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Review Article

A Review of the Topologies Used in Smart Water Meter Networks: A Wireless Sensor Network Application

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This paper presents several proposed and existing smart utility meter systems as well as their communication networks to identify the challenges of creating scalable smart water meter networks. Network simulations are performed on 3 network topologies (star, tree, and mesh) to determine their suitability for smart water meter networks. The simulations found that once a number of nodes threshold is exceeded the network's delay increases dramatically regardless of implemented topology. This threshold is at a relatively low number of nodes (50) and the use of network topologies such as tree or mesh helps alleviate this problem and results in lower network delays. Further simulations found that the successful transmission of application layer packets in a 70-end node tree network can be improved by 212% when end nodes only transmit data to their nearest router node. The relationship between packet success rate and different packet sizes was also investigated and reducing the packet size with a factor of 16 resulted in either 156% or 300% increases in the amount of successfully received packets depending on the network setup.

1. Introduction

Residential, commercial, and industrial sectors receive and pay for utilities such as natural gas, electricity, or water through the use of a utility company. These resources are carefully managed to ensure sustainability and customer's use is recorded for billing as well as demand prediction purposes.

Customers who have a utility meter installed are billed according to their use and this process for water meters traditionally involved an employee from the utility company visiting the premises to manually record the meter's reading [1]. This process is time consuming, inaccurate and susceptible to corruption and theft [1, 2]. To solve these problems utility companies are focusing their attention on technologies which will enable automatic meter reading (AMR). Through use of new technologies, utility meters become smart sensor nodes that are part of a sensor network that communicates with a centralized control and data location.

AMR will not only allow utility companies to collect measurements automatically but also pave the way for remote control and configuration of meters by adding a networked and intelligent electronic controller. A rising trend is to either replace or retrofit water meters to enable AMR. The movement towards AMR is part of the smart grid movement as well as the bigger smart city movement where technology is being developed and used to improve every aspect of human life with goals such as automation, reducing power consumption, and lowering costs [3].

The smart grid movement mainly focuses on adding communication infrastructure to the existing power system infrastructure to increase efficiency of the whole power system [4]. While the smart grid focuses on the provision of electricity the water sector shares many of the same challenges such as cyber security, scalability, and interfacing with legacy systems.

The use of AMR generates a vast continuous stream of data which must be correctly handled before the benefits of applying analytical tools to this data flow will be achieved [5]. A scalable communication architecture is also required to handle the large amount of nodes in a smart utility network. Utility companies can use a carefully developed system architecture for all of their supplied utilities to create integrated utilities sharing management, database, and communication systems.

Creating smart utility networks requires more than just smart meters but rather the creation of an Advanced Metering Infrastructure (AMI) to provide monitoring and control capabilities from the source all the way to the consumer. Current utility networks were built as a centralized system with the intelligence aspects of the system at central locations with little intelligence found in the geographically spread out distribution elements [4]. Future networks will however make use of two-way communication between intelligent components to increase reliability and efficiency [4].

By enabling automatic meter reading through the use of smart utility meters, utility companies receive several benefits. AMR allows utility companies to implement automated billing systems, monitor supply and demand in real-time, provide remote control over meters, detect theft, and remotely detect faults [2, 6]. An AMR system can also be expanded to measure not only water quantity but also water quality [7]. When water shortages arise utility companies often respond with activating water restrictions such as forbidding the watering of gardens outside provided time periods. Without any real-time data of consumer's water consumption it can be difficult to determine if consumers are breaking these restrictions but AMR can serve as a source of usage data in near real-time.

With no or only infrequent manual readings utility companies make estimates based on historical data when calculating a household's use [1]. The use of real-time monitoring allows for monthly bills to not only be accurate but also provide much more information about a household's monthly use patterns [8]. This new source of accurate usage data can also be used to improve customer rewards schemes and will allow consumers to better save money when they limit their use to nonpeak hours. Consumers would therefore also benefit from automatic meter reading.

The use of AMR and AMI has many benefits but negatives also exist. Their implementation will not only require a large financial commitment but also must be supported and desired by consumers. The cost of AMR extends beyond the meters themselves to the upgrading of the central control and data locations to add data storage and processing capabilities. Staff will have to be retrained and campaigns to gain the support of consumers will have to be created.

