Communication Infrastructures for Distributed Control of Power Distribution Networks

Qiang Yang, Javier A. Barria, *Member, IEEE,* and Tim C. Green, *Senior Member, IEEE*

***Abstract*—Power distribution networks with distributed generators (DGs) can exhibit complex operational regimes which makes conventional management approaches no longer adequate. This paper looks into key communication infrastructure design aspects, and analyzes two representative evolution cases of Active Network Management (ANM) for distributed control. Relevant standard initiatives, communication protocols and technologies are introduced and underlying engineering challenges are highlighted. By analyzing two representative case networks (meshed and radial topologies) at different voltage levels (33kV and 11kV), this paper discusses the design considerations and presents performance results based on numerical simulations. This study focuses on the key role of the telecommunications provision when upgrading and deploying distributed control solutions, as part of future ANM systems.**

***Index Terms*—Power distribution networks, Active Network Management, Distributed Generators, SCADA, communication system, distributed control**

I. Introduction

Today's electric power networks were built with an integrated and vertical structure in mind. The power energy is mostly generated in centralized power plants and transported over a long distance transmission network to a distribution network before reaching the end users. In this context the distribution network is regarded as a passive system used to deliver reliable unidirectional power flows to end users. At present most Distribution Network Operators (DNOs) manage their networks via single (backed up) control center relying on Supervisory Control and Data Acquisition (SCADA) systems which were designed for simple and centralized operations.

In recent years, medium voltage (MV) distribution networks have been faced with a continuity of modifications as renewable energy generation resources in the form of small-scale DGs (e.g. wind turbines, Combined Heat and Power (CHP) and solar energy) are being connected to the utility grid. This trend has mainly been driven by advances in Distributed Energy Resources (DER) technology and the desire to achieve low-carbon energy provision targets. Amongst other characteristics of DGs is that they can be deployed closer to the loads and the surplus energy could be absorbed by the grid with the added benefit that demand during peak times could be better managed. The UK Government expects the renewable sources to provide 10% of the total national electricity supply by 2010, which implies about 14 GW of generation from current MV distribution networks.

With DGs, the distribution grid is no longer a passive system, but an active system interconnecting generators (e.g. wind power) which allows coexistence of bi-directional power flows. Moreover, the energy supplied by these generators is often intermittent and hence more difficult to predict and control. This brings about new operations and control challenges to cope with, e.g. voltage raise effect, increased fault level, protection degradation and altered transient stability [17]. We envisaged that a great number of DGs will be integrated into future power grids across a large geographical span. Moreover, at present many power utilities are being faced with the reality of conventional centralized control systems limitations, as they can greatly degrade due to the complexity of dealing with network events that would require enormous amount of data to properly manage them. To meet this emerging challenge, Active Network Management (ANM) solutions need to be incorporated in the network when DGs are part of the system.

IntelliGrid [16] and SmartGrids [30] are two research initiatives that investigate the realization of future "smart" or "intelligent" energy networks. Another notable effort is the Advanced Metering Infrastructure (AMI) (e.g. see [10]) which is designed to measure, collect and analyze energy usage through interacting with smart meters via various communication media. AMI allows distribution of information to customers, utilities and service providers enabling them to participate in or provide demand response solutions, often with a requirement of significant communication infrastructure reinforcement. The AuRA-NMS (autonomous regional active network management system) project [4] has also investigated a cost-effective ANM solution by implementing distributed and intelligent active network control to enhance energy security and quality of supply. The key idea behind this approach is to devolve the management authority from DNO's control center to networked regional controllers deployed locally to carry out management tasks in either autonomous or cooperative operational regimes. The AuRA-NMS identified many requirements on the underlying communication system which current SCADA systems can barely meet and that needs to be well understood. This paper investigates communications infrastructure design aspects, and analyzes two representative evolution cases of Active Network Management (ANM) for distributed control. We envisage that a plausible transition to

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Q. Yang is with the College of Electrical Engineering, Zhejiang University, Hangzhou, 310027 PRC (e-mail: qyang@zju.edu.cn).

J. Barria is with the Department of Electrical and Electronic Engineering, Imperial College, London, SW7 2AZ, UK (tel:+44-(0)20-7594-6275; fax:+44-(0)20-7594-6274; email:j.barria@imperial.ac.uk).

T. Green is with the Department of Electrical and Electronic Engineering, Imperial College, London, SW7 2AZ, UK (email:t.green@imperial.ac.uk).

a fully automated ANM solution will be incremental due to the nature of the current installed facilities, and hence, we take the view that gradual upgrades of the communications infrastructure will be the most likely roadmap. In this sense we also constrain our analysis to established technologies and standards so that ANM solutions would not depend on customized solutions and/or proprietary communications protocols. To obtain the results reported in this paper we develop a simulation environment that is flexible enough to assess various scenarios in which different technologies and protocols could co-exist [1]. The simulation environment includes all the major features of legacy communication technologies so that the selected solutions could also be assessed in terms of its backward compatibility. In this paper we present:

1) A generic and flexible methodology for modeling and assessing different types of data traffic and its associated communications system, to support distributed control using ANM systems. Communications requirements from distributed sensors, control commands and agent communications, can be easily specified.
2) Two case studies: the communication system designs are analyzed through two representative medium voltage networks (33kV and 11kV) based on aforementioned modeling approach and assessment framework.

Even though, the proposed methodology is flexible enough to analyze a variety of heterogeneous end-to-end communications infrastructures performance, when different communications technologies inter-operate, this paper presents only a subset of results due to space limitations.

The remainder of the paper is organized as follows: Section II presents an overview of current communication provision in DNOs. Section III explains the regional active network management approach and its key features, followed by a discussion of related communication standards, protocols and technologies in Section IV. The major communication system engineering challenges are discussed in Section V. Section VI presents in details the approach of communication system and traffic modeling. Section VII and VIII discusses the design considerations of two case networks and provides numerical results obtained from simulation experiments, respectively. Finally, some concluding remarks are given in Section IX.

II. Background: current distribution network management

Current power distribution network operations rely mostly on simple extension of SCADA systems which were mostly designed with a centralized architecture in mind interconnecting a master terminal (at control center) and a large number of Remote Telemetry Units (RTUs) located at geographically dispersed sites, as shown in Figure 1. The underlying feature of these systems is their heterogeneity in terms of communication medium (e.g. leased digital fibre, private wire, telephone lines, satellite and mobile radio) and channel capacity (from a few hundred to a few thousand bits per second). These characteristics mean frequent communication media conversions with the undesirable impact on its end-to-end availability and average Bit Error Rate (BER). Furthermore, SCADA protocols are mostly proprietary and designed specifically with error detection and message retry mechanisms to guarantee data delivery under most circumstances.

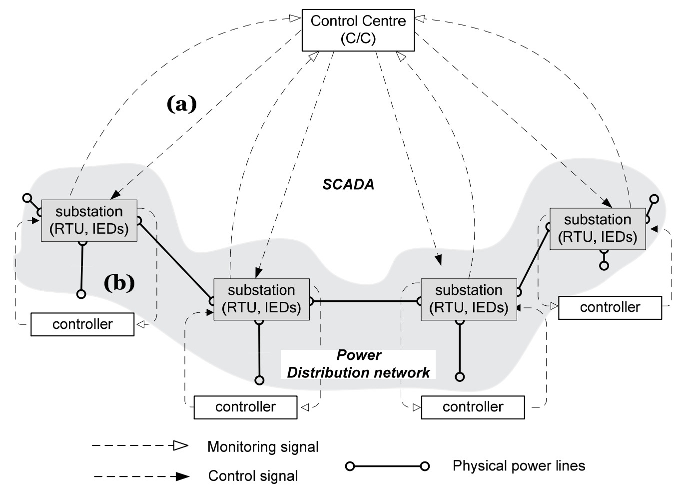


Fig. 1: Current control schemes: central control (a) and local control (b)

RTUs act as relays to collect network operational states from sensors (analogue and/or binary) and route control signals to actuating devices. Data acquisition is often carried out through polling in a non-continuous fashion, e.g. every 10-20 seconds at higher voltage sites (e.g. 33kV) and hours or even days at lower voltage sites (e.g. 11kV). In addition, RTUs may also be able to send event driven data, e.g. field alarms. At the control center, state data is analyzed to detect anomalous conditions (e.g. under voltage) that may require corrective actions (e.g. operating an on load tap changer) which will include the sending of relevant control signals to remote network elements. In this way, DNOs use periodic polling and event-driven messages to ascertain the state of network operation. At present most SCADA systems lack of sensing and control capabilities at low voltage levels, e.g. 11kV, which makes their service largely depend on manual operation.

In addition to the central control approach, some tasks, e.g. protection, could be performed through local control loops with controllers equipped in the field, as shown in Figure 1. These controllers merely monitor and control the devices connected to them without taking into account the impact of their control decisions on peer areas and the decisions are generally made following pre-defined logic designed for specific operation conditions. Thus, the control actions are restricted in scope and not flexible, and hence only sub-optimal network operation would be achieved.

III. Regional active network management

The key concept of regional active network management approach is to delegate network management tasks to a set of loosely-coupled autonomous regional controllers that can manage their geographical sub-network whilst cooperate with

[1]The simulation environment source code can be obtained from the corresponding author.

peer controllers when necessary to achieve global optimal operation. Figure 2 illustrates the principle by using a section of an 11kV network as an example which is divided into three regions (I, II and III) with each region covering a single 33/11kV substation area. Hardware controllers are installed in individual regions which are able to access sensing and actuating devices of power network elements (e.g. DG, transformer) in their area of influence via regional communication channels (dotted-dash lines). The controllers are inter-connected with their peers via inter-regional peer-to-peer channels (dashed lines). While the operation of regional controllers ("C") are no longer dictated by the DNO's control center ("C/C"), the latter can still instruct the former when necessary via communication channels between them (solid lines) to adapt the overall network operation to meet certain goals. With such an approach, the overall centralized management system is transformed into a number of autonomous and coordinated control subsystems:

1) Regional autonomy: the network monitoring and control actions are taken locally by the regional controller in its designated region. If the impact of the anomalous condition does not exceed the regional boundary, the controller will carry out control actions autonomously without consulting its peers.
2) Inter-regional coordination: in the case that the detected anomalous conditions could impact adjacent regions, the controllers in adjacent regions will cooperate to find control decisions which should minimize the spread of the anomaly.

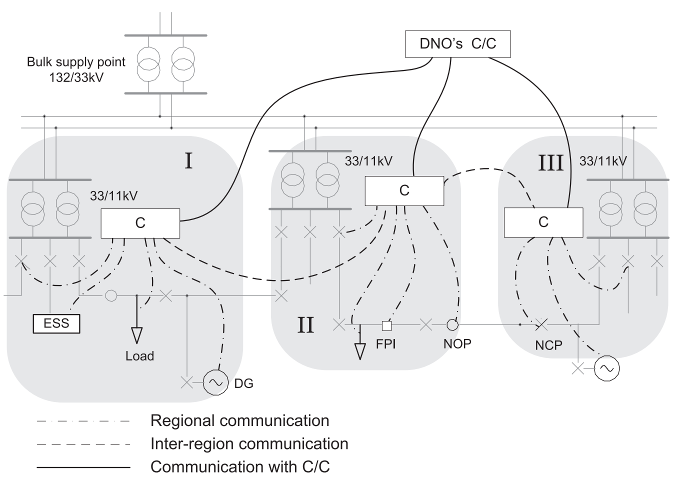


Fig. 2: Regional active network management approach (C/C: control center; C: regional controller)

Such a management paradigm will work only if it is underpinned by an efficient communication system, which might be able to use deployed SCADA system. Otherwise, new communication infrastructures will need to be provided.

Three ANM control functions are investigated in AuRA-NMS project, namely voltage control, automated supply restoration and power flow management [7] and they can potentially run in each one of the regional controllers. Intelligent approaches, e.g. Case-Based Reasoning (CBR), are explored to find voltage control solutions to efficiently maintain the voltage profile within the regulated limits under various conditions, e.g. load variation, intermittent DG outputs, by using various control measures, e.g. on-load tap changer (OLTCs) control, DG power factor control, DG real power curtailment control, or a combination of them (e.g. moving taps in a transformer and reducing real power of a certain DG). This approach works based on up-to-date network measurements, including voltage (V), current (I) and real power (P) measurements on all feeders, transformer states (V, I, tap position), V, P and reactive power (Q) on all DGs. Fault management is another key aspect of ANM to improve the power supply quality by restoring power supply to as many customers and quickly as possible after a fault whilst meeting some certain operational criteria, e.g. within feeder/switch ratings or minimum switching operations. The function requires network load and controllable switch status information to derive control solutions. The power flow management can be modeled as a Constraint Satisfaction Problem (CSP) and solved by various algorithmic solutions to find suitable control instructions, e.g. charging/discharging Energy Storage System (ESS), tripping/trimming DG or load shedding, to meet load flow constraint (i.e. for a given level of DG generation, network operates within thermal limits) and contractual constraint (i.e. higher priority DGs are not tripped or trimmed before lower priority DGs). The function requires P and Q information on all system loads and DGs. Although these ANM algorithms have shown to enhance distribution network operation, the underlying assumption is that the network information can be timely and reliably delivered to the regional controllers.

In AuRA-NMS, agent-based technology, which has been widely accepted in industry (e.g. [31]), is considered a more suitable underpinning tool than other alternatives (e.g. data exchange via peer-to-peer protocols like IEC61850 or web-based services) to support inter-regional coordination due to the inherent agent characteristics (e.g. pro-activeness, autonomy and sociability) and the distributed nature of multi-agent system (MAS). It represents a decentralized approach with parallelism that distributes computational resources or tasks to agents across a set of interconnected hardware controllers, and hence could avoid performance degradation due to resource limitations and critical failures if the control functionalities are sufficiently shared among agents. The modularity of MAS leads to efficient software integration and upgrade and simple interoperation with legacy systems. In summary, MAS can enhance overall system performance, specifically in terms of computational efficiency, reliability, extensibility, maintainability and software reuse. In AuRA-NMS, rather than using agents to represent physical network elements, e.g. DGs and feeders, MAS is applied in a distinct way as an efficient and flexible tool of building the software architecture across the networked controllers by encapsulating the ANM functionalities as agents to achieve "plug and play" management [7].

In this ANM solution, another two questions remain open: (1) where the regional controllers are going to be physically located in the network; and (2) how to define the boundaries of the controlled regions. In principle, the controllers can be allocated across the distribution network with great flexibility and the decision may be determined by the communication availability and DNO's specific requirements. The partition of distribution network into a set of control regions can be complex, particularly when networks are with a meshed structure, and sophisticated techniques may need to be involved to tackle this problem. These issues are out of the scope of this paper and left out for future investigation.

IV. Standards, protocols and technologies

This section presents relevant standards, protocols, and communication technologies in the context of AuRA-NMS.

A. Standards

To enable communication interoperability, it is essential to adopt a unified approach for data modeling across the distribution networks. Two IEC standards (61970-301 [11] and 61968-11 [12]) are collectively known as the Common Information Model (CIM) which is able to provide extendable object-oriented semantics with a hierarchical architecture to describe different network elements and their inter-relationships. The IEC 61850 standard [13] has been adopted for substation automation for years which models substation equipments and functions as abstract objects to improve the interoperability among Intelligent Electronic Devices (IEDs). Recent efforts are being made to expand the scope of IEC 61850 to the whole power networks [5] and harmonize it with CIM towards a comprehensive standard data definition to enable monitoring, control or protection applications developed on different platforms to represent and exchange information in a consistent format, and in turn, enable seamless data communication throughout various voltage levels across the overall distribution networks. Therefore, CIM and IEC 61850 are suggested to build standard data model in AuRA-NMS solution and they could be further extended if needed to meet certain requirements [7].

Foundation for Intelligent Physical Agents (FIPA) is currently the most accepted standardization effort for MAS [31] and hence is adopted in AuRA-NMS solution. The FIPA specification provides the normative framework for agents to be deployed and operate. It specifies the necessary interface to support interoperability in MAS and offers the logical reference model for the creation, registration, location, communication, migration and retirement of software agents.

B. Protocols

Current proprietary communication is a major obstacle for DNOs to adopt advanced automation and intelligent network applications. Some recent proposals have suggested migrating to the IP based monitoring and control paradigm for industrial automation (e.g. [20], [32]). Current DNOs face severe communication inadequacy due to the presence of analogue circuits and low speed modems in their SCADA systems and interoperability problem due to proprietary protocols. Present TCP/IP based communication systems are generally provided with sufficient bandwidth and high availability, and hence more comprehensive operational data can be obtained to achieve timely network awareness and more sophisticated management tools can be applied to optimize network operation with greatly improved interoperability.

However, apart from the reinforcement costs of communication infrastructure, there are still two major concerns over such migration. Firstly, TCP protocol can be problematic due to its "slow-start" nature and unpredictable performance. Authors in [21] argued that TCP is not quite suitable for system monitoring due to its non-deterministic latency and proposed a UDP-based protocol instead. Another concern is that such open technologies are more vulnerable to malicious attacks, and hence with high security risk, compared to isolated private circuits with proprietary protocols as data may traverse through public communication infrastructures in a standard format. Lots of research efforts (e.g. [6], [32]) have been conducted to remove these concerns. In addition, some alternatives are developed with more efficient polling mechanisms (e.g. [2]) or smarter protocols (e.g. retransmission strategies, see [9]) for enhancing the reliability and flexibility of data acquisition and transportation in various communication conditions. In this paper we restrict the view in assessing the TCP/IP based systems for the AuRA-NMS operation by using standard TCP/IP and UDP/IP transport protocols with round-robin polling scheme to carry different types of data traffic.

C. Technologies

One key aspect of ANM communication design is to deploy suitable and future-proof wired/wireless or hybrid technologies. Previous work (e.g. [3], [8], [34]) have comprehensively addressed this issue, and the following merely highlights a number of promising ones.

In general, the wired technologies, e.g. Digital Subscriber Lines (DSL) and optical fibre, provide more capacity, reliability and security but are costly for large-scale deployment. For example, optical fibre can support data rate up to several Giga bits per second with BER as low as 10^{-15}. The major limitation is its high renting and installation costs, and hence it should only be considered when high bandwidth and stringent performance guarantees are required. Recent technological advances enables power Line Carrier (PLC) to transmit data over existing medium (15/50 kV) and low (110/220 V) voltage power lines with an improved data rate (maximum capacity of 45 Mbps with a prototype modem [34]). However, many technical problems are still unresolved, e.g. large BER due to high noise sources over power lines and signal attenuation and distortion, and lack of security and regulation.

The wireless technology could save installation costs with fast deployment and flexible configuration, but with constrained bandwidth and security. For example, Ultra High Frequency (UHF) radio (300MHz-1GHz) can provide point-to-point or point-to-multipoint communication with typical data rates of 9600 b/s (full-duplex) or 19.2 kb/s (half-duplex) at the range of 30-50 km and typical BER of $(10^{-6}, 10^{-3})$. Low Earth Orbit (LEO) networks are promising to power utilities due to its ubiquitous coverage, flexible configuration and affordable cost. Existing constellations (e.g. Iridium, Globalstar) can deliver low bit-rate voice and data services (e.g. 4.8 or 9.6 kb/s) and Teledesic system is designed as "Internet-in-the-Sky" to offer high quality broadband services (16 kb/s to 2048 kb/s). In a LEO constellation, a single hop generally contributes about 20 ms to the propagation delay and additional satellite hops could add to the latency depending on the distances between satellites, resulting an end to end propagation time of 20-200 ms. In addition, the delay can vary over time due to the relative satellite motion, handover process and routing path changes. The well-known limitation of LEO network is signal shadowing due to environmental blockage and diffraction effects (e.g. urban buildings and mountains in rural areas) which results in high BER and temporary channel outage. Fortunately, LEO constellations have dynamic, yet deterministic topology [35], and its performance in terms of channel quality and availability can be greatly enhanced from many aspects, e.g. fade margins and advanced transmission techniques to compensate multipath fading, and use of visible satellites and path or satellite diversity to minimize blockage impairments (e.g. [29]). Therefore, this work uses BER $(10^{-8}, 10^{-5})$ to characterize the channel error behavior assuming that the bit errors are random and the burst errors due to convolution encoding schemes are not considered. As an alternative to the wired technologies, microwave radio operates at frequencies above 1GHz offering high transmission data rates (few Mb/s to 155 Mb/s) which can be used for long distance communication. However, it requires line of sight between the two ends of the connection, and hence high mast installation is required which can be costly. Finally, WiMax offers a standardized point-to-multipoint high speed communication with a large geographical coverage (i.e. IEEE 802.16) which greatly improves the communication performance of power utilities suffering from environmental obstacles.

As current MV distribution networks are often geographically large (including rural, urban, sub-urban and some very remote sites), it will be more cost-effective to adopt a mixture of technologies. Also, DNOs could build their "utility-Intranet" to obtain full control on communication with increased flexibility, security and reliability. The candidate technologies at given voltage levels need to be carefully evaluated prior to deployment against various criteria, e.g. availability, reliability, security, expected traffic pattern and cost.

V. Communication system engineering challenges

The operation of regional ANM system brings many challenges on engineering underlying communication infrastructure. Some key requirements are highlighted as follows and a more detailed discussion can be found in [26].

A. Data Availability, QoS and Security

The efficient operation of ANM strongly relies on high data availability (i.e. data is accessible when needed, at the right locations, and in the expected formats). When DGs are connected to the distribution network, the network can exhibit dynamic behavior in the scale of milliseconds. The advances in substation automation permits fast data sampling, and hence enhances the capability of obtaining detailed operational states in substations. Unfortunately, existing SCADA can hardly make these data available to the regional controllers in a timely manner due to constrained bandwidth. Furthermore, very little information may be available from some parts of the network due to limited number of sensing and control devices. The enhancement of data availability needs to be taken into account in the process of communication system design. In ANM system, different algorithms need to act in their designed time scales to fulfil their functions. For example, under-voltage load shedding control action needs to be operated in several seconds, while on-load tap changers act in the time-scale of tens of seconds, and thermal phenomena (e.g. transformer overheating) may allow several minutes before a control action is taken. Therefore, the underlying communication system needs to be carefully designed with quality of service (QoS), e.g. service prioritization and resource management ([19], [25], [33]), to meet diverse latency requirements. Also, as the data security is extremely vital for power utilities, advanced mechanisms (e.g. [6]) need to be adopted in the communication system for secure information storage and transportation.

B. System Extensibility, Robustness and Reliability

Since the number of network elements in distribution networks is steadily growing, the underlying communication system and software architecture need to be scalable to accommodate such growth, e.g. easily incorporating and managing the newly-added network devices with minor configuration efforts (e.g. [28]). In addition, as the ANM functions may operate across several distributed controllers, this requires the system to have a certain level of redundancy (e.g. backup channels, devices and software components) to cope with potential failures (e.g. channel failure and device outage) and varied computation requirements. For highly critical sites, it is not uncommon that multiple communication channels with different medium coexist to ensure high reliability.

C. Communication Interpretability and Compatibility

The information exchange in ANM system is expected to be based on a standard data model, e.g. IEC61850. However, at present, both IEC61850-compliant devices and devices running proprietary protocols co-exist in substations. Properly interfacing with the legacy system is crucial to provide system backward compatibility and transparent communication. One viable solution is to integrate a protocol converter through a gateway into the substation SCADA system. Such conversion can be implemented through IEC61850 and Object Linking and Embedding (OLE) for Process Control (OPC) technology by defining the mapping between IEC61850 and the legacy protocols. The IEC61850-compliant devices can be directly connected to the substation local area network (LAN). As a result, regional controllers executing ANM algorithms can communicate with all substation monitoring, protection and control devices with minimum reinforcement cost.

VI. Communication system and traffic modeling

A. Communication System Modeling

For the sake of clarity, the following notations are used:

c_a	Communication channel capacity
d_p	Propagation delay
d_t	Transmission delay
d_r	Processing delay
d_q	Queuing delay
e_r	Channel bit error rate (BER)
l_c	Congestion loss
l_e	Corruption loss
p_e	Packet error rate (PER)
σ	Message size in bits
b_s	Buffer size in messages

Consider a heterogeneous communication infrastructure consisting of a variety of communication media, as shown in Figure 3(a). Data may be transported traversing a number of them before reaching their destinations, e.g. Internet and LEO satellite (point A to B) or Internet and radio system (point A to C). In the proposed framework, the communication path between source (s) and destination (d) is modeled as a set of communication nodes (representing routers, switches, or even local area networks) interconnected with links (representing communication channels), as shown in Figure 3(b).

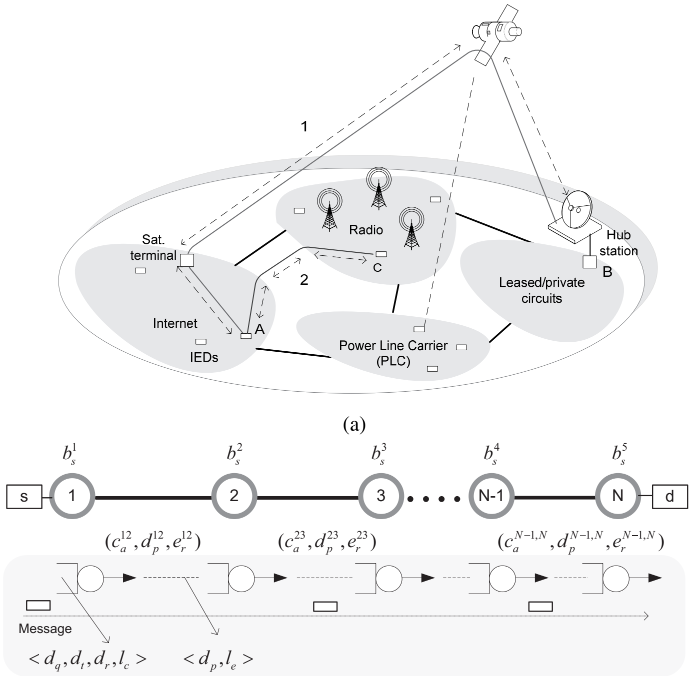


Fig. 3: Communication infrastructure (a) and its modeling (b)

From the control actions perspective, the relevant parameters from the communication system are: channel capacity, message latency and probability of message loss. Channel capacity (c_a) indicates the maximum data transmission rate in a communication channel. Message latency is referred as the amount of time for a message to be delivered from the sender to the receiver along the communication path which comprises of four components: (1) propagation delay (d_p), refers to the amount of time for data to propagate over a link, which is generally constant and dependent on the distance and channel medium; (2) transmission delay (d_t), is determined by channel capacity and message length; (3) processing delay (d_r), is the time takes by routers for routing and error checking which is generally small enough (on order of microseconds or less) to be neglected; and (4) queuing delay (d_q), is a dynamic part which refers to the message waiting time in the node buffer before being processed when temporary communication congestion occurs.

There are two types of data loss need to be considered: (1) congestion loss (l_c), which occurs when the communication system is congested which causes intermediate communication elements (i.e. routers) to drop messages; and (2) corruption loss (l_e) due to transmission errors caused by a variety of environmental effects, e.g. signal interference, noise, and is often dominate in wireless channels. Although primarily influenced by the BER, the message corruption loss rate also depends on message length and the effectiveness of error correction mechanism. We approximate packet error rate (p_e) assuming that the bit errors are independent and identically distributed:

$$p_e = 1 - (1 - e_r)^{\sigma} \tag{1}$$

For the investigation of packet level performance, it is sufficient to characterize the delay and error behavior without the transmission channel details. Therefore, only a set of relevant parameters are used to characterize the communication system, including three channel parameters: capacity (c_a), propagation delay (d_p) and BER (e_r) and one node parameter: buffer size (b_s) of 50 (in messages).

B. Communication Traffic Modeling

In IEEE SCADA standard [14], three generic data transaction modes are identified for communication between two entities (sender and receiver) in power utility. These modes are borrowed in this study to characterize different traffic in ANM system which are described below.

1) Mode A: one or more messages are sent with no receipt confirmation and retransmission upon loss. This is used in applications where the data reception is not essential.
2) Mode B: one message is sent followed by a receipt acknowledgement and message is retransmitted if lost. This is suitable for applications where reliable data delivery is required.
3) Mode C: characterized as "select-before-operation". Following the first "select" message, a "confirm" message is sent to verify that the device acts correctly to the selection. Then a "control" command is transmitted upon the confirmation and followed by an acknowledgement indicating the message is properly received. This procedure effectively avoids operating wrong devices or receiving bad control messages.

There are three types of data traffic identified to support the regional ANM operation:

1) Sensing traffic (cyclic and acyclic): network measurements (e.g. V, I, P) are cyclically sent to their assigned regional controller with a pre-defined time interval; urgent field events (e.g. alarms) are sent to controllers as acyclic data once generated. Both cyclic and acyclic data

are set with message size of 32 bytes, but with mode A and mode B respectively.

2) Control traffic: control commands issued by regional controllers are delivered to the actuating devices to take certain actions using mode C. A command may consist of several messages (assuming up to 10 messages) with message size of 60 bytes.
3) Coordination traffic: the controllers coordinate with peers in finding control solutions when needed through exchanging a number of asynchronous Agent Communication Language (ACL) messages based on mode B. The message size is set to 1000 bytes.

Due to the different nature of data transaction modes, the mode A is modeled by using UDP protocol without message acceptance confirmation and retransmission mechanism, whereas, mode B and C are modeled by using reliable protocol, TCP, providing confirmation following message receipt and data retransmission upon loss.

To evaluate the communication systems for supporting regional ANM, extensive numerical simulation experiments are conducted with *ns2* [24]. Figure 4 schematically shows the system model in simulations with three hierarchical levels: sensor/actuator level representing the field sensing and actuating devices, SCADA level showing the existing communication provision in DNOs and an ANM level on above showing the infrastructure that may potentially need to be deployed. This effectively provides us with an efficient communication assessment framework as the system model can be flexibly configured with different topologies (e.g. additional routers labeled as 3, 5, 8 and 9 at the SCADA level can be used to produce larger or more complex topologies), channel and node parameters to reflect a variety of system and traffic scenarios and allows us to carry out a range of assessment, e.g. to identify where existing SCADA system could be used or new communication provisions have to be deployed to achieve acceptable performance.

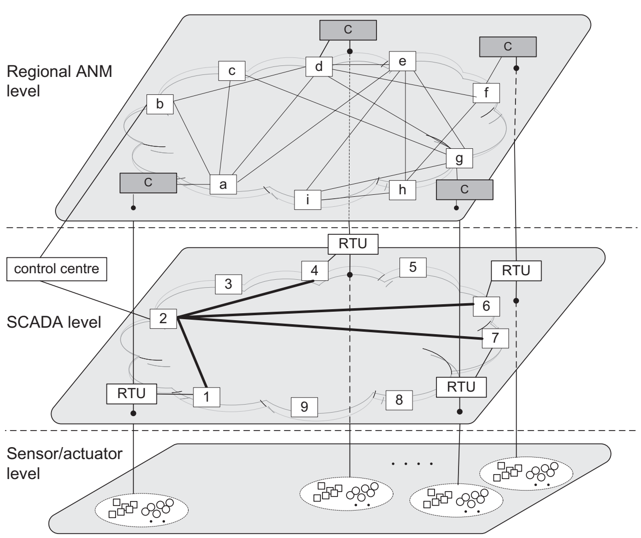


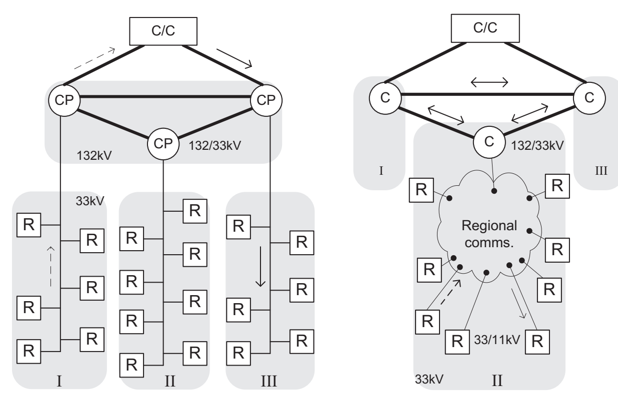
Fig. 4: Communication infrastructure simulation model (C-regional controller; routers are labeled as 1∼9 and $a \sim i$)

VII. Communication systems for two case distribution networks

This section addresses the design of communication systems for controlling two representative case networks, 33kV meshed network and 11kV radial network, and evaluates the communication performance based on proposed assessment framework.

A. 33kV Meshed Network

Figure 5(a) illustrates the structure of SCADA system in the 33kV meshed network covering three grid substation (132/33kV) areas. At 33kV level, primary substation (33/11kV) RTUs ("R") are organized in a multi-dropped structure via leased analogue phone lines or private wires, and RTUs are polled by the control center ("C/C") in sequence at fixed intervals to retrieve data to the control center via data Concentration Points ("CP") at grid substations (dashed arrow). At 132kV level, grid substations are inter-connected in a semi-meshed topology by channels (e.g. microwave or leased digital circuits) with high reliability (through triangulation and duplicated links) and bandwidth, from 512kb/s to a few Mb/s. However, the multi-drop lines are often operated with a low data rate, e.g. 1200b/s, as conventional SCADA data volume are generally limited, e.g. a few to tens of bytes per substation. Except for constrained bandwidth, the multi-drop lines have some other limitations: (1) low degree of security as every connected RTU may see every message, even those that are not destined for it; (2) tedious process for line diagnosis and fault isolation as the fault can be anywhere along the line; and (3) becoming bottlenecks preventing immediate communication access when data traffic are heavy.



(a) (b)

Fig. 5: 33kV meshed network: SCADA (a) and communication system for ANM (b) (dashed arrow: monitoring; solid arrow: control; double arrow: coordination)

In 33kV network, regional controllers ("C") are located at grid substations with each controller covering one grid substation area (I, II and III). The substation automation makes almost all of the required measurements for ANM available at the 33/11kV substation RTUs. However, both the low data rate and restricted structure become major obstacles to make these data timely available at the regional controllers. To solve this problem, Figure 5(b) shows that a new regional communication system, e.g. based on DSL technology, is adopted to replace the multi-drop lines in region II to connect the controller and RTUs in the region for collecting network states (dashed arrow) periodically and delivering control commands (solid arrow) once issued. On the other hand, SCADA channels providing the connectivity among grid substations may be used to carry the data traffic for coordination (double arrows) between peer controllers. If these channels cannot meet the needs, additional channels have to be set up.

B. 11kV Radial Network

Figure 6(a) depicts the SCADA system in the 11kV radial network comprising three primary substation (33/11kV) areas. Topologically, the RTUs ("R") at primary sites and secondary units (11kV/LV) are directly connected with the control center ("C/C") separately for network monitoring (dashed arrow) and control (solid arrow). To adopt AuRA-NMS solution, the control region is determined as each substation area and controllers ("C") are installed at 33/11kV substations as the substation operation has the dominating influences on all its downstream feeders.

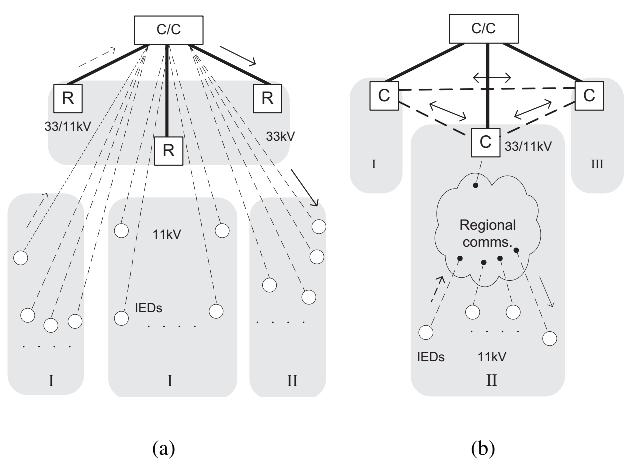


Fig. 6: 11kV radial network: SCADA (a) and communication system for ANM (b) (dashed arrow: monitoring; solid arrow: control; double arrow: coordination)

In this case, two issues need to be addressed. Firstly, there are no existing connections between 11kV network units and 33/11kV substations and among substations. Therefore, additional communication infrastructure needs to be deployed for communication among these sites for network monitoring (dashed arrow) and control (solid arrow) in each control region and message exchange for coordination among regions (double arrow), as depicted in region II in Figure 6(b).

Another issue is that, the number of measurements required by ANM algorithms to make reliable control solutions (e.g. V and I measurements on all feeders) can be very high in 11kV network due to its large number of feeders and laterals. However, the current situation is that very few operational details can be obtained due to limited sensing and control capability. This implies that additional IEDs coupling with communication channels need to be installed in 11kV network which is in practice not cost-effective. One viable solution is to adopt Distribution State Estimation (DSE) technique which predicts network operational state based on a set of pseudo measurements and a small number of actual measurements obtained from some key locations [1]. Taking voltage control as an example, only a few measurements may be needed, e.g. tap position, DG voltage level and power outputs. DNOs need to make a tradeoff between adopting sophisticated DSE and deploying more sensing devices to make the solution cost-effective. In each control region, the locations where network measurements need to be obtained could be very dispersed and the 11kV network units communicate with the controller following a point-to-multipoint pattern. This makes the wireless based systems particularly attractive to be adopted with the desirable features of flexible configuration and affordable costs. One of the key issues is to select suitable Medium Access Control (MAC) protocol to coordinate transmission among multiple devices sharing common wireless medium with minimized collisions and access delay while maximizing throughput. Due to the fact that the measurement data is generated in 11kV units in a regular and stable pattern, and needs to be timely delivered to the controller, the round-robin polling based time-division multiple access (TDMA) technique is considered suitable for wireless channel access to enable the 11kV units to exclusively use the channel and take turn in sending their measurement data in their assigned time slots with enhanced reliability and reduced randomness [2]. In contrast, random access approach, e.g. Aloha and Carrier-Sense Multiple Access (CSMA), needs devices to compete for transmission with a random back-off process with no absolute guarantees of channel access and collision avoidance. This could make the 11kV units wait a non-deterministic long time to access the channel for data transmission.

VIII. Numerical Results

This section evaluates the performance of communication systems in the networks of the case studies. Some preliminary results are presented in [27]. We are interested in evaluating data delivery duration which is defined as the total communication time to complete a measurement cycle (including polling events), a control command delivery or a coordination process. DNOs require different traffic types to be delivered in different time scales to fulfil their functions. The general requirements are briefly described in [19] as "slow for post-event analysis, near real-time for monitoring and as close to real-time as possible for control or protection". The delivery time of data acquisition and control outside the substation is suggested to be within 1 s [15]. In this paper we directly adopt this requirement in the assessment of 33kV network. At the lower voltage level, the events in 11kV network are generally considered less critical, and hence the requirement is set as 10 s. For the same reason, the time requirement for coordination between peer-controllers in 33kV and 11kV network are set as 10 s and 100 s, respectively. The communication infrastructure simulation model introduced in Figure 4 is configured (in terms of topology, traffic demand, node and channel parameters) such that a range of network and traffic scenarios of three AuRA-NMS regions are obtained for the performance assessment of 33kV and 11kV network (i.e. covering three grid substation areas and three primary substation areas, respectively, as shown in Figure 5 and Figure 6). All simulation experiments are carried out with the simulation time of 10000 seconds (about 2.8 hours) to capture the steady-state performance measurements (no significant difference in measurements was observed with a longer simulation time).

In this section, we start with some analytical performance analysis which will be further validated by simulation experiments presented in the rest of this section. From [18], without considering the negligible time of processing polling message (only several bits) and state switching (e.g. from idle to transmission), given the volume of the data to be delivered from a field entity (e.g. RTU or 11kV unit) at each cycle, v_d, the duration of extracting data from N field entities (including the propagation time of polling messages) based on a round-robin polling mechanism via a single switch can be absolutely bounded by D^s_{min} and D^s_{max}:

$$\begin{aligned} D^s_{min} &= \sum_{i=1}^{N}\left(\frac{v_d}{c_a} + 2\cdot d_p\right) \\ D^s_{max} &= \sum_{i=1}^{N}\left(\frac{v_d}{c_a} + b_s\cdot\frac{\sigma_s}{c_a} + 2\cdot d_p\right) \end{aligned} \quad (2)$$

where σ_s is the sensing message size (i.e. 32 bytes). D^s_{min} only considers message propagation and transmission delay assuming no temporary congestion occurs induced by other traffic and D^s_{max} assumes the extreme case that the node buffer is full (the term $b_s\cdot(\sigma_s/c_a)$ gives the maximum queuing delay experienced by a sensing message when buffer overflows).

In respect to the control performance, a simple approximation formula of the upper bound on the average TCP throughput, R, is given in [22], assuming that TCP is running over a lossy path with a constant round trip time, RTT, and random packet loss at a constant probability, p, as follows:

$$R < \frac{MSS}{RTT}\cdot\frac{1}{\sqrt{p}} \quad (3)$$

where MSS is the system maximum segment size, and hence with the the control message size, σ_c (i.e. 60 bytes), the lower bound on average deliver duration of k control messages, D^c_{min}, can be analytically estimated as

$$D^c_{min} = \frac{k\cdot\sigma_c}{R} \quad (4)$$

A. Sensing and Control in 33kV Network

The first set of experiments look into the 33kV network and assess the feasibility of using existing SCADA multi-drop lines (see Figure 5(a)) to carry the data traffic for ANM with the channel configuration of (c_a=1.2 kb/s, d_p=5 ms, e_r=10^{-5}). It is assumed that each substation RTU is associated with 50 bytes of data (i.e. v_d) to be periodically delivered to its regional controller with the polling interval of 100 s. The acyclic data and control events in respect to each RTU are randomly generated following a uniform distribution with the arrival intensity of 0.02 s^{-1} and 0.005 s^{-1}, respectively. Figure 7 shows the result of mean data delivery duration (errorbars showing the variations and applied to all the rest of figures) for sensing (line with circles) and control (line with squares) events against the number of RTUs per region increasing from 1 to 20 (i.e. 3 to 60 RTUs in total in the simulated network) with the theoretical bounds (dashed lines) from (2) and (4).

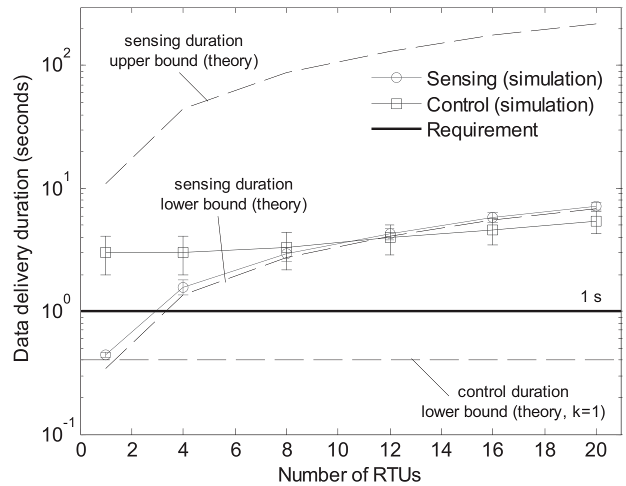


Fig. 7: 33kV network sensing and control data delivery duration using multi-drop lines (c_a=1.2 kb/s, d_p=5 ms, e_r=10^{-5}), polling interval:100 s

In principle, the sensing duration should be deterministic and proportional to the number of polled RTUs. However, some variations are observed in the experiments which is due to the randomness induced by the presence of acknowledgement messages of control commands and acyclic sensing data. Thus, DNOs need to design their system to ensure that all field information can be completely obtained with the pre-defined polling interval. The analytical bounds are confirmed by the simulation results, e.g. for the case of 12 RTUs per region, D^s_{min} and D^s_{max} are about 4.12 s and 132.12 s, respectively. In respect to network control, it is assumed that a control command may consist of a random number of messages (up to 10). Based on (4), the best-case average time duration to deliver a control command consisting of 1 ($k=1$) and 10 ($k=10$) control messages can be approximated as 0.4 s and 4.0 s, respectively. In reality, the delivery duration could be larger as it is also influenced by many unpredictable factors, e.g. "slow-start" behavior, data retransmissions due to channel errors and randomness introduced by RTU cyclic and acyclic data. The simulation results can provide further insights on the control performance. It is clearly indicated that current low data rate SCADA legacy in 33kV network cannot meet the time requirement of 1 s for network sensing and control.

With the recognition of 33kV SCADA limitation, we propose an ADSL based infrastructure in AuRA-NMS solution with generous capacity (T1 link, 1.544Mb/s) and low BER of 10^{-7} to the 33kV network. With the same network scenario, we evaluate the data delivery performance with a high RTU polling rate (every 1 s). Figure 8 shows that the high data rate of T1 links can efficiently accommodate the impacts of randomness even with a high polling rate and provides required timeliness performance in 33kV network for all experimented scenarios, i.e. the sensing (line with circles) and control (line with squares) durations are within 1 second.

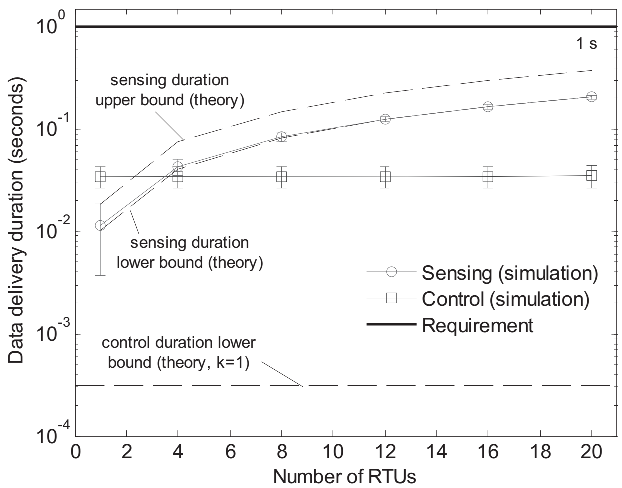


Fig. 8: 33kV network sensing and control data delivery duration using T1 channels (c_a=1.544Mb/s, d_p=5 ms, e_r=10^{-7}), polling interval:1 s

B. Sensing and Control in 11kV Network

Now, the performance assessment is conducted in the 11kV network in which a wireless based communication infrastructure is the focus of the investigation. As the network operation at 11kV level is generally less critical compared with higher voltage sites, we assume that the 11kV units are polled with a relative low rate of every 20 s. The control events in each region and the acyclic data in respect to each unit occur randomly with an intensity of 0.005 s^{-1} and 0.02 s^{-1}, respectively. The wireless channel is characterized as (c_a=9.6kb/s, d_p=10 ms, e_r=10^{-6}) which could represent a single hop LEO channel or other wireless media with similar properties. We consider a range of scenarios with the number of 11kV measurement points from 10 to 100 to represent different trade-offs between the sensing device deployment and sophistication of state estimator. Assuming each point is associated with 5 sensors (each sensor has 32-byte data to deliver), it results in the sensor population from 50 up to 500 per region (i.e. 150 to 1500 sensors in total in the simulated network). Figure 9 shows the mean sensing (line with circles) and control duration (line with squares) performance against different sensor population. Again, formula (2) can be applied to validate the bounds of sensing duration, e.g. when the number of measurement points is 40 (i.e. 200 sensors), the minimum sensing duration is about 6 s. The result suggests that although almost all the control commands can be delivered within about 1 s, the sensing duration violates the time requirement (i.e. 10 s) when the sensor population exceeds a certain number, i.e. 350 per region. The result indicates that suitable state estimation algorithms need to be incorporated in 11kV network to reduce the number of required measurement points (and hence the sensor data needs to be transported) to meet the operational requirements.

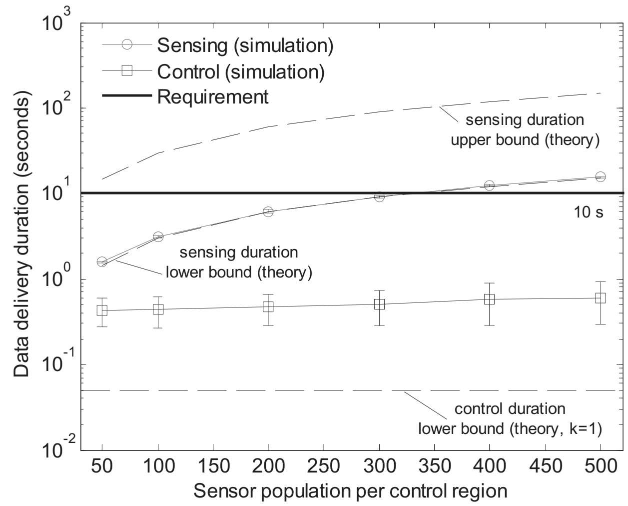


Fig. 9: 11kV network sensing and control data delivery duration using wireless channels (c_a=9.6kb/s, d_p=10 ms, e_r=10^{-6}), polling interval: 20 s

It is well known that wireless channels often exhibit various BER levels due to environmental effects resulting in data corruption and ultimately discard if it cannot be recovered. TCP deems this as an indication of congestion, and in turn undergoes a number of unnecessary “slow-start” phases with degraded throughput. Keeping other channel parameters fixed, Figure 10 shows the mean sensing (line with circles) and control (line with squares) performance against different PER values from 0.01 to 0.1 (resulting in BER from $2.1 \cdot 10^{-5}$ to $2.2 \cdot 10^{-4}$ for control data based on Equation (1)), assuming moderate sensor population (200 per region). The result is as expected as the control data delivery duration increases when PER becomes larger, which is mainly due to data retransmissions upon message corruption drops (the errorbars become dots due to the logarithmic scale). It also shows that the average delivery duration of control data is well within the time requirement in 11kV network (i.e. 10 s) for all simulated PER scenarios. However, it must be aware that even with the most advanced physical layer, MAC, and error control technologies, channel errors cannot be fully eliminated. Therefore, the adoption of additional mechanisms (e.g. [23]) still need to be considered to handling errors in practice.

C. Inter-regional Coordination

Finally, the performance of inter-regional coordination is evaluated through simulation experiments for both 33kV and 11kV network. Under the circumstance that multiple controllers need to cooperate in finding control solutions, inter-regional coordination process will be initiated. Two scenarios are considered: scenario (i) in 33kV network, SCADA communication connections are available among 132/33kV substations and their effectiveness of supporting inter-regional

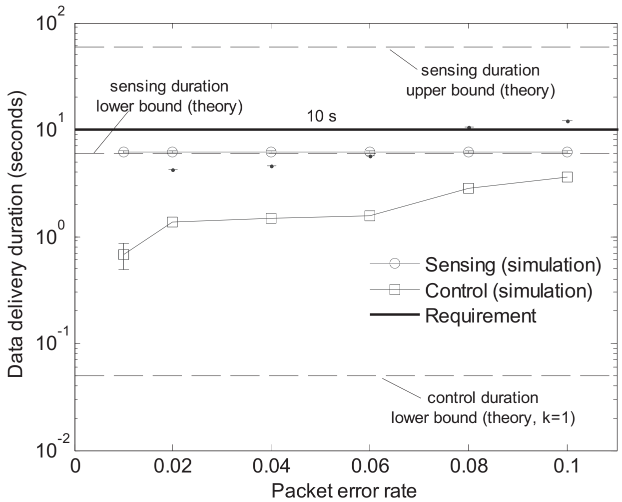


Fig. 10: 11kV network control duration against PER (0, 0.1), sensor population per region: 200, polling interval: 20 s

coordination needs to be evaluated. We assume that two controllers are connected via an existing SCADA path comprising a microwave channel (c_a=1024kb/s, d_p=10 ms, e_r=10^{-6}) and an optical fibre link (c_a=2048kb/s, d_p=1 ms, e_r=10^{-15}); and scenario (ii) in 11kV network, the data traffic is assumed to be carried by an underlying wired/wireless hybrid system comprising a LEO network (c_a=1024kb/s, d_p=200 ms, e_r=10^{-5}) and terrestrial optical fibre (c_a=2048kb/s, d_p=1 ms, e_r=10^{-15}) with satellite propagation delay set to 200 ms to represent multiple LEO constellation hops. For both scenarios, the coordination events occur randomly following a uniform distribution with an intensity of 0.005 s^{-1}. These experimental scenarios aim to identify and highlight the impacts of bottleneck technology on the end-to-end path.

Figure11 shows the mean coordination duration with the number of exchanged messages per coordination session increased from 50 to 1000 and the theoretical lower bound of average delivery duration which can be derived from formula (4) in the similar way as the control duration, e.g. 0.78 s and 3.12 s for exchanging 200 and 800 messages. The different numbers are used to indicate a range of degrees of complexity in coordination, i.e. a more complex decision-making process could result in more message exchanges, and hence a longer time to derive control solutions. The simulation result shows that the coordination data delivery duration increases with the growth of the number of exchanged agent messages and meets the time requirements in both scenarios (10 s in 33kV, 100 s in 11kV). Compared with the result of 33kV network (scenario i), the slow communication in 11kV network (scenario ii) is mainly due to the large propagation time of LEO network which is identified as the bottleneck on the communication path. Therefore, LEO channels would need to be replaced by high-performance terrestrial systems with low propagation latency if enhanced performance is required. In addition, the result of both scenarios highlights the fact that in order to speed up the coordination process, the distributed power network control algorithms operated in regional controllers could be designed in such a way that message exchanges are minimized. Alternatively, the underlying communication channels might need to be upgraded.

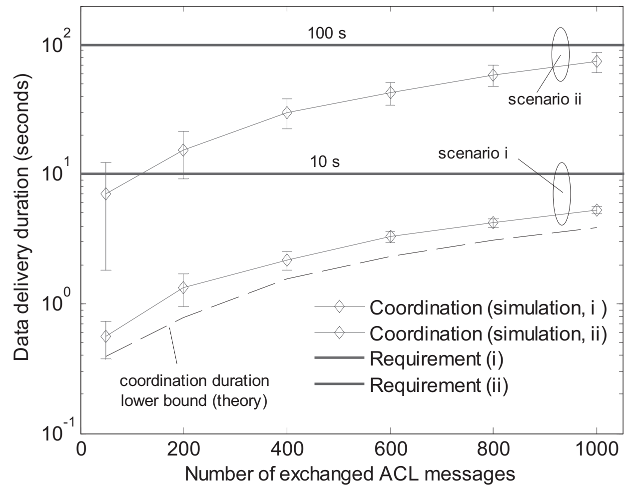


Fig. 11: Coordination duration in 33kV network (SCADA: microwave and optical fibre) and 11kV network (hybrid channel: LEO and optical fibre)

IX. Final Remarks

This paper investigates communications infrastructure design aspects, and analyzes two representative evolution cases of Active Network Management (ANM) system for distributed control of a Power distribution network. To obtain the results reported in this paper we develop a simulation environment that is flexile enough to assess various scenarios in which different technologies and protocols could co-exist. The simulation environment includes all the major features of legacy communication technologies so that the assessed solutions could also be assessed in terms of its backward compatibility.

We highlight the fact that current DNOs' communication infrastructures need fundamental change and significant reinforcements from a variety of aspects to support future ANM solutions in distribution networks with DGs. Even though DNOs have accepted the need to evolve into a distributed control management paradigm they envisage their system upgrade to be a gradual process following a cost-effective roadmap which implies that the backwards compatibility of future solutions, and the impact of co-existence with legacy technology should be evaluated and understood before the communication infrastructure upgrading are deployed. In view of this, when an end-to-end heterogeneous communication system is part of the solution, e.g. concatenation of wired and wireless systems, the identification and assessment of the impact of the bottleneck technology should be carefully evaluated. We also highlights the relevance and impact on the communication infrastructure if state estimator algorithms are available. The requirements in terms of volume of sensor data that need to be transported could be greatly reduced if state estimator are deployed in the network.

In summary we can say that current SCADA systems can hardly meet the communication needs for advanced ANM due to the constraints in both capacity and structure. Communication enhancement is required to facilitate network monitoring and control with desired performance. The ANM system needs to adopt a unified data modeling standard to enable transparent communication across the overall distribution network where interface with legacy network elements running proprietary protocols needs to be provided. Finally the migration from DNO's proprietary communication via closed circuits to TCP/IP based monitoring and control systems is suggested for building future "utility-Intranet" which is becoming more acceptable by industry.

Two research aspects are worth further investigation. The first one is to further quantify the impacts of communication performance, e.g. latency, data corruption, on ANM control algorithms, e.g. voltage control and power flow management, in a computer based test-bed. The other aspect is to analyze the communication system with enhanced features for future ANM systems, e.g. the adoption of standard data models (i.e. IEC61970-310 and IEC61968-11) and security mechanisms. Both these aspects will be able to further reassure DNOs and make more expedite their decision on the specific roadmap to upgrading communications infrastructures for next-generation smart energy ANM systems.

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Qiang Yang received the MSc (with distinction) and Ph.D. degree both in Telecommunications from Queen Mary, University of London, UK in 2003 and 2007, respectively. Afterwards, he worked as a Postdoctorial Research Associate at the Dept. of Electrical and Electronic Engineering, Imperial College London, UK from 2007 to 2010. He has been involved in a number of high-profile UK and European research projects during his stay in the UK. Since Sept. 2010, he is an Assistant Professor of the College of Electrical Engineering, Zhejiang University, PRC. His research interests over the years include communication networks, smart energy systems, and large-scale complex network modeling, optimization and simulation.

Javier A. Barria (M'02) is a Reader in the Intelligent Systems and Networks Group, Department of Electrical and Electronic Engineering, Imperial College London. His research interests include monitoring strategies for communication and transportation networks, sensor fusion systems and network traffic modeling and forecasting using signal processing techniques, and distributed resource allocation in dynamic topology networks. He has been a joint holder of several FP5 and FP6 European Union project contracts and EPSRC UK all concerned with aspects of communication systems design and management.
Dr. Barria is a Fellow of the Institution of Engineering and Technology and a Chartered Engineer in the UK. He was a British Telecom Research Fellow from 2001 to 2002.

Tim C. Green (M'89-SM'03) received a B.Sc. (Eng) (first class honours) from Imperial College, London, UK in 1986 and a Ph.D. from Heriot-Watt University, Edinburgh, UK in 1990. Both degrees were in electrical engineering. He was a Lecturer at Heriot Watt University until 1994 and is now a Professor of Electrical Power Engineering at Imperial College London and Deputy Head of the Electrical and Electronic Engineering Department. His research interest is in formulating the future form the electricity network to support low-carbon futures. A particular theme is how the flexibility of power electronics and control can be used to accommodate inflexibility elsewhere in the system and the part this plays in a smart grid. He leads the FlexNet consortium of 10 UK universities researching future networks. He is a Chartered Engineer in the UK.