OPTIMIZING THE ADVANCED METERING INFRASTRUCTURE ARCHITECTURE
IN SMART GRID

by
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of the requirements for the degree
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in
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ABSTRACT

Optimizing the Advanced Metering Infrastructure Architecture in Smart Grid

by

Alireza Ghasempour, MASTER OF SCIENCE
Utah State University, 2016

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Department: Electrical and Computer Engineering

Advanced Metering Infrastructure (AMI) is one of the most important components of smart grid (SG) which aggregates data from smart meters (SMs) and sends the collected data to the utility center (UC) to be analyzed and stored. In traditional centralized AMI architecture, there is one meter data management system to process all gathered information in the UC, therefore, by increasing the number of SMs and their data rates, this architecture is not scalable and able to satisfy SG requirements, e.g., delay and reliability. Since scalability is one of most important characteristics of AMI architecture in SG, we have investigated the scalability of different AMI architectures and proposed a scalable hybrid AMI architecture. We have introduced three performance metrics. Based on these metrics, we formulated each AMI architecture and used a genetic-based algorithm to minimize these metrics for the proposed architecture. We simulated different AMI architectures for five demographic regions and the results proved that our proposed AMI hybrid architecture has a better performance compared with centralized and decentralized AMI architectures and it has a good load and geographic scalability.

(64 pages)
The gathered data from smart meters in current advanced metering infrastructure (AMI) of smart grid is huge. This much data causes serious challenges for reliability, performance, and scalability of smart grid. Therefore, we have investigated the scalability of different AMI architectures and proposed a scalable hybrid AMI architecture. We formulated deployment cost of different AMI architecture and used a genetic-based algorithm to minimize the deployment cost for the proposed architecture. We simulated different AMI architectures for five demographic regions and the results proved that our proposed AMI hybrid architecture has a better scalability compared to other AMI architectures.
ACKNOWLEDGMENTS

I would like to thank my family who, from far away, have given me their support and strength. I express my gratitude to Prof. Jacob H. Gunther for his help and support.

Alireza Ghasempour
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<td>AM</td>
<td>Asset Management</td>
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<td>AMI</td>
<td>Advanced Metering Infrastructure</td>
</tr>
<tr>
<td>BI</td>
<td>Business Intelligence</td>
</tr>
<tr>
<td>BMWI</td>
<td>das BundesMinisterium fur Wirtschaft und energie</td>
</tr>
<tr>
<td>BS</td>
<td>Billing System</td>
</tr>
<tr>
<td>CIS</td>
<td>Consumer Information System</td>
</tr>
<tr>
<td>DC</td>
<td>Data Concentrator</td>
</tr>
<tr>
<td>DER</td>
<td>Distributed Energy Resources</td>
</tr>
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<td>DRMS</td>
<td>Demand Response Management System</td>
</tr>
<tr>
<td>ERP</td>
<td>Enterprise Resource Planning</td>
</tr>
<tr>
<td>GA</td>
<td>Genetic Algorithm</td>
</tr>
<tr>
<td>GIS</td>
<td>Geographic Information System</td>
</tr>
<tr>
<td>HAN</td>
<td>Home Area Network</td>
</tr>
<tr>
<td>HU</td>
<td>Housing Units</td>
</tr>
<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronics Engineers</td>
</tr>
<tr>
<td>LFS</td>
<td>Load Forecasting Systems</td>
</tr>
<tr>
<td>MDMS</td>
<td>Meter Data Management System</td>
</tr>
<tr>
<td>MWM</td>
<td>Mobile Workforce Management</td>
</tr>
<tr>
<td>NAN</td>
<td>Neighborhood Area Network</td>
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<tr>
<td>OMS</td>
<td>Outage Management System</td>
</tr>
<tr>
<td>PLC</td>
<td>Power Line Communication</td>
</tr>
<tr>
<td>PQM</td>
<td>Power Quality Management</td>
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<td>RA</td>
<td>Regional Aggregator</td>
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<td>SG</td>
<td>Smart Grid</td>
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<td>SM</td>
<td>Smart Meter</td>
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<td>TLM</td>
<td>Transformer Load Management</td>
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<td>UC</td>
<td>Utility Center</td>
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<td>Definition</td>
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<tr>
<td>UW</td>
<td>Utility Website</td>
</tr>
<tr>
<td>WAA</td>
<td>Wide Area Aggregator</td>
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<tr>
<td>WiMAX</td>
<td>Worldwide Interoperability for Microwave Access</td>
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</table>
1.1 Electricity Grid

The electricity grid has contributed greatly to our daily life. It uses an interconnected network to deliver electricity from generating stations to customers (residential, commercial, and industrial). The electrical grid has four elements: power plants, transmission lines, distribution substations, and customers (see Fig. 1.1 [1]).

There are three types of power plants:

- **Renewable and Variable** (e.g., Wind and Solar)
- **Renewable and Non-variable** (e.g., Hydro, Biomass, Geothermal, storage, and Pumped storage)
- **Non-renewable and Non-variable** (e.g., Nuclear, coal, and gas)

Power stations generate 3-phase alternating current electricity. Step-up transmission substations increase generated electricity to extra high voltage (and low current) via transformers for long-distance delivery over transmission lines to distribution systems. Step-down
transmission substations decrease extra high voltage to high voltage and then distribution substations step down high voltage to a level which is suitable to distribute between customers. Power is transported to customers via above or underground feeders. Finally, when the feeders reach the vicinity of customer locations, distribution transformers step down the distribution line voltage again (see Fig. 1.2).

Fig. 1.2: Power grid diagram
Due to the following reasons, conventional power grids are inefficient and unreliable systems and these issues must be addressed:

1. **Reliability:**

   The existing power grid is based on Nikola Tesla’s patent alternating current dynamo-electric machine) which was published in 1888 and has been evolved after 1896, but its basic infrastructure has remained unchanged. Since the existing power grid is based on out-of-date technologies that were originally designed more than 100 years ago, it cannot meet the increasing demand for energy and causes many outages (the world energy consumption will grow by 56% between 2010 and 2040 [2]). For example, in the India, blackouts in July 2012 affected over 620 million people [3] and in the U.S., the number of outages affecting more than 50,000 customers has been more than doubled during 2005-2009 compared to 2000-2004 [4]. These outages have cost of interruptions (e.g., outages, surges and spikes are estimated to ring up more than $150 billion damages to the U.S. economy annually [5]) and causes disturbances in power quality.

2. **Greenhouse gas and carbon emissions:**

   Fossil fuels used in power plants is the largest source of CO$_2$ emissions in the nation (37% of total U.S. CO$_2$ emissions and 30% of total U.S. greenhouse gas emissions in 2014) [6].

3. **Economics:**

   Sometimes conventional electrical grids cannot provide enough power at times of shortage or transmission congestion, so, service providers have to pay high prices for electricity that is imported from grid-connected neighbors (e.g., day-ahead wholesale market prices for 2014 has a variation from 12-550 $/MWh [7]).

4. **Safety:**

   Working on power grid may cause injuries and loss of life for humans.
5. Energy security:

The source of some power plants is oil that must be imported. To reduce imports of foreign oil and to lessen the dependency on fossil fuels, one strategy is the electrification of vehicles. But it causes additional load and challenges for the power grid.

1.2 Smart Grid

To address power grid challenges, smart grid (SG) is introduced. The term “smart grid” (also called smart electrical/power grid, intelligent grid, intelligrid, future grid, intergrid, or intragrid) has been used since 2005, when Amin and Wollenberg published their paper entitled “Toward A Smart Grid: Power delivery for the 21st century” [8]. However, this term had been used previously as far back as 1998 [9].