Consumers have privacy issues with the large amount of data about their everyday habits being recording by their smart meters [9]. One of their main concerns is the detection of their presence in their homes through the use of this data [10]. Privacy preserving schemes are in development for the smart grid to ensure customer privacy [10]. The security of the data as well as the network itself is also a concern as the network could be targeted with cyber threats [11]. Usage habits could be presented to the customer through the use of cloud services but security concern with this approach must also be addressed [12].

A commonly used communication technology in applications such as home automation, remote monitoring, and smart lighting is ZigBee, which is based on the IEEE 802.15.4 specification [3]. Zigbee focuses on the upper layers of the networking stack as IEEE 802.15.4 only defines the lower two layers [13]. In addition to being recommended by the US National Institute for Standards and Technology (NIST) for smart grid networks in the residential domain, ZigBee based meters are also preferred by several smart grid vendors [3]. ZigBee based designs are popular in the smart utility field because of low power consumption and cost-effectiveness [14–16]. There are however drawbacks to using ZigBee such as a proportional increase in interference when the number of nodes is increased as well as low bandwidth capabilities [2]. These drawbacks will only present themselves when researchers in the AMR field create an experimental setup of sufficient size, for example, large networks instead of a small proof of concept network.

While gas, electricity, and water meters each have unique challenges in measuring their respective resource, the design challenges in building smart meter systems are very similar. For example, in all three cases meter installations are normally done during building construction and upgrading existing meters to create smart meters requires retrofittable designs. Existing meters would have been originally installed without any considerations to the power and networking requirements of a smart meter system.

2. Smart Water Meters

Smart water meters can be developed using different technologies, depending on several factors: cost, scalability, and networking requirements and if existing meters are retrofitted or replaced with a new smart water meter design. Before designing a network for a smart water meter system it is beneficial to first examine the meter itself to gain an understanding of not only the data that has to be sent but also any other design requirements.

Smart water meters measure the flow of water using mainly two approaches: image processing or through the use of sensors. Image processing of the meter's display allows for the easy retrofit of existing analogue meters [17–19] while sensor based approaches use either magnetic [1, 20] or capacitive sensors [21].

2.1. Smart Water Meters Using Magnetic Sensing. A smart water meter system with the design goal of monitoring water consumption in near real-time was successfully developed in [1]. A meter interface node was built which counts pulses generated by a reed switch inside the water meter. Every time a specific amount of water has flown through the meter another pulse is generated.

In a retrofittable system flow rate is measured externally to the existing analogue water meter by attaching a custom magnetic sensor [20]. The already installed water meter

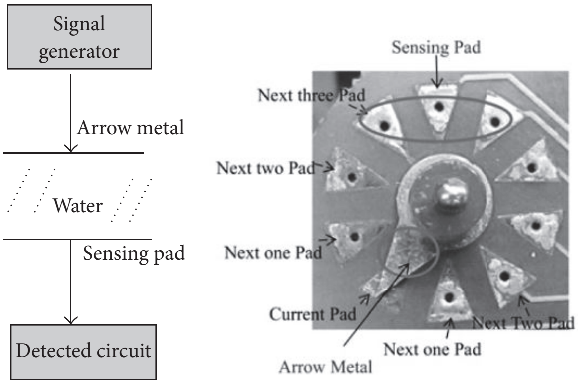


Figure 1: Arrow sensor's structure (from [21]).

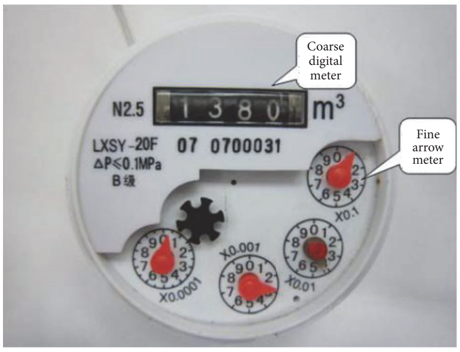


Figure 2: Example of a water meter's display (from [17]).

measures flow by monitoring a rotating magnetic coupling. The coupling's magnetic field is however detectable outside the meter and by using a Tunneling Magnetoresistive (TMR) device an external system can also measure the flow rate without any modifications to the meter's internal components [20].

A smart water meter was built in [22] with magnetic hall sensors sensing a magnet attached to the impeller of a water meter. An algorithm was developed to determine the direction of water flow to determine periods where the controller can be put into sleep mode.

