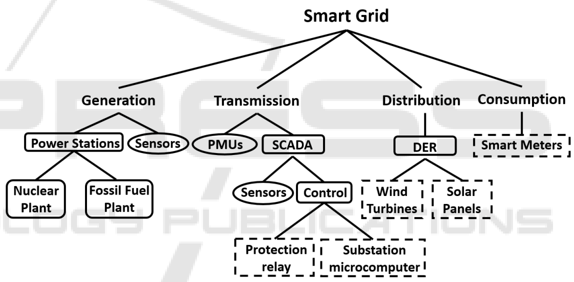

Figure 3: Devices in the smart grid domain.

DDS requires its implementation to be capable of scaling to a large number of subscribers (Object-Managment-Group, 2014). It also requires the implementation to have a built-in discovery service that allows publishers to dynamically discover the existence of subscribers and vice-versa. The DDS specification also prescribes publishers and subscribers to be able to set up QoS contracts at the time when their intent to publish/subscribe data is declared (Object-Managment-Group, 2014). Given that, we focus on two aspects in tailoring DDS to SG – i) tailoring QoS to satisfy reliability and restrictive time constraints and ii) tailoring the discovery service to improve the dynamism in SG.

5.1 Tailoring QoS

A significant feature of DDS is the provision of QoS on a per-entity base. This is important especially in systems whose involved devices have different requirements the same quality concern (e.g, different latency requirements). DDS does not only offer a set of QoS, but also allows system developers to set different QoS parameters for different entities such as Topics, Data Readers, and Data Writers.

To satisfy time constraints and requirements for reliable communication in SG, the QoS in the DDS framework needs to be tailored. Different components should be able to set different contracts. The communication between publishers/ subscribers cannot be established unless both parties agree on the set of QoS. Given that, we suggest the following QoS attributes to be tailored:

- **Latency (Deadline):** This attribute can be used to set restrictive time constraints for components, which allows publishers/subscribers to specify how fast they can publish/receive data (Object-Managment-Group, 2015). The attribute can be tailored depending on the constraints of the component on communication. For example, mission-critical components (e.g., protection relays) in SG must tailor this attribute to set up a rigid deadline for data transmission.
- **Latency Budget:** This is another important quality attribute that can be used for implementing optimization on the publisher side to accommodate the maximum acceptable latency of subscribers which refers to the delay from the time the data is written until the data is inserted into the subscriber's cache. It can be tailored to define communication rules to satisfy restrictive time constraints for devices. One approach to tailoring this attribute is to use it in conjunction with a priority-based transport protocol to set up higher priority for data with low latency budget.
- **Reliability:** This enables a Reader to receive data reliably sent by a Writer. It can be used in SG to satisfy reliability constraints. There are two sub-parameters for setting this QoS – *Reliable* and *Best Effort*. The Reliable setting enforces reliable data exchange. For example, for the components (e.g., smart meters) that can tolerate a certain latency to receive data, the Reliable parameter can be set to retransmit data until received. On the other hand, the Best Effort setting has no reliability mechanism. Thus, it can be used for the components that periodically publish data samples where only the latest one matters (e.g., data sensors). Tailoring this quality attribute is carried out by making appropriate setting for the given reliability constraints.

5.2 Tailoring Discovery Mechanism

The key for establishing communication between publishers and subscribers is discovering the existence of participants. In the DDS context, this requires DDS entities to be informed of each other's existence for communication. Not only this, the discovery feature should also provide communication guides between different publishers and subscribers. For example, communication guides can be provided as IP multicasting by devices where the DDS infrastructure manages the group membership.

The DDS specification defines a Real-Time Publish Subscribe protocol (RTPS) which describes a discovery functionality. The main purpose of RTPS is to support the interoperability of applications built upon different implementation platforms of vendors. RTPS (Object-Managment-Group, 2014) defines two discovery protocols – Participant Discovery Protocol (PDP) and Endpoint Discovery Protocol (EDP). PDP is used for discovering different domain participants, while EDP is used for matching data readers and data writers. However, these protocols are defined in a generic way, which may cause some drawbacks with respect to system dynamism. For example, they require a large amount of periodic data exchange, which is not applicable to the components that have limited computing resources, processing, or power resources (e.g., batteries). In the following, we describe features with respect to DDS discovery service that need to be tailored to improve SG dynamism.

- **Providing Communication Guides for Different Components:** As mentioned in Section 4, SG requires a dynamic communication system. Thus, it is important to allow system components to be added and removed in a dynamic way. For example, when a new component (e.g., new publishers/subscribers) is added to the system, the component can be reached efficiently by the use of discovery hints (e.g., the group membership provided by DDS).
- **Enabling Multiple Discovery Strategies for Different Components:** The DDS specification allows the separation of its implementation from discovery services (Object-Managment-Group, 2014). However, a DDS implementation in SG should have a built-in discovery service to support flexible and dynamic discovery of components. Components with limited resources may not be able to handle heavy interactions. For smooth integration of these components, the DDS infrastructure must provide alternative discovery mechanisms. For example, IEDs or sensors in SG need a simple discovery protocol such as Simple

Service Discovery Protocol (SSDP). On the other hand, for the components that use fixed servers and are capable of managing heavy interactions, static discovery or file-based or server-based discovery mechanisms can be used. It is worth mentioning that RTPS allows different implementations to support multiple discovery protocols (i.e., multiple implementations of PDPs and EDPs).

6 CONCLUSION

We have described identifying communication requirements for SG and tailoring DDS to SG based on the identified requirements. Requirements are identified for the devices involved in the four different domains of SG. Given the identified requirements, we suggested tailoring the QoS and discovery mechanism of DDS. We described tailoring latency, latency budget, and reliability for QoS and tailoring the features of providing communication guides and enabling multiple discovery strategies for the discovery mechanism.

For the future work, we plan to investigate how the tailoring points identified in this work should be applied to the design specification of DDS. In particular, we will look into Data Centric Publish/Subscribe (DCPS) in DDS which is responsible for efficient delivery of data between publishers and subscribers. We also envision to study the data model that fits both DDS and SG to facilitate interoperability of involved systems.

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