1.2.1 Smart grid definitions

The definition of SG varies among organizations, companies, and authors (see Table 1.1 [10] and [11]). For example, U.S. Department of Energy defined SG as a data communications network which is integrated with the power grid to collect and analyze data that are acquired from transmission lines, distribution substations, and consumers. Based on these data, SG can provide predictive information to its suppliers and customers on how best to manage power.
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<th><strong>Definition</strong></th>
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<tr>
<td>ABB</td>
<td>Smart Grid is the future evolution of the entire power network that focuses on the integration of renewable generation, reliability and efficiency of the grid. It includes transmission, distribution, demand response, automation, Information Technology, and controllable power devices.</td>
</tr>
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<td>Adam &amp; Wintersteller</td>
<td>A smart grid would employ digital technology to optimize energy usage, better incorporate intermittent green sources of energy, and involve customers through smart metering.</td>
</tr>
<tr>
<td>Australian Energy Mar-</td>
<td>Smart grid creates opportunities for consumers to change their energy consumption at short notice in response to a variety of signals that include price.</td>
</tr>
<tr>
<td>Ket Operator</td>
<td></td>
</tr>
<tr>
<td>Alberta Utilities Com-</td>
<td>Smart grid is a broad concept that describes the integration of hardware, software, computer monitoring and control technologies, and modern communications networks into an electricity grid.</td>
</tr>
<tr>
<td>mission</td>
<td></td>
</tr>
<tr>
<td>BMWi</td>
<td>E-Energy (smart grid) has towards convergence of information and energy technology.</td>
</tr>
<tr>
<td>CISCO Systems</td>
<td>The smart grid is a data communications network integrated with the electrical grid that collects and analyzes data captured in near-real-time about power transmission, distribution, and consumption.</td>
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<th>Definition</th>
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<td>Climate Group</td>
<td>A smart grid is a set of software and hardware tools that enable generators to route power more efficiently, reducing the need for excess capacity and allowing two-way, real time information exchange with their customers for real time demand side management. It improves efficiency, energy monitoring and data capture across the power generation and T&amp;D network.</td>
</tr>
<tr>
<td>Department for Energy and Climate Change</td>
<td>Building a smarter grid is an incremental process of applying information and communications technologies to the electricity system, enabling more dynamic real-time flows of information on the network and more interaction between suppliers and consumers.</td>
</tr>
<tr>
<td>Department of Energy</td>
<td>Smart Grid will be characterized by a two-way flow of electricity and information and will be capable of monitoring everything from power plants to customer preferences to individual appliances.</td>
</tr>
<tr>
<td>Electricity Networks Strategy Group</td>
<td>A Smart Grid as part of an electricity power system can intelligently integrate the actions of all users connected to it - generators, consumers and those that do both - in order to efficiently deliver sustainable, economic and secure electricity supplies.</td>
</tr>
<tr>
<td>Electric Power Research Institute</td>
<td>The ElectriNet recognizes the evolution of the power system into a highly interconnected, complex, and Interactive network of power systems, telecommunications, the Internet, and electronic commerce applications.</td>
</tr>
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Table 1.1 A summary of various smart grid definitions (continued)

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<th>Definition</th>
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<tr>
<td>European Regulators Group for Electricity and Gas</td>
<td>An electricity network that cost efficiently can integrate the behavior and actions of all users connected to it (generators, consumers and those that do both) in order to ensure a sustainable power system with low losses and high levels of quality, security of supply and safety.</td>
</tr>
<tr>
<td>European Technology Platform Smart Grids</td>
<td>Smart Grid is an electricity network that can intelligently integrate the actions of all users connected to it (generators, consumers, and those that do both) in order to efficiently deliver sustainable, economic and secure electricity supplies.</td>
</tr>
<tr>
<td>Franz et al.</td>
<td>Convergence of Information and Communications Technologies with the electricity system.</td>
</tr>
<tr>
<td>Federal Energy Regulatory Commission</td>
<td>Smart Grid advancements will apply digital technologies to the grid, and enable real-time coordination of information from both generating plants and demand-side resources. This will improve the efficiency of the bulk-power system, with the goal of achieving long-term consumer savings, and will enable demand response and other consumer transactions and activities that give consumers the tools to control their electricity costs.</td>
</tr>
<tr>
<td>Institute of Electrical and Electronics Engineers (IEEE)</td>
<td>the smart grid is a revolutionary undertaking—entailing new communications and control capabilities, energy sources, generation models and adherence to cross jurisdictional regulatory structures.</td>
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Table 1.1 A summary of various smart grid definitions (continued)

<table>
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<tr>
<th>Author/organization</th>
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<tr>
<td>Independent Electricity</td>
<td>The smart grid harnesses the power of information technologies to monitor, control, and optimize the usage of the electricity system. These efforts are designed to increase efficiency, reduce outages, integrate more renewable forms of generation, and empower consumers to more effectively control their energy use.</td>
</tr>
<tr>
<td>System Operator</td>
<td></td>
</tr>
<tr>
<td>Institution of Engineering</td>
<td>The Smart Grid will cost efficiently integrate the actions of all users connected to it (generators, consumers, and those that do both) in order to ensure an economically efficient, sustainable power system with low losses and high levels of quality and security of supply and safety.</td>
</tr>
<tr>
<td>and Technology</td>
<td></td>
</tr>
<tr>
<td>Miller</td>
<td>The Smart Grid will enable active participation by consumers, accommodate all generation and storage options, enable new products, services and markets, provide power quality for the Digital Economy, optimize asset utilization and operate efficiently, anticipate and respond to system disturbances (Self-heal), and operate resiliently against attack and natural disaster.</td>
</tr>
<tr>
<td>Organisation for Economic</td>
<td>The smart grid is an innovation that has the potential to revolutionize the transmission, distribution and conservation of energy. It employs digital technology to improve transparency and to increase reliability as well as efficiency.</td>
</tr>
<tr>
<td>Co-operation and Development</td>
<td></td>
</tr>
<tr>
<td>Pacific Gas and Electric</td>
<td>The Smart Grid is a modernized electric system that combines advanced communications and controls to create a responsive and resilient energy delivery network.</td>
</tr>
<tr>
<td>company</td>
<td></td>
</tr>
</tbody>
</table>

Continued on next page
Table 1.1 A summary of various smart grid definitions (continued)

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<tr>
<th>Author/organization</th>
<th>Definition</th>
</tr>
</thead>
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<tr>
<td>SIEMENS</td>
<td>The big picture for the Smart Grid is improved energy delivery, informed consumption and reduced environmental impact.</td>
</tr>
<tr>
<td>SmartGrid.GOV</td>
<td>The Smart Grid will consist of controls, computers, automation, and new technologies and equipment working together to respond digitally to our quickly changing electric demand. The Smart Grid represents an unprecedented opportunity to move the energy industry into a new era of reliability, availability, and efficiency that will contribute to our economic and environmental health.</td>
</tr>
</tbody>
</table>

Therefore, distinguishing characteristics of the SG cited in Energy Independence and Security Act of 2007 are as follows [12]:

1. **Dynamic optimization of grid operations and resources with full cybersecurity**

2. **Deployment and integration of distributed resources and generation including renewable resources**

3. **Integration of “smart” appliances and consumer devices**

4. **Provision to consumers of timely information and control options**

5. **Increased use of digital information and controls technology to improve reliability, security, and efficiency of the electric grid**

6. **Development and incorporation of demand response, demand-side resources, and energy-efficiency resources**
7. Identification and lowering of unreasonable or unnecessary barriers to adoption of SG technologies, practices, and services

8. Deployment of “smart” technologies for metering, communications concerning grid operations and status, and distribution automation

9. Development of standards for communication and interoperability of appliances and equipment connected to the electric grid, including the infrastructure serving the grid

10. Deployment and integration of advanced electricity storage and peak-shaving technologies, including plug-in electric and hybrid electric vehicles, and thermal-storage air conditioning

According to the mentioned characteristics of SG, a comparison between current power grid and SG is shown in Table 1.2 [13].

Table 1.2: Comparison between current power grid and SG

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Current power grid</th>
<th>Smart grid</th>
</tr>
</thead>
<tbody>
<tr>
<td>System type</td>
<td>Electromechanical</td>
<td>Digital</td>
</tr>
<tr>
<td>Information flow</td>
<td>Unidirectional communications</td>
<td>Bidirectional communications</td>
</tr>
<tr>
<td>Sensors</td>
<td>Few sensors</td>
<td>A large number of sensors</td>
</tr>
<tr>
<td>Monitoring ability</td>
<td>Manual monitoring</td>
<td>Self-monitoring</td>
</tr>
<tr>
<td>Checking and testing</td>
<td>Check equipment manually</td>
<td>Check equipment remotely</td>
</tr>
<tr>
<td>Grid topology</td>
<td>Radial/hierarchical topology</td>
<td>Network topology</td>
</tr>
</tbody>
</table>

Continued on next page
<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Current power grid</th>
<th>Smart grid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control ability</td>
<td>Limited control over power flows</td>
<td>Pervasive control systems</td>
</tr>
<tr>
<td>Overall efficiency</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Environmental pollution</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Electricity generation</td>
<td>Centralized generation</td>
<td>Distributed generation</td>
</tr>
<tr>
<td>Liable to failures</td>
<td>Prone to failures and blackouts</td>
<td>Adaptive protection and islanding</td>
</tr>
<tr>
<td>Integrating distributed energy resources (DERs)</td>
<td>Seldom, many obstacles exist for DERs interconnection</td>
<td>Often, many DERs with plug-and-play convenience focus on renewables</td>
</tr>
<tr>
<td>Decision making in emergency situations</td>
<td>Emergency decisions by phone and committee</td>
<td>Decision support systems, predictive reliability</td>
</tr>
<tr>
<td>Provides power quality for the digital economy</td>
<td>Focus on outages - slow response to power quality issues</td>
<td>Power quality is a priority with a variety of quality/price options - rapid resolution of issues</td>
</tr>
<tr>
<td>Enables active participation by consumers</td>
<td>Consumers are uninformed and non-participative with power system</td>
<td>Informed, involved, and active consumers - demand response and DERs</td>
</tr>
</tbody>
</table>

Continued on next page
Table 1.2 Comparison between current power grid and SG (continued)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Current power grid</th>
<th>Smart grid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimizes assets and operates efficiently</td>
<td>Little integration of operational data with asset management - business process silos</td>
<td>Greatly expanded data acquisition of grid parameters, focus on prevention and minimizing impact to consumers</td>
</tr>
<tr>
<td>Operates resiliently against attacks and natural disasters</td>
<td>Vulnerable to malicious acts of terror and natural disasters</td>
<td>Resilient to attack and natural disasters with rapid restoration capabilities</td>
</tr>
<tr>
<td>Enables new services, markets, and opportunities for consumer choices</td>
<td>Limited wholesale markets, not well integrated - limited opportunities for consumer choices</td>
<td>Mature, well-integrated wholesale markets, growth of new electricity market choices for consumers</td>
</tr>
<tr>
<td>Anticipates and responds to system disturbances and outage recovery (self-heals)</td>
<td>Responds to prevent further damage- focus is on protecting assets following fault (manual restoration)</td>
<td>Automatically detects and responds to problems, focus on prevention and minimizing impact to consumer (self-healing and self-reconfiguration)</td>
</tr>
</tbody>
</table>

1.2.2 Smart grid conceptual model

National Institute of Standards and Technology presented a conceptual domain model for SG [14] (see Fig. 1.3 [12]). This model divides the SG into seven domains (customer, markets, service provider, operations, generation, transmission, and distribution) [15]. Each domain and its sub-domains encompasses roles and services to make decisions and exchange information necessary for predefined objectives as described in Table 1.3 [12].
Based on conceptual model of National Institute of Standards and Technology, anticipated benefits of SG are as follows [12]:

1. **Improves power reliability and quality**
2. **Accommodates distributed power sources**
3. **Automates maintenance and operation**
4. **Presents opportunities to improve grid security**
5. **Facilitates expanded deployment of renewable energy sources**
6. **Improves resilience to disruption by natural disasters and attacks**
7. **Enhances capacity and efficiency of existing electric power networks**
8. **Optimizes facility utilization and averts construction of backup (peak load) power plants**
Table 1.3: Domains and Roles/Services in SG conceptual model

<table>
<thead>
<tr>
<th>Role</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Customer</td>
<td>The end users of electricity which may also generate, store, and manage the use of energy.</td>
</tr>
<tr>
<td>Markets</td>
<td>The operators and participants in electricity markets.</td>
</tr>
<tr>
<td>Service Provider</td>
<td>The organizations provide services to electrical customers and utilities.</td>
</tr>
<tr>
<td>Operations</td>
<td>The managers of the movement of electricity.</td>
</tr>
<tr>
<td>Generation</td>
<td>The generators of electricity which may also store energy for later distribution. This domain includes traditional generation sources and DER.</td>
</tr>
<tr>
<td>Transmission</td>
<td>The carriers of bulk electricity over long distances which may also store and generate electricity.</td>
</tr>
<tr>
<td>Distribution</td>
<td>The distributors of electricity to and from customers which may also store and generate electricity.</td>
</tr>
</tbody>
</table>

9. Enables predictive maintenance and self-healing responses to system disturbances

10. Reduces greenhouse gas emissions by enabling electric vehicles and new power sources

11. Enables transition to plug-in electric vehicles and new energy storage options

12. Provides consumers with actionable and timely information about their energy usage

13. Increases consumer choice, and enables new products, services, and markets

14. Reduces fossil fuel consumption by reducing the need for gas turbine generation during peak usage periods

1.2.3 Smart grid requirements

To implement SG, a lot of standards are needed. Some of them are more urgently needed than others. National Institute of Standards and Technology chose to focus on seven key functionalities plus cybersecurity and network communications. These functionalities
are especially critical to ongoing deployments of smart grid technologies and services and are as follows [12]:

1. **Demand response and consumer energy efficiency**
   
   Provide mechanisms and incentives for utilities, business, industrial, and residential customers to modify energy use during times of peak demand or when power reliability is at risk.

2. **Wide-area situational awareness**
   
   Utilizes monitoring and display of power-system components and performance across interconnections and over large geographic areas in near real time.

3. **Distributed Energy Resources**
   
   Covers generation and/or electric storage systems that are interconnected with distribution systems, including devices that reside on a customer premise.

4. **Energy storage**
   
   Means of storing energy, directly or indirectly.

5. **Electric transportation**
   
   Refers primarily to enabling large-scale integration of plug-in electric vehicles.

6. **Network communications**
   
   Refers to a variety of public and private communication networks, both wired and wireless, that will be used for smart grid domains and subdomains.

7. **Advanced metering infrastructure (AMI)**
   
   Provides near real-time monitoring of power usage.

8. **Distribution grid management**
   
   Focuses on maximizing performance of feeders, transformers, and other components of networked distribution systems and integrating them with transmission systems and customer operations.
9. **Cybersecurity**

Encompasses measures to ensure the confidentiality, integrity, and availability of the electronic information communication systems and the control systems necessary for the management, operation, and protection of the smart grid’s energy, information technology, and telecommunications infrastructures.
CHAPTER 2
ADVANCED METERING INFRASTRUCTURE

AMI is one of the most critical components of SG which creates a two-way communication network between smart meters (SMs) and utility systems to measure, collect, transmit (either on-demand or periodic), and analyze energy consumption data of consumers [16,17]. Actually, AMI is an enhanced version of automatic meter reading that provides a huge improvement over it. Automatic meter reading was developed in 1972 (after 85 years that meter measurements were read manually [18]) which automatically and remotely gathers data from different types of meters and transmits these information to the utility center (UC) via a unidirectional communication scheme in order to analyze them for billing purposes. Since automatic meter reading is not able to meet the current requirements for two-way communications, AMI is introduced.

Some functionalities of AMI are near real-time power quality (voltage, current, phase, frequency, etc.) monitoring/management and control, improving energy efficiency, adaptive power pricing (to decrease costs, to enhance service delivery to customers, and to update energy prices in real time), demand side management (the supplier directly and immediately influences the energy consumption), self-healing ability to protect SG against malicious sabotage and natural disasters, providing communications between utility companies and SMs to remotely read usage reading, energy saving expected load, improving the reliability of SG by avoiding line congestion and generation overloads, outages management/alert, upgrading meter firmware, and interfacing with other systems [19,20].

AMI does not have a standardized architecture, so, various implementations exist and based on each implementation, the requirements of the communication infrastructure change. Therefore, it is important to analyze the network requirements to choose what kind of communication technology can meet the needs and thereby avoiding design of a network infrastructure which is too expensive or its performing is very low [21].
Fundamentally, general requirements which a communication infrastructure in the SG should meet, are as follows [22]:

- **Being standard-based**: The communication infrastructure should be based on standards to support diverse set of utility applications.

- **Being IP-based network**: An IP-based network provides the broadest possible platform for the delivery of a wide range of applications.

- **Providing real-time communications**: The network should provide the real-time low latency communications capabilities.

- **Scalability**: The network should have the capability of following the expansion of the SG to serve a large number of devices.

- **Resilience and high availability**: the network architecture must be capable of continuing to operate even in the presence of localized faults.

- **Security**: the communication infrastructure needs to provide a secure environment for information flow.

- **Supporting traffic prioritization**: The communication network must be capable of prioritized delivery of latency-sensitive applications such as distribution automation.

- **Mobility**: The network must support mobility to enable mobile workforce connectivity applications.

- **Being future-proof**: The network architecture and its elements must be selected so as to provide broad investment protection.

- **Being cost competitive**: The communication infrastructure must be cost-competitive with wide area network alternatives.

- **Having broad coverage**: The communications network should have broad coverage over a large geographical area to monitor and control of the overall power system.
• **Connecting multiple types of systems:** The communications network must connect different types of hardware, ranging from smart sensors to transformers and beyond for exchanging data between them.

• **Transmitting data over multiple media:** The communication infrastructure must be able to transmit data over a variety of media such as copper cables, fiber optics, wireless networks, etc.

• **Collecting and analyzing massive amounts of data:** The communication infrastructure must be able to capture massive amounts of data and analyze it.

AMI is usually composed of SMs, data concentrators (DC), UC, and two-way communication infrastructure among them [23]. AMI components are usually located in various networks and different realms (public and private). Electrical appliances and other integrated devices/systems are connected to the SM via a home area network (HAN), building/commercial/business area network (BAN), or industrial area network (IAN). ZigBee or power line communication (PLC) can be used for communication among SM and HAN elements. A number of individual SMs communicate to a DC through neighborhood area network (NAN). Worldwide interoperability for microwave access (WiMAX), Long Term Evolution, and other cellular technologies are used in NAN. A number of DCs are connected to a UC in the utility side using wide area network. Communication technologies such as fiber optic and digital subscriber line are used in wide area network. The UC consists of meter data management system (MDMS), geographic information system (GIS), configuration system, etc. A local area network can be built to communicate between subsystems of the UC [20].

The HAN is basically a multi-vendor environment composed of electrical appliances and devices that need to communicate with the AMI [24]. In other words, HAN is a residence local area network that connects the SMs, smart appliances, in-home energy display, power consumption control tools, plug-in electric or hybrid electric vehicles, DER (energy storages, solar panels, small-scale distributed wind turbines, etc.), gateways (or energy services interfaces which provide a secure interface for utility-to-customer interactions [12] and
provide access to higher layer NAN [25]) such as automatic meter reading gateway, energy management gateway, home automation and customer premises equipment (i.e. Internet modem/router [25]), and other control devices [20,26] (see Fig. 2.1).

Technologies such as Bluetooth, PLC [20], KNX, Wi-Fi, HomePlug, IPv6 over Low power Wireless Personal Area Networks, Devices Profile for Web Services, LonTalk, building automation and control networks [25], IEEE 802.11b, IEEE 802.11s, IEEE 802.3az-2010 standard [26], and ZigBee [20,25,26] are candidates to use in HAN.

SM is the key equipment installed at customer locations and other load points for measuring, recording, aggregating, and sending consumption data (electric, gas, water, and heating) via bidirectional communications to the utility company [20,21]. Additionally, some SMs provide an overview of the power consumption of each appliance and schedule on/off time of each device and thereby save power. Some SMs give access to remotely turn off/on devices which can help to shift the load on the SG, this is called direct load control.

Fig. 2.1: Some elements of a HAN
Direct load control provides access to devices with a significant power usage and turns them off to lower power consumption on a SG or can add some energy resources to the power grid in order to take away load on the grid when having an overproduction of power. These resources that can be used to shift load on the SG are called DER [21]. Smart meter data is used for electricity billing, consumer awareness about consumption, critical events etc. [27].

Some features of SM are as follows [18]:

- Data recording and interval reads
- Communication link
- Remote connect/disconnect
- Outage detection/reporting
- Tamper/theft detection
- Remote programing
- Backward compatibility
- Home Area Network support
- Bi-directional metering

NAN is one of the crucial domains in AMI which carries a large volume of heterogeneous data with different quality of service requirements and supports a large number of SMs [26]. Actually, a group of HANs (building area networks or industrial area networks) possibly fed by the same transformer forms a NAN [26]. NAN allows bi-directional communication between the SMs and a DC [24]. Equipment in the field need to be monitored and controlled. Hence these equipment are managed by a separate network called field area network. The geographical scale of a field area network is similar to NAN, so, similar communication technologies can be used for both [26].
There are many technologies and networks that can be used in NAN such as device language message specification, smart message language, IEC 61334-5, PRIME, SITRED [25], PLC-based technologies [26], IEEE 802.11 family standards [26], WiMAX, third generation and fourth generation cellular technologies such as Universal Mobile Telecommunications System, wideband code-division multiple access [20,26], Fiber-to-the-Home, Passive Optical Networks, Ethernet code-division multiple access [20,26], WiMAX, third generation and fourth generation cellular technologies such as Universal Mobile Telecommunications System, Wideband Code Division Multiple Access, Fiber-to-the-Home, Passive Optical Networks, Ethernet Code Division Multiple Access, Long-reach Passive Optical Networks, Fiber-Wireless networks, Fiber-Wireless sensor networks technology, point-to-point optical networks, hybrid fiber coaxial networks, and fiber to the node [26].

Also, A wide area network uses long-range and high-bandwidth communication technologies, such as WiMAX [26], cellular networks (e.g., EVolution, Data Only/Optimized, Enhanced Data rates for Global System for Mobile Communications Evolution, General Packet Radio Service, or code-division multiple access), satellite, PLC, fiber optic, Universal Mobile Telecommunications System, Long Term Evolution and Long Term Evolution-Advanced technologies, Coordinated Multi-Point, Multi Input Multi Output, cognitive radio [26].

A DC is connected to a set of SMs through some form of a mesh network and aggregates their data and sends data to the control center. It operate as aggregator and relay in uplink and downlink, respectively. Also, DC can compress the data due to the correlation between the received packets. A compression ratio 0.1 is achievable in some fusion algorithms, but, the exact factor depends on the correlation properties of the data as well as the fusion algorithm. DC enhances scalability of SG by enabling communications in large networks. Another advantage of DC is reduction of power consumption of the SMs, because SMs do not need to transmit their data directly to the UC. DC slightly increases delay of transmitting data but it significantly increases reliability of the SG and decreases collisions between transmitted data of SMs.

UC collects, stores, and analyzes data from SMs and interfaces with the suppliers which can query customer meters for billing purposes or issue tariff commands and demand
response alarms. UC can have the following modules [28] (see Fig. 2.2):

1. GIS

2. MDMS

3. Outage Management System (OMS)

4. Transformer Load Management (TLM)

5. Mobile Workforce Management (MWM)

6. Consumer Information System (CIS)

7. Billing System (BS)

8. Utility Website (UW)

9. Enterprise Resource Planning (ERP)

10. Power Quality Management (PQM)

11. Asset Management (AM)

12. Business Intelligence (BI)

13. Demand Response Management System (DRMS)

14. Load Forecasting Systems (LFS)

MDMS is a database with analytical tools that collects meter data (such as power usage, electricity generation and storage information) [29] and performs long term data storage, processing and management for the vast quantities of usage data and events [27]. In Table 2.1, some features of SM, DC, and UC are compared with each other [20].
2.1 Previous Work

In traditional power grid, the measured data are gathered once a month while in current SG, SMs mostly send their data every 15 minutes. Although collecting information every 15 minutes instead of once a month, is a significant improvement but for special applications of SG such as wide area monitoring and control which uses phasor measurement unit to sample frequency, voltage, and current up to 30-120 times per second and send accurate measurements to a dedicated server [30], is not sufficient and suitable. Therefore, a huge amount of data that must be processed by MDMS, imposes a serious challenge on the scalability of current power grid architecture.

Scalability is a desirable characteristic of a system to accommodate a growing number of components and to process increasing number of tasks gracefully. Some kinds of scalability are load scalability, geographic scalability, functional scalability, and administrative scalability. Load scalability is the capability of a system to easily use its resources to accommodate heavier or lighter loads and geographic scalability is the ability to maintain performance regardless of expansion from a local area to a more distributed geographic area [31,32]. In this thesis, we concentrate on the load scalability and geographic scalability.

There are some papers which consider scalability issue from a different point of view.
Table 2.1: Comparison of SM, DC, and UC features

<table>
<thead>
<tr>
<th></th>
<th>SM</th>
<th>DC</th>
<th>UC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amount of data in an individual SM is small as data sources are customer’s HAN and its associated devices</td>
<td>Amount of data is comparatively larger as it has to handle data from about a few hundred to tens of thousands of SMs</td>
<td>Data amount in UC is in a huge volume as it has to tackle data from about several millions of SMs</td>
<td></td>
</tr>
<tr>
<td>Resources like main memory (in kilobyte range), processor capacity, etc. are very restrictive</td>
<td>Resources like main memory (in megabyte range), processor capacity, etc. are more powerful</td>
<td>Resources are very powerful, because they are usually high-end servers.</td>
<td></td>
</tr>
<tr>
<td>Data speed is comparatively low because of non-frequent requests at the SM</td>
<td>Data speed is high as it aggregates a good number of SMs’ data</td>
<td>Data speed is very high as it has to handle huge amount of meter data, event data, commands, etc.</td>
<td></td>
</tr>
</tbody>
</table>

In [33], horizontal scalability of different database storage and processing architectures has been investigated to provide a basis for data storage and monthly bill processing of SM readings. Their proposed architectures are simple, abstract, and far from practical SG specifications.

In [34], a cloud-based SG information storage and computation model is proposed and a resource optimization framework is presented to minimize total cost of computation, storage and sharing.

In [35], the authors proposed a hierarchical structure of secure cloud computing centers to provide different types of computing services for information management and big data analysis in smart grids. In this thesis, we propose and analyze several architectures and model the cost of each part of AMI based on the physical topology of the grid.

2.2 Contribution

In this thesis, we have investigated different AMI architectures for SG and propose a new hybrid architecture which contains relays, regional and wide-area aggregators, and
MDMSs. We have considered different wired and wireless technologies for designing a new AMI. We have derived formulas for different AMIs based on some defined metrics, constructed optimization problem and proposed an algorithm to solve it and found optimum location of elements in the new AMI. We have simulated and implemented the new AMI for different number of SMs based on the SM density of five demographic regions (low density rural, rural, suburban, urban, and dense urban) and evaluated its scalability.

The major contributions of this thesis are as follows:

1. We investigate the structure of existing electric grid and some AMIs in SG and propose a new AMI (based on current power grid and company products) that includes repeaters, regional and wide-area aggregators, and MDMSs.

2. We consider data density requirements of five different demographic areas in development of the AMI for SG.

3. We consider different wire and wireless technologies (PLC, Ethernet, optical fiber, and microwave) to design a new AMI and compare and assist their performances from different aspects.

4. We define some new metrics to evaluate performance of different AMIs in SG.

5. We derive formulas for different AMIs based on new metrics, construct optimization problems and propose an algorithm to solve them, and find optimum number and locations of elements in a new AMI by minimizing new metrics in the new AMI.

6. We consider more realistic design by taking into account the limitations of current aggregators and MDMSs such as the total number of connections to each aggregator or MDMS.
CHAPTER 3
OPTIMIZING ADVANCED METERING INFRASTRUCTURE ARCHITECTURE

3.1 Different Architectures of AMI

AMI has two different architectures: direct and indirect. Direct architecture has the simplest architecture, where SMs connect directly to UC via a wireline or wireless network with star topology (see Fig. 3.1). This scheme does not have any aggregators. Due to high density of SMs and their distances to UC in urban areas, this architecture is not suitable and scalable or even feasible. However, it can be used in low density areas such that a low cost communications link is established between each SM and UC. The effectiveness of this architecture depends on the number of SMs and their data rates. When bit rate is high, the existing bandwidth may not be enough or providing enough bandwidth may not be cost effective.

Fig. 3.1: Direct architecture of AMI

In an indirect architecture, SMs send their data to the UC through routers or aggregators (see Fig. 3.2, 3.3, and 3.4). An indirect architecture can be based on a cloud or
In cloud-based AMI, SMs use Internet connection to send their information to the UC (see Fig. 3.2). This AMI has a very low cost for the customers (no additional monthly charges for using communication infrastructures) and can be quickly deployed (due to no limitation of building communication infrastructures).

In an aggregation-based AMI, aggregators sit between SMs and the UC to gather and aggregate data of SMs before transmitting them to the UC (see Fig. 3.3 and 3.4). Advantages of this architecture with respect to direct architecture are possibility of using low bandwidth between SMs and aggregators, reducing the number of direct connections to the UC, increasing reliability, being more distributed, and decreasing vulnerability to global effects of attacks.

Indirect architectures can be divided to two categories: centralized and decentralized (distributed). In centralized architectures (see Fig. 3.3), the UC only analyzes the data and stores them (via only one MDMS), but in the decentralized ones, there are some MDMSs so that the processing of gathered data are done by them (see Fig. 3.4). Direct architecture is a centralized architecture.

![Fig. 3.2: Cloud-based indirect architecture of AMI](image)

SMs can typically record and transmit data in 1, 5, 6, 10, 12, 15, 20, 30, and 60 minute
intervals and store data for a month [18]. Based on determined requirements for SM in current standards [12] and some implemented SGs, each SM generates less than 1 bps [36]. Based on the results of the research report [37], the gathered data from SMs will be huge and in order of petabytes referred to as “Big Data” [28]. Sources of data in SG that create the Big Data are as follows [28]:

- **SMs**: Collecting consumption data at given frequency.

- **Distribution network automation system**: For controlling of SG and increasing its reliability, necessary data must be collected in real time using time-synchronized, high-data-rate sensors (such as phase measurement units).

- **Third-party systems connected to the grid**: For example, storages, DER or electric vehicles.

- **Asset management**: For communication between utility center and smart components in the network including updating firmware.

In [37], it is mentioned that 95 million SMs will generate 799 petabytes data annually (in 2020) or equivalently one SM will produce 8.8 GB per year. It means each SM will produce 2.397 kbps. By considering future needs (less transfer intervals, sending more data, e.g., gas, water, and heat data with the current power consumption data), we assume that the average data rate of SMs will be 5 kbps. This much data causes serious challenges for reliability, performance, and scalability of SG. All collected data must be sent to a UC (which has a limited and specific hardware (processor, RAM, Hard disk,...), software, and communication characteristics such as bandwidth,...) to be processed and analyzed in real time and if processing of the huge amount of data is beyond the capability of the UC, some data will be lost, delay will be increased, and consequently, reliability and performance of the SG will be decreased and resources of the network cannot be used efficiently.

To manage and analyze these huge Big Data, special and improved AMI is crucial. Therefore, we introduce decentralized hybrid indirect architecture of AMI (see Fig. 3.5). In Fig. 3.5, each SM connects to some sensors (such as electric, gas, water, heat, and other
Fig. 3.3: Centralized aggregation-based indirect architecture of AMI

sensors) to collect and aggregate their data. Some SMs connect to a regional aggregator (RA) to transmit their information. Wide area aggregator (WAA) aggregates data from its RAs and send it through the cloud to its corresponding MDMS. Repeaters are used between SMs and RAs and/or RAs and WAA, when their distances are larger than a specific value. Finally, only a fraction of all gathered data which are necessary for specific tasks such as OMS is sent by MDMSs to the UC. In other words, UC processing load is distributed among MDMSs and the scalability of new decentralized AMI is improved. Since a fraction of data are sent to UC, thus, bandwidth, hardware, and software requirements of UC decreases with compared to centralized architecture.

3.2 Problem Formulation for Different Architectures of AMI

In the following subsections, we define the objective functions subject to some constraints for the discussed AMI architectures. We have formulated the optimization problem
Fig. 3.4: Decentralized aggregation-based indirect architecture of AMI

to find the location of RAs and WAAs in our proposed AMI. Then, a Genetic-based algorithm is used to find its near optimum solution.

Total deployment cost of an AMI architecture ($C_t$) in dollars is divided into two parts: Fixed cost ($C_f$) and Cost per month ($C_m$) in dollars. Therefore, total deployment cost can be calculated as follows:

$$C_t = C_f + (S_m \times C_m) \quad (3.1)$$

where $S_m$ is the service time of the SG (in month).

3.2.1 Centralized aggregation-based indirect architecture of AMI

To formulate this architecture, we consider the following conditions and assumptions:

1. Each SM connects to only one aggregator.

2. The PoweRline Intelligent Metering Evolution (PRIME) technology v1.4 [38] is used among SMs, aggregators, and the UC. The PRIME PLC technology is an orthogonal frequency division multiplexing-based technology to address the challenges of smart grid in existing Low Voltage and Medium Voltage electricity grids and uses power lines as a communication medium. The biggest advantage of using PLC is that no
additional wiring is required other than the preexisting power lines. So, we don’t need to pay monthly cost (i.e., $C_m = 0$).

3. In PRIME technology robust mode, the distance between SMs and its aggregator must be less than 700m and the maximum SM data rate is 5 kbps [39].

4. The UC implemented in an substation which supplies the maximum 30 feeders.

5. Since the maximum data rate in PRIME technology version 1.4 is 1 Mbps [39] and the maximum data rate of SMs is assumed to be 5 kbps, the maximum number of connection to each aggregator is 2000 (if it is possible). Thus, the maximum output data rate of aggregators is 1 Mbps. Due to their high data rate, their distances to the UC is less than 700 m. We assume that this distance is 200 m.

Based on the above assumptions, the maximum distance between SMs and the UC is 700 + 200 = 900m. So, the coverage area of the UC (or area substation) is a circle and its maximum area is $\pi r^2 = 2.5447 \text{ km}^2 \approx 1 \text{ mile}^2$. In United States, the density of residential housing units (HU), by county, range from 1 HU/mile$^2$ to more than 34,000 HU/mile$^2$ [40], so, we assume that we have the maximum 60,000 SMs/mile$^2$. The cost of this architecture can be formulated as follow:

$$C_m = 0 \text{ and } C_t = C_f = C_M + \sum_{i=1}^{N_A} (C_i^A + I_i^A) \tag{3.2}$$

$$C_M = N_S, \ N_A = \lceil \frac{N_S}{N_P} \rceil \tag{3.3}$$

subject to:

$$N_P \leq a, \ N_A \leq N_F \tag{3.4}$$

where $C_M$ is the cost of the MDMS in dollars (based on current MDMS, cost of the MDMS is proportional to the number of SMs, so, we assume $C_M = N_S$), $N_A$ is the number of aggregators, $C_i^A$ is the cost of a aggregator $i$ in dollars, $I_i^A$ is the installation cost of a aggregator $i$ in dollars, $N_S$ is the total number of smart meters, $\lceil \ldots \rceil$ calculates nearest
integer value towards positive infinity, \( N_F \) is the maximum number of SMs per aggregator, \( a \) is a constant integer (e.g., 2000, it depends on the specifications of the aggregator) which shows the maximum number of connections to an aggregator, and \( N_F \) is the number of feeders. In (3.2), the summation term shows the total cost of aggregators in dollars. In (3.4), the second inequality shows that the number of aggregators must be less than the number of feeders, because each feeder can connect to at most one aggregator. In addition to the constraints in (3.4), we have the following constraints:

1. Each SM can connect to only one aggregator.

2. Each aggregator can connect to only one MDMS.

Limitations of this architecture are as follows:

1. Based on the technology which is used between SMs and aggregators, the number of SMs can connect to aggregators, bit rate and distance between SMs and aggregators and also between aggregators and UC are very limited, e.g., in the PRIME technology is 700 m for data rate 5 kbps. So, for rural areas, this architecture cannot be applied. Also, coverage area of this architecture is limited and SMs that are far from the UC cannot connect to the SG.

2. IF we don’t have any substation in a 1 square miles, this architecture does not have any performance, because all SMs can send their data to the UC which can be implemented in a substation.

3. If we use wireless communications between SMs and aggregators and/or between aggregators and UC, the number of SMs can send data is limited.

4. If the maximum number of connection to each aggregator is reduced (due to structure of power grid that connect SMs to aggregators), the number of SMs which can be supported, will be reduced a lot, e.g., 100 instead of 2000.
3.2.2 Decentralized aggregation-based indirect architecture of AMI

To formulate this architecture, we have the same assumptions as the centralized aggregation-based architecture. We assume that there are Ethernet links between substations and also between substations and the UC. MDMSs are implemented in substations. Therefore, the cost of this architecture can be formulated as follow:

\[
C_f = N_S + \sum_{i=1}^{N_U} \sum_{j=1}^{N_A^i} (C_{ij}^A + I_{ij}^A) \tag{3.5}
\]

\[
C_m = \sum_{i=1}^{N_U} \sum_{j=1}^{N_U} (E_{ij}^S \times s_{ij}) + \sum_{i=1}^{N_U} (E_{i}^U \times m_{i}) \tag{3.6}
\]

\[
N_M = \lceil \frac{N_S}{N_M} \rceil, \quad N_A^i = \lceil \frac{N_i^S}{N_P} \rceil, \quad \forall i = 1 \text{ to } N_U \tag{3.7}
\]

subject to:

\[
N_P \leq a, \quad N_A^i \leq N_F^i (\forall i = 1 \text{ to } N_U) \tag{3.8}
\]

\[
s_{ij} = 0 \text{ or } 1, \quad \sum_{j=1}^{N_U} s_{ij} = 1, \quad \sum_{i=1}^{N_U} \sum_{j=1}^{N_U} s_{ij} = N_M \tag{3.9}
\]

\[
m_{i} = 0 \text{ or } 1, \quad \sum_{i=1}^{N_U} m_{i} = N_M, \quad N_S = \sum_{i=1}^{N_U} N_S^i \tag{3.10}
\]

where \(N_U\) is the number of substations, \(N_A^i\) is the number of aggregators which connect to substation \(i\), \(C_{ij}^A\) is the cost of an aggregator \(j\) in dollars which is connected to substation \(i\), \(I_{ij}^A\) is the installation cost of an aggregator \(j\) in dollars which is connected to substation \(i\), \(E_{ij}^S\) is the cost of renting an Ethernet link between substation \(i\) (without MDMS) and substation \(j\) (with MDMS) in dollars, \(s_{ij}\) indicates that the substation \(i\) is connected to substation \(j\) or not (i.e., \(s_{ij}\) can be 0 (no connection between substation \(i\) and \(j\)) or 1 (a connection between substation \(i\) and \(j\))), \(E_{i}^U\) is the cost of renting an Ethernet link between substation \(i\) (with MDMS) and UC in dollars, \(m_{i}\) shows that the substation \(i\) is connected
to the UC or not (i.e., $m_i$ can be 0 (no connection between substation $i$ and UC) or 1 (a connection between substation $i$ and UC)), $N_S^i$ is the number of SMs which are connected to substation $i$ via aggregators, $N_{F_i}$ is the number of feeders of substation $i$, $N_M$ is the number of substations which have MDMS, and $N_M^S$ indicates that each MDMS is able to process the data of how many SMs. In (3.5), the first term shows the MDMS cost and the second term indicates the cost of aggregators. In (3.6), the first term shows the total cost of renting Ethernet links between substations and the second term indicates the total cost of renting Ethernet links between substations and UC. In (3.9), the first summation shows that the substation $i$ can connect to only one other substation and the second double summation indicates that we have $N_M$ number of connections from the substations without MDMS to the substations with MDMS. In (3.10), the first summation shows that the substation without MDMS can connect to only one substation with MDMS and the second summation indicates that the summation of the number of SMs connected to different substations are the total number of SMs.

### 3.2.3 Decentralized hybrid indirect architecture of AMI

We assume that SMs and RAs use PRIME technology to send their data to RAs and WAA, respectively. WAA uses the Internet to send data to its corresponding substation. Some substations send the data to a substation which has MDMS via microwave links. Finally, Substations with MDMS transmit a part of information for further processing to the UC through the Internet links. The cost of this architecture can be formulated as follow:
\[ C_f = \sum_{i=1}^{N_U} \sum_{j=1}^{N_U^i} (C_{ij}^R + I_{ij}^R) + \sum_{i=1}^{N_U} \sum_{j=1}^{N_W^i} (C_{ij}^W + I_{ij}^W) \]
\[ + \sum_{i=1}^{N_U} \sum_{j=1}^{N_U} ((B_{ij}^U + A_{ij}^U + I_{ij}^U + M_{ij}^U) \times s_{ij}) \]
\[ + \sum_{i=1}^{N_U} \sum_{j=1}^{N_R^i} \sum_{k=1}^{N_S^i} (C_{ijk}^S \times \left\lceil \frac{d_{ijk}^x}{d_S^x} \right\rceil \times x_{ijk}) + F + N_S \]
\[ + \sum_{i=1}^{N_U} \sum_{j=1}^{N_W^i} \sum_{k=1}^{N_R^i} (C_{ijk}^W \times \left\lceil \frac{d_{ijk}^y}{d_W^y} \right\rceil \times y_{ijk}) \] (3.11)

\[ C_m = \sum_{i=1}^{N_U} \sum_{j=1}^{N_W^i} R_{ij}^W + \sum_{i=1}^{N_U} I_{ij}^U + I^U + \sum_{i=1}^{N_M} (I_{i}^S \times m_i) \] (3.12)

\[ N_U = \left\lceil \frac{N_S}{c} \right\rceil, \ N_R^i = \left\lceil \frac{N_i^j}{N_R^i} \right\rceil, \ N_W^i = \left\lceil \frac{N_{R^i}}{N_W} \right\rceil \] (3.13)

\[ M_{ij}^U = p (B_{ij}^U + A_{ij}^U) \] (3.14)

subject to:

\[ N_R \leq a, \ N_W \leq b, \ N_S^i \leq c \] (3.15)

\[ x_{ijk} = 0 \ or \ 1, \ \sum_{i=1}^{N_U} \sum_{j=1}^{N_R^i} x_{ijk} = 1, \ \sum_{k=1}^{N_S^i} x_{ijk} \leq a \] (3.16)

\[ y_{ijk} = 0 \ or \ 1, \ \sum_{i=1}^{N_U} \sum_{j=1}^{N_W^i} y_{ijk} = 1, \ \sum_{k=1}^{N_R^i} y_{ijk} \leq b \] (3.17)

where \( N_R^i \) is the number of RAs which connect to substation \( i \), \( C_{ij}^R \) is the cost of jth RA which is connected to substation \( i \) in dollars, \( I_{ij}^R \) is the installation cost of jth RA which is connected to substation \( i \) in dollars, \( C_{ij}^W \) is the cost of jth WAA which is connected to substation \( i \) in dollars, \( I_{ij}^W \) is the installation cost of jth WAA which is connected to
substation i in dollars, $B_{ij}^U$ is the cost of microwave backhaul system between substation i and j in dollars, $A_{ij}^U$ is the cost of antennas, cables and power for the microwave link between substation i and j in dollars, $I_{ij}^U$ is the installation cost for a microwave backhaul system, cabling and ancillary equipment between substation i and j in dollars, $M_{ij}^U$ is the annual maintenance cost for the microwave link between substation i and j in dollars, $s_{ij}$ indicates that the substation i is connected to substation j or not, $C_{ij}^S$ is the cost of a relay between SM k and RA j which belong to substation i in dollars, $d_{ijk}^E$ is the Manhattan distance between SM k and RA j which belong to substation i, $d_{ij}^R$ is the maximum allowable distance between a SM and an RA without using a relay in between, $x_{ijk}$ shows that whether or not SM k is connected to the RA j which belongs to substation i (i.e., $x_{ijk}$ can be 0 (SM k is not connected to the RA j which belongs to substation i) or 1 (SM k is connected to the RA j which belongs to substation i)), $F$ is a one-time federal communications commission fee for the license and frequency band coordination, $C_{ijk}^W$ is the cost of a relay between RA k and WAA j which belong to substation i, $d_{ijk}^W$ is the Manhattan distance between RA k and WAA j which belong to substation i, $d_{ij}^W$ is the maximum allowable distance between a WAA and an RA without using a relay in between, $y_{ijk}$ shows that whether or not the RA k is connected to the WAA j which belongs to substation i (i.e., $y_{ijk}$ can be 0 (RA k is not connected to the WAA j which belongs to substation i) or 1 (RA k is connected to the WAA j which belongs to substation i)), $⌊...⌋$ calculates nearest integer value towards negative infinity, $R_{ij}^W$ is the cost of providing an Internet connection with a necessary bandwidth in Mbps for WAA to upload its data, $I_{i}^U$ is the cost of providing an Internet connection for substation i to get data from its corresponding WAAs, $I_{i}^S$ is the cost of providing an Internet connection for substation i to send data to the UC, $I_{i}^U$ is the cost of providing an Internet connection for the UC to get data from substations, $m_i$ shows that the substation i is connected to the UC or not (i.e., $m_i$ can be 0 (no connection between substation i and UC) or 1 (a connection between substation i and UC)), p shows how many percentages of the Microwave equipment cost is considered as its annual maintenance cost, $N_R$ is the maximum number of SMs per a RA, $N_W$ is the maximum number of RAs per
a WAA, $a$ shows the maximum number of connections from SMs to one RA, $b$ shows the maximum number of connections from RAs to one WAA, and $c$ shows the maximum number of supported SMs by substation $i$. In (3.11), the first term shows the total cost of regional aggregators, the second term shows the total cost of wide area aggregators, the third term shows the total cost of establishing the microwave link with its equipment, the fourth term shows the total cost of relays between SMs and their corresponding RAs, the sixth term shows the cost of MDMS, and the seventh term shows the total cost of relays between RAs and their corresponding WAAs. In (3.12), the first term shows the total monthly cost of uploading data from WAAs to their corresponding substations, the second term indicates the total monthly cost of receiving data from WAAs by their corresponding substations, and the fourth term denotes the total monthly cost of uploading data from substations to the UC. In (3.16), the first double summation shows that each SM can connect to only one RA and that RA can only connect to one substation through its corresponding WAA and the second summation term(161,432),(986,992) indicates that the total number of connection to each RA must be less than a specific number. In (3.17), the first double summation shows that each RA can connect to only one WAA and that WAA can only connect to one substation and the second summation term indicates that the total number of connection to each WAA must be less than a specific number.

$C_f$ and $C_m$ are minimized when the optimum location of RAs and WAAs are obtained. Due to a large number of variables in $C_f$ and $C_m$, minimization of them is a complicated NP-hard optimization problem, so, we use a Genetic-based algorithm to solve it.
Fig. 3.5: Decentralized hybrid indirect architecture of AMI
CHAPTER 4
GENETIC-BASED ALGORITHM

Genetic algorithm (GA) has been proposed by Holland [41]. He introduced a novel optimization algorithm that is in-depth different from the two major classes of classical calculus-based and enumerative techniques. In solving a given optimization task, the GA starts with a collection of solutions (i.e. parameter estimates) called by chromosomes. Each individual (chromosome) is evaluated for its fitness. In each iteration of the GA, the fittest chromosomes (parents) are allowed to mate and bear offspring (produce new individuals). These individuals (children) or new parameter estimates provide the basis for the next generation. The conventional GA can be described by the following steps:

1. Initialization
2. Generate a random population
3. Apply the selected crossover operator to the individuals
4. Apply the selected mutation operator to the individuals
5. Replace the old population with the resulting individuals
6. Repeat steps 3-5 until the termination criterion is satisfied

The Genetic-based algorithm (which is inspired by recombination accomplished by some insects such as bees) is a kind of structured random search that can be obtained by applying some changes in GA [42]. To make it more clear, we proceed as follows. Consider a conventional GA in which the recombination is done in a way that one chromosome is recombined with the best chromosome that exists in the present population. In other words, all selected chromosomes are recombined with the best chromosome of the current population called as the queen chromosome. The recombination procedure can be better observed from Fig. 4.1.
With more precise look at Fig. 4.1, it becomes clear that the produced chromosomes are indeed the queen with some changes. In other words, the new chromosomes may represent new queens who inherit some parent queen characteristics. Therefore, instead of employing the procedure given in Fig. 4.1, we use recombination procedure as shown in Fig. 4.2. This represents the core of our method.

As observed in Fig. 4.2, some portions of the queen are randomly mutated to generate a new chromosome. This results in new queen candidates. Each queen candidate becomes a queen and replaces the original queen if it has a better performance with respect to the previous queen. If the performance of the queen candidate gets worse than the current queen’s performance, the new chromosome (queen candidate) is disregarded and a part of the original queen is again selected and mutated randomly.

Our method can be summarized as follows:

1. Selecting a suitable coding scheme (a real-value matrix) to show the number of parameters and their values in a chromosome.

2. Generating a queen chromosome and evaluating it regarding its fixed and monthly cost.

3. Making a copy of queen chromosome (queen candidate).

4. Applying mutation operator to some parts of queen candidate and evaluating its performance. If the queen candidate performance is better than the queen’s performance, replacing queen chromosome by queen candidate, otherwise, going to step 3. Repeating steps 3 and 4 until termination criteria is reached.

Fig. 4.1: Crossover operation at points a and b in conventional GA.
We used a $4 \times N_R$ ($N_R$ is the total number of RAs) matrix with real-value elements for the coding scheme of each chromosome. First two rows of the matrix are used to store the location of RAs (i.e., their Cartesian coordinations) and the 3rd and 4th rows are used to store the location of WAAs. Based on the locations of RAs and WAAs, $d_{ijk}^x$ and $d_{ijk}^y$ are calculated. Then, $C_f$ and $C_m$ are obtained. To evaluate the performance of the queen and queen candidate, we used the values of $C_f$ and $C_m$ as fitness functions. At each time, at most 10% of queen candidate chromosome are mutated. We used the notion of dominance to compare the queen and queen candidate. Queen $q$ is said to dominate queen candidate $c$ in respect of the defined objectives if $C_f(q) \leq C_f(c)$ and $C_m(q) \leq C_m(c)$ but equality cannot happen in these two inequalities simultaneously. The algorithm terminates if it cannot find a better solution after a specific number of iterations (e.g., 5000). For each specific number of SMs, the Genetic-based algorithm are executed 100 times and the minimum values of $C_f$ and $C_m$ are considered to calculate $C_t$.

4.1 Performance Evaluation

In implementation of AMI centralized aggregation-based indirect architecture, SMs and aggregators are distributed uniformly in 1 mile$^2$ and we assume that aggregation is done in two stages/levels, i.e., first 100 SMs connect to an aggregator in 1st level and then 20 of these aggregators connect to another aggregator in 2nd level so that the aggregator in 2nd level collects the data of 2000 (20*100) SMs and aggregates and compressed it by factor of 0.1. Due to the maximum data rate in the PRIME technology, data rate of each SM can be up to 5kbps so that the maximum data rate of the 2nd level aggregator becomes 1Mbps. The following values are assumed for parameters in (3.2)-(3.4): $N_S = 1$ to 60,000, $a = 2000$, $N_F = 1$ to 30, cost of each aggregator is $700$, and its installation cost is $10$. 

Fig. 4.2: Recombination procedure by applying mutation operator.
We have the same assumptions to implement AMI decentralized aggregation-based indirect architecture as AMI centralized one. In addition, we implement this architecture in 100 mile$^2$ with different density of SMs from 100 to 60,000 SMs per mile$^2$ (to consider five demographic regions [40]) and 100 MDMSs are distributed evenly in 100 mile$^2$. The UC is implemented in the middle of 100 mile$^2$ area in a substation. Again in this architecture, the maximum data rate of each SM can be 5kbps. The following values are assumed for parameters in (3.5)-(3.10): $N_S = 10,000$ to $6,000,000$, $a = 2000$, $N_F = 1$ to $30$, $N_U = 100$, cost of each aggregator is $\$700$, and its installation cost is $\$10$, $E_{ij}^S = E_i^U = \$250$, $N_M^S = 1,200,000$.

We implement AMI decentralized hybrid indirect architecture in 100 mile$^2$ with different density of SMs from 1 to 60,000 SMs per mile$^2$. SMs, RAs, and WAAs are distributed uniformly in each mile$^2$. We consider that the maximum data rate of each SM is 8.33kbps, each WAA sends its data via an Internet connection with 5Mbps upload capacity, each substation receives data through an Internet connection with 100Mbps download capacity, each substation can receive data from at most 60 WAAs, each substation which has MDMS, sends its data to UC via an Internet connection with 10Mbps upload capacity, and UC receives data from substations through an Internet connection with 100Mbps download capacity. The following values are assumed for parameters in (3.11)-(3.17): $N_U = 1$ to $50$, $C_{ij}^R = C_{ij}^W = \$700$, $I_{ij}^R = I_{ij}^W = \$10$, $D_{ij}^U = \$5000$, $A_{ij}^U = \$3500$, $I_i^U = \$3000$, $N_M = 1$ to $5$, $C_{ijk}^S = C_{ijk}^W = \$50$, $d_{S}^R = 500m$, $d_{R}^W = 200m$, $F = \$1500$, $P_{ij}^W = \$30$, $I_i^U = I_i^S = I_i^U = \$50$, $p = 5\%$, $a = 100$, $b = 20$, $c = 120,000$, $N_M^S = 1,200,000$, and $N_S = 500$ to $6,000,000$. The results for these AMI architectures are shown in Fig. 4.3.

As it is mentioned, these results are sketched for SM’s data rate range from current data rate (0.5bps) up to predicted future data rate of 5kbps (specially up to 8.3kbps for AMI hybrid indirect architecture). It means AMI decentralized hybrid indirect architecture has an excellent load scalability in terms of SM’s data rate so that for example for this range of data rate its cost is not be changed. Fig. 4.3 shows that the AMI centralized aggregation-based indirect architecture has a very limited scalability and it can be used in a situations that we have a small number of SMs. Since our new AMI decentralized hybrid architecture...
indirect architecture can be applied for different demographic regions (Fig. 4.3) and if the number of SMs increased (e.g., 100 times, from 60,000 to 6,000,000), total deployment cost will not increase too much (e.g., 55 fold for 100 fold increment in the number of SMs), the propose AMI architecture has a good geographic scalability. Also, Fig. 4.3 verifies that AMI hybrid indirect architectures outperforms other AMI architectures.

In Fig. 4.4 and 4.5, total deployment cost of AMI decentralized and hybrid indirect architectures are shown for different years correspondingly. By comparing Fig. 4.4 and 4.5, we can see that when service time of the SG is increased (i.e., 1 year, 5 years, and 10 years), AMI hybrid indirect architecture is more cost effective than decentralized one. By comparing corresponding curves in Fig. 4.4 and 4.5 (e.g., corresponding curves for 1 year, 5 years, and 10 years), we can see that performance of AMI decentralized hybrid indirect architecture is better than AMI decentralized aggregation-based indirect architecture. Fig. 4.6 proves better performance of AMI decentralized hybrid indirect architecture with respect to AMI decentralized aggregation-based indirect architecture.
Fig. 4.3: Total deployment cost ($C_t$) of AMI centralized aggregation-based, decentralized aggregation-based, and hybrid indirect architectures for 1 year.
Fig. 4.4: Total deployment costs \( (C_t) \) of AMI decentralized aggregation-based indirect architecture for 1 to 10 years.
Fig. 4.5: Total deployment costs ($C_t$) of AMI decentralized hybrid indirect architecture for 1 to 10 years
Fig. 4.6: Comparison of total deployment cost ($C_t$) of AMI decentralized aggregation-based indirect architecture with AMI decentralized hybrid indirect architecture for 1 year and 10 years.
CHAPTER 5
CONCLUSION AND FUTURE WORK

5.1 Conclusion

Growing the number of SMs and increasing their data rates impose a serious problem for scalability of traditional centralized AMI architecture in SG. So, in this thesis, different AMI architectures are investigated and a scalable AMI architecture is proposed to enhance performance of current AMI architecture and satisfy future requirements of SG. We defined three performance metrics (monthly, fixed, and total deployment cost of AMI architecture) and based on them, we formulated each AMI architecture. Then, we used a genetic-based algorithm to minimize these metrics for the new proposed AMI architecture and find its near optimal solutions (location of RAs and WAAs). The simulation results demonstrated that our proposed AMI architecture can achieve a better performance compared with other AMI architectures.

5.2 Future Work

In future, various work can be done as the extension to this study which some of them are as follows:

1. We can develop an energy consumption model for each RA and define delay of transmitting data from SMs to UC. Then, we can find the optimum number of RAs based on energy consumption of each RA, WAA and RA cost, and delay.

2. We can develop a power consumption model for each RA and define NAN lifetime. Then, we can find the optimum number of RAs based on RA power consumption, WAA and RA cost, and NAN lifetime.

3. We can model AMI as a queuing system and derive an expression for packet delay. Then, we can find the optimum number of RAs based on RA cost and packet delay.
4. We can propose a queue-based AMI and derive an expression for packet delay. Then, we can define objective functions such as total cost, payoff, or reward so that by minimizing them, we can obtain the optimum value of packet service and arrival rates of RAs.

5. We can deploy a queuing system for AMI and develop models to calculate energy consumption of each RA and packet delay. Then, we can find the optimum number of RAs based on WAA and RA cost, delay, and packet delay.

6. We can add the cost of packet delay in RAs and/or WAAs to the total deployment cost and find the optimum configuration of RAs and WAAs.
REFERENCES