2.2. Smart Water Meters Using Capacitive Sensing. A low-cost noncontact arrow sensor was developed for a water meter [17, 21]. The smart meter consists of mechanical water meter with an electronic circuit embedded in the display capable of detection the location of a pointer's arrow. Figure 1 shows the structure of the sensor. Underneath each of a dial's numbers (see Figure 2) copper foil was added as shown in Figure 1.

The electronic circuit uses a signal generator to send a square wave (of a specific frequency) through the metal arrow and the combination of the metal arrow, the copper foil, and the water between these two conductive objects form a capacitor [21]. By applying capacitive signal sensing techniques via detection pads each connected to a sensing pad (copper foil under a number) the location of the arrow can be determined. The system was tested using 300 test samples taken over a 30-day period and had a success rate exceeding 95% [21].

Figure 3: Example of digits incrementing in a water meter (from [18]).

A Field-Programmable Gate Array (FPGA) was used to implement a signal generator, perform signal processing, and send data via an RF module to a server [21].

2.3. Smart Water Meters Using Image Processing. Image processing is a popular method in smart water meters and is particularly useful if a retrofittable design is desired, as an external camera module can be used to capture a water meter's display for processing. This approach requires no modification of the existing meter's internal structure. An example of an analogue water meter's display is shown in Figure 2. The display consists of multiple pointer (or arrow) dials as well as a digital dial. An image processing based approach would have to be developed with specific water meter models in mind as the displays will differ.

2.3.1. Processing of Numerical Character on the Digital Dial. The digital dial on a water meter uses the multiple sets of the numerical characters 0–9 to display water use. One identified challenge when using image processing on this dial is that the digits roll over as they are incremented and captured images may contain two half characters for a specific digit [18]. An example of this phenomenon is shown in Figure 3.

A proposed solution was found in the literature where two adaptive learning back propagation artificial neural networks were trained with either samples of full characters or samples of rolling characters [18]. The system distinguishes if a single or double row of characters appear in an image and then uses the corresponding trained network. The accuracy that was achieved with 500 test images was approximately 99%.

An artificial neural network (ANN) is a processing algorithm/model loosely modeled after a biological nervous system (e.g., the brain) and is made up of a network of interconnected nodes performing processing [23, 24]. These nodes are trained by using input data for which the correct output data is known and then based on the correctness of network's output the inner nodes are adjusted [18, 23]. There are several different types of ANNs that have been used for image processing [18, 23, 25].

Image processing using a Kohonen artificial neural network was performed in an Indonesian water meter application [25]. A MATLAB application interprets images taken with a cell phone camera of the digital dial of a water meter. Limitations of this system are that images of a water meter have to be taken manually at the meter and that these images have to be transferred from the cell phone to a computer for processing [25]. The photos were taken in ideal weather conditions and the system was evaluated using only 15 images.

The chosen preprocessing phase does not deal effectively with unbalanced brightness, reflections, or scratches and/or dirt on the glass of the meter [25]. The overall accuracy of the image processing was 86.67% [25].

2.3.2. Processing of Pointer Dials. Detection of pointer location in a multipointer display was performed using a custom algorithm [19]. The algorithm attempts to locate each subdial through the use of circle detection. The algorithm was developed as an alternative to commonly used methods based on the Hough Transform as the Hough Transform is too slow for real-time systems [19]. Testing of the algorithm was performed using 48 images and the pointers could be located with an accuracy rate of 93.75% [19]. No speed comparisons between their algorithm and methods based on the Hough Transform was completed. No work on determining the value shown by these located pointers was presented.

A different method for locating the pointer dials was based on the Fourier transform [26]. When images of a meter's dial are captured from different angles the results are varying degrees of tilt in the image which must be corrected [26]. Instead of using a Hough Transform based algorithm for tilt correction a new algorithm based on the Fourier transform is used. The system was tested using 200 images and a location accuracy of 100% was achieved (no detail on the testing setup is however presented) [26].

2.3.3. Image Recognition in Non-Water Smart Meter Systems. Image processing was used to interpret remotely obtained readings from existing mechanical gas meters [27]. A smart sensor node uses a camera and a 2.4 GHz 802.15.4 RF module to monthly send a picture via a multihop ZigBee network to a server for processing. The server software used the OpenCV image processing library for digital image recognition which uses an automatic transform algorithm [27]. No indication of the nature of the performance of this algorithm is provided.

In another image processing based smart gas meter system images are transmitted using an RF module to a gateway device [28]. The gateway devices save readings in a database which can be accessed remotely through the Internet. The gateway device (a BeagleBone board) performs image processing with a Probabilistic Neural Network (PNN) recognizing numerical characters. It should be noted that this system cannot successfully handle the digit rolling over problem described previously and discards the current image and reattempts the process by using a new image [28].

The image recognition rate of this system is 87.97% (recognition of all 8 digits of a given measurement). The image processing time of the gateway device compared to a computer for two different file sizes was ≈8 times slower [28].

3. Networking and Communication

In order for utility companies to successfully implement an AMR system, smart water meters must be omnipresent in the residential, commercial, and industrial sectors. The system will therefore consist of a large number of smart water meters (possibly millions) all of whom must be able to effectively send and receive data. Utility companies therefore have to implement a smart utility network (SUN) [29], capable of supporting geographically spreaded devices. The challenges in building effective SUNs are very similar to the challenges faced in industrial wireless sensor networks (IWSNs) [30]. Both areas face problems such as the lack of existing networking infrastructure and large scale deployment [30]. Shared networking considerations include power consumption, latency, security, and reliability [3].

SUN networks can either be wire-based or wireless, each with unique benefits. AMR systems also have different network topologies ranging from each meter being directly in communication with the processing hub(s) to large mesh grids of meters that communicate to the processing hub(s) through gateway devices. These gateway devices can collect data from several meters before sending the data to the processing hub(s).

3.1. Wire-Based Systems. Wire-based systems range from simple systems utilizing RS232 or USB cabling to more advanced systems using power-line communication or by using the telephone line network [1, 2, 8, 14]. Work has already been done on the use of power-line communication and telephone line networks [2, 3] for AMR applications. Depending on the distance required, wire-based systems can hold many advantages over wireless systems, such as simplicity, low interference levels, and high data security. As the required transmission distance increases, these advantages are diminished, especially if a wire-based system's higher installation and maintenance costs are taken into account [1, 14].

3.2. Wireless Systems. Wireless communication technologies differ from one another in terms of transmission rates, maximum communication range, and line of sight requirements. In addition, the desired network topology's requirements will also determine which technology is suitable [1]. The IEEE 802.15.4 standard provides procedures for the Physical (PHY) and the Medium Access Layer (MAC) for a low-rate wireless personal area network (LR-WPAN). The IEEE 802.15.4 standard is specifically designed for low power and low data rate sensor networks [13].

3.2.1. Network Topologies. The two main topologies in the IEEE 802.15.4 standard are star and peer-to-peer [13]. Different network topologies can be constructed from the main topologies, for example, star, tree, cluster tree, and mesh, with each having different advantages [31]. The destination node in an IEEE 802.15.4 network is normally referred to as the sink node and a network may have multiple sink nodes [13]. The wireless network can either be homogeneous or heterogeneous depending on if the sensor nodes have the same capabilities and functions [32].

An IEEE 802.15.4 network consists of Full-Function Devices (FFDs) or Reduced-Function Devices (RFDs) with RFDs normally being sensor devices (also referred to as sensor nodes) that simply transmit or receive data to FFDS for further transmission/processing. A coordinator node is an FFD which handles network management as well as the creation of the network while the router nodes are FFDs responsible for transmitting data via the most optimal route [13, 31].

The procedure which allows devices to join IEEE 802.15.4 Wireless Personal Area Network (WPAN) is referred to as the association procedure. After a device has scanned for available WPANs and selected a desired network the association procedure is started [13]. If this procedure is successful a parent-child relationship is established between devices in the network. These relationships can be seen as a tree with the root being the network's coordinator device [13].

The topology forming strategies in IEEE 802.15.4 networks were investigated for different network settings [13]. A cluster-tree topology with either a single sink or multiple sinks was simulated (using ns-2 network simulation software) and the performance of the resultant networks measured. The resultant network's mean number of children per parent, maximum number of children per parent, and the tree height were calculated. Trees with high depth result in long data routing paths while short trees resulted in excessive numbers of nodes in the lowest levels [13]. The analysis found that the tree depth must be properly controlled for a network to be effective but that the process can be difficult. A very low tree depth causes some nodes to have no network connectivity [13].

The analysis also found that the IEEE 802.15.4's native unconstrained association procedure results in trees with too much depth. This problem was addressed by the ZigBee Alliance in the ZigBee technology which allows for constraints on the depth of a tree and the number of children a parent node can have and allows for coordinator selection rules [13].

3.3. ZigBee Smart Energy. When using ZigBee technology data is transmitted using an application profile [33]. Application profiles can either be public (specified by the ZigBee Alliance) or private profiles defined by a manufacturer. Application profiles each have a unique identifier number and are used to specify that a device is aimed for a domain such as home automation, healthcare, or several others. A wide range of ZigBee supporting devices can belong to a given domain and the aim of a domain is to ensure that devices from different manufacturers will work in harmony with one another [33].

One public application profile is the ZigBee Smart Energy specification. This specification is aimed at the water and energy delivery and use sectors. Products responsible for monitoring, controlling, and automation in these sectors can use the different versions of this specification (1.0, 1.1, and 2.0) to ensure compatibility with one another when connected to the same Home Area Network (HAN).

3.4. ZigBee Network Topologies. The choice of network topology is critical to the success of a SUN and a correctly chosen topology will allow for easy scaling as the network grows, elimination of bottlenecks, redundancy, and self-organization as well as low cost. The 3 topologies supported in ZigBee based systems [34] can be seen in Figure 4.

In the star network topology in Figure 4 end devices directly communicate with the coordinator. All communication must pass through the coordinator and this type of topology suffers from congestion as the number of end nodes increases. This type of topology is unsuitable for a SUN due to the large amount of devices (smart meters) in the network.

In a design schema for a wireless intelligent water meter system [15] a star network topology is used for an arbitrary network of water meters with a central data processing server. The design schema is however only a theoretical network and no network was built and evaluated.

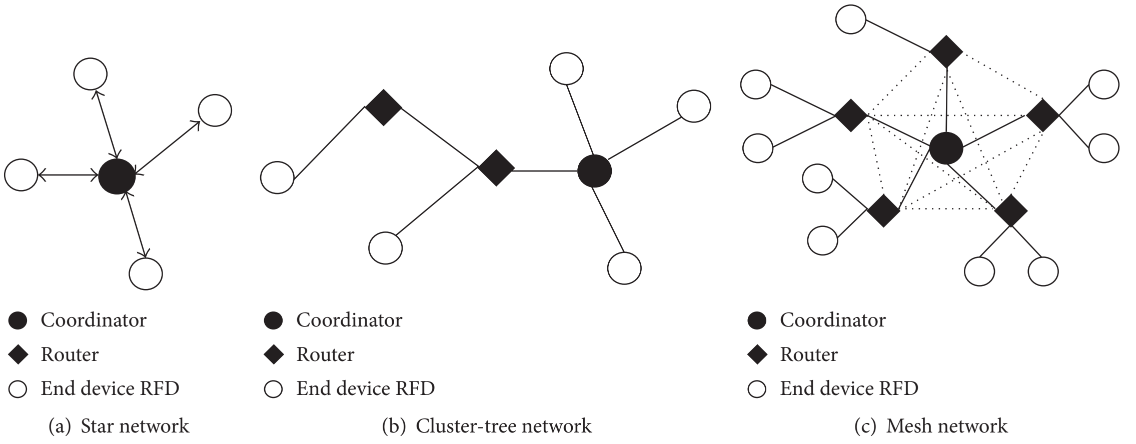
The cluster-tree network in Figure 4 is a special case of a tree topology and adds router devices to the network which act as intermediaries between devices [31]. This type of topology increases the range of the network by creating clusters and allows data to hop between routers during data transmission in the network [34].

A mesh (also referred to as a peer-to-peer) network topology has one coordinator and any device can communicate with another directly or via multiple hops to route data through the network. This topology increases reliability as data can be rerouted if a node fails [13, 34].

3.5. Wireless Communication Options. The wireless communication used in utility networks can be separated into 3 areas: home area networks (HANs) on the premises consisting of smart meters as well as other devices, Neighbourhood Area Networks (NANs) consisting of meters, and gateways in a neighbourhood and finally Wide Area Networks (WANs) in which gateways communicate with the utility's network [29].

In 2012 a new amendment (4g) dealing with the NAN element of smart utility networks was added to the IEEE 802.15.4 standard for LR-WPANs [29]. This amendment was to provide a standard to enable the creation of nonproprietary solutions for these networks.

Depending on where a smart meter will be installed a direct line of sight to a nearby gateway device or another meter may be infeasible. Communication technologies such as Near Field Communications (NFC), Bluetooth, Wi-Fi, or Infrared can assist in the automation of meter readings by enabling utility workers to carry handheld devices which communicate with a smart water meter. These technologies have a short range (a few meters) of communication and would be unpractical in a NAN as their data transmission



(a) Star network

(b) Cluster-tree network

(c) Mesh network

Figure 4: Topology examples of a ZigBee network (from [31]).

ranges would require a large amount of gateways. Communication options for smart water meters include [2]

(i) short range Radio Frequency (RF),

(ii) Global System for Mobile (GSM) communications,

(iii) Worldwide Interoperability for Microwave Access (WiMAX),

(iv) Long Term Evolution (LTE).

Detailed comparisons between the various communication technologies used for smart grids [3] and for automatic meter reading applications [2] have been performed. These comparisons found that each technology has unique advantages but also has resulting disadvantages. High data rates can be achieved but drive up the cost and low-cost solutions such as ZigBee are susceptible to interference from the 802.11 networks in the vicinity.

3.6. Existing and Proposed Smart Water Meter Networks. An example of a smart metering system for a power utility company was built in Malaysia [14]. This system uses a ZigBee module attached to each meter to transmit measurements to a collector node which then uses GSM to send data to a central computer for processing. This system uses a mesh network topology to allow meters too far away from the collector node to transmit their data to nearby meters for forwarding to the collector node. This approach increases the effective coverage range of the collector node. The collector node is however a bottleneck, as well as a single point of failure as all data needs to flow through this node in order to reach the central computer.

A smart water meter system uses an IEEE 802.15.4 compliant RF module to send data from the smart water meter to a gateway device [1]. The gateway runs a Real-Time Operating System (RTOS) known as Contiki OS with 6LoWPAN (IPV6 over Low Power Wireless Area Network) support. The data is then sent to a back-end system for analysis and display. Collected data is displayed using a web interface as well as using a monitoring tool (Pandora FMS) [1].

A multihop (mesh) topology ZigBee network is used to transmit images taken of a gas meter's display to a server for processing [27]. A picture transform algorithm is described which divides images into blocks before transmitting the blocks via the network. At the destination node the images are reconstructed from the individual blocks [27]. A shortest path selection algorithm is also used to determine the shortest route to send packets. No information on the performance of these algorithms or the network was provided [27].

A star network topology is used in another smart gas meter system and wirelessly transmitted images from different meters are sent a gateway device [28]. The gateway device is also connected to the Internet to allow for remote access to readings saved in a database. Performance testing of the network was conducted by sending images to the gateway from increasing distances and packet loss was experienced at distances greater than 10 m [28]. The transmission time of varied image file size at a fixed distance of 10 m was also investigated and larger file sizes resulted in longer transmission times [28].

A proposed real-time water monitoring system [21] relies on GPRS technology to transmit data from multiple meters to a control centre. Several meters send their data to a data collector node which then relays the data to the control centre. The monitoring system of multiple meters is only theoretical and no consideration into factors such as scalability and reliability has been taken.

A proposed remote power meter system uses a combination of Bluetooth, GPRS, and Infrared technologies [35]. A central monitoring centre sends instructions via GRPS to data concentrators who in turn request data from data collectors using Bluetooth. The data collectors are connected to several digital power meters using a RS485 bus. In the event that either the GPRS or Bluetooth technology cannot successfully communicate, the proposed system suggests that personnel equipped with Infrared handheld meter readers collect measurements from each meter [35]. The collected measurements are then transmitted to the monitoring system using a RS232 interface [35]. No network simulations to determine the performance of the proposed system were presented.

While a well-designed system would cater for a communication outage the proposed system would require a lot of manual labour and travel, as personnel would have to potentially travel long distances between the meters and the monitoring centre.

Most communication outages are normally temporary so a system where measurements are instead stored locally, to be transmitted once communication is reestablished would not require human intervention. This local storage method would require a local access method (e.g., via a USB port) should communication still be disrupted and personnel need to manually record measurements.

3.7. Network Simulation. Various network topologies and technologies have been used in the various smart water meter networks reviewed in this paper. In order to evaluate the suitability of these chosen topologies, network simulation software can be used to evaluate their performance.

Several simulators for wireless sensor networks (WSN) have been developed [36]. Network simulation can be performed in a computing environment such as MATLAB, with the ns series (ns-1, ns-2, and ns-3) of network simulators or with several other suitable network modeling programs. Key differences between the various programs are cost, supported protocols, network scalability, and extension support [36].

A commonly used network simulator is Riverbed Modeler, which was previously known as OPNET Modeler. Riverbed Modeler supports 802.15.4 ZigBee MAC and uses detailed models when simulating radio transmissions [36]. The feasibility of using OPNET Modeler to study ZigBee networks was investigated and it was found that simulation results are consistent with other software simulators and that networks are easy to deploy [37].

An issue in wireless sensor networks is referred to as the hot-spot problem and occurs in large networks in situations where far away nodes have to communicate with the rest of the network and do so through another node [16]. This node is responsible for not only its traffic but also all traffic to and from the far away node resulting in higher power consumption. This problem also occurs in multihop networks where nodes closest to the base station handle the most traffic. This also occurs in ZigBee networks as all nodes have to communicate with the coordinator node.

A suggested solution for this problem is to have the coordinator node be mobile. OPNET Modeler was used to determine how the mobility of the coordinator influences the throughput of the network [16]. From the simulations it was determined that the best throughput is achieved when the coordinator remains static. In cases where the coordinator has to be mobile, careful consideration of the movement path must be performed otherwise throughput will drop significantly due to packet loss. A random route can be used to avoid extremely low throughput [16].

4. Riverbed Modeler Network Simulations

4.1. Simulation Setup. Simulations were created to evaluate the performance impact of implementing different network topologies in a ZigBee based smart water meter network. Simulations for star, mesh, and tree networks were created in Riverbed Modeler.

Table 1: General settings and MAC and physical layer parameters for all nodes.

MAC layer parameters	
Status	Enabled
ACK wait duration (seconds)	0.05
Number of retransmissions	5
Minimum backoff exponent	3
Maximum number of backoffs	4
Channel sensing duration	0.1
Physical layer parameters	
Data rate	Autocalculate
Packet reception-power threshold	−85
Transmission bands	Only 2450 MHz band enabled
Transmit power	0.05
General	
PAN ID	2
Altitude	1.0

In a typical smart water meter network, leaf nodes (simulated by ZigBee end device nodes) would periodically send their measured water use to a collection point (simulated by a ZigBee coordinator node). In addition to receiving these measurements the collection point could also periodically communicate with specific meters to manually request measurements or to perform administrative tasks. To simulate this behaviour the ZigBee end devices were configured to periodically send data to the coordinator node while the coordinator node was configured to send data to random nodes in the simulated network.

Simulations were used to evaluate the MAC end-to-end delay for the different topologies, packet loss versus number of nodes, transmission success rates versus data destination, and application layer packet reception rates versus packet size. Simulations were limited to the first 10 minutes of network traffic for any given network.

All ZigBee devices were set up with the settings shown in Tables 1, 2, and 3. The network as constructed in Riverbed Modeler can be seen in Figures 5–7. These figures were created via the snapshot feature in Riverbed Modeler. At the specific moment of the snapshot some nodes may not be actively communicating and therefore appear unconnected (they do however have network connectivity).

4.2. MAC End-to-End Delay Evaluation. The topologies' MAC end-to-end delay versus number of end nodes was evaluated. In an optimal network one coordinator node should be able to service a large amount of end nodes without the network becoming congested resulting in delays and message retry attempts. This evaluation was performed with the simulation setting "children position" set to "logical."

Before the performance results of the three topologies are presented the procedure of this evaluation will first be presented. For each topology the MAC end-to-end delay

Table 2: Network and application layer parameters for the coordinator node.

Network parameters	
Maximum children	250
Maximum routers	5
Maximum depth	5
Mesh routing	Disabled
Application traffic	
Destination	Random
Packet interarrival time	Constant (1.0)
Packet size	Constant (1024)
Start time	Uniform (20,21)
Stop time	Infinity

Table 3: Application layer parameters for all end device and router nodes.

Application traffic	
Destination	Coordinator
Packet interarrival time	Constant (1.0)
Packet size	Constant (1024)
Start time	Uniform (20,21)
Stop time	Infinity

experienced by the coordinator is measured for a created network with $n = 10, 20, 30, \ldots, 70$ end nodes. A graph of the resultant data of one such a simulation for a 40-end node star network can be seen in Figure 8. To determine the average of the graph's data, the data values of a 10-minute simulation were used and the average was calculated.

This process was repeated for all three network topologies with $n = 10, 20, 30, \ldots, 70$ end nodes (see Figure 9).

Figure 9 shows the measured end-to-end delay for the three possible ZigBee network topologies. From this figure it can be seen that when the number of nodes is limited (≤ 50 nodes) the delay for a star topology network remains stable but when the number of nodes exceeds this threshold the delay increases sharply.

The delays for tree and mesh topologies closely follow each other in Figure 9 with the mesh topology resulting in a slightly lower delay. Similar to the star topology the end-to-end MAC delay increases when the number of nodes exceeds 50 for both these topologies but at a much slower rate than for a star topology. These results follow the same upward trend reported for similar simulations performed by other researchers [37].

4.3. Packet Loss

4.3. Packet Loss. The second performance aspect that was evaluated was each topologies' percentage packet loss versus number of end nodes. In an optimal network even when there a large amount of end nodes no packet loss should be experienced. This evaluation can be seen in Figure 10.

The packet loss experienced for each topology is provided in Figure 10 and for all three topologies is smaller than 0.14%. The figure shows that the packet loss experienced in star networks are initially lower than the other topologies but increase sharply after 30 nodes. Mesh and tree topologies have higher initial packet loss and their packet loss increases or decreases sharply depending on the number of nodes.

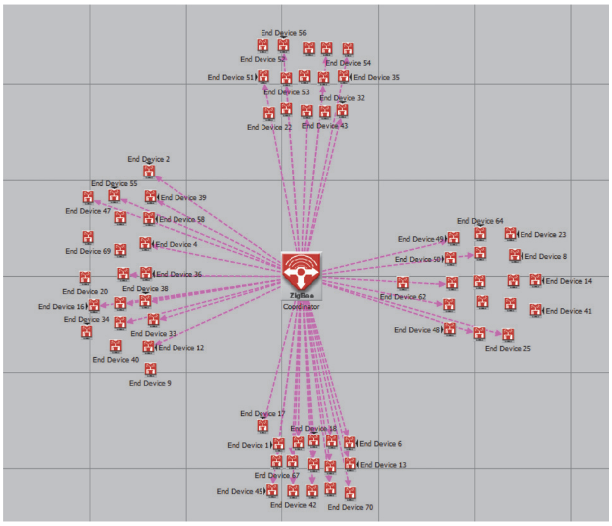


Figure 5: The star topology simulated in Riverbed Modeler.

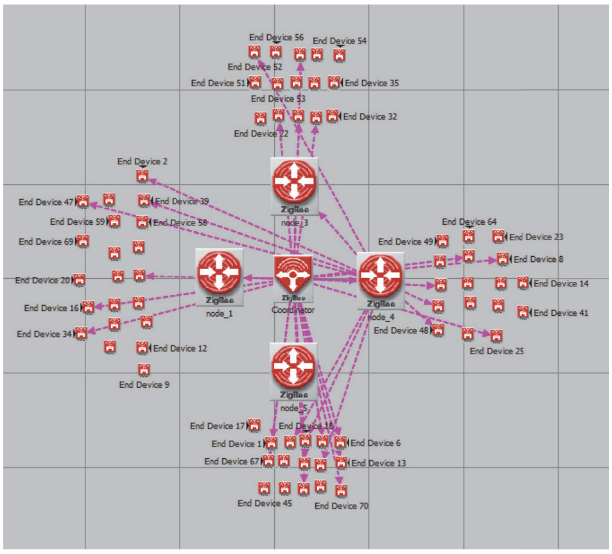


Figure 6: The tree topology simulated in Riverbed Modeler.

4.4. Data Destination Evaluation. The third performance aspect evaluated is the performance impact of modifying the end nodes so that they no longer send data directly to coordinator node but send their data to their nearest router devices. The router nodes can use high data rate technologies such as Ethernet or optical fiber to transmit the received data to the coordinator node at much higher rates than wireless transmission.

The reasoning behind this evaluation is that, in a $n = 70$ end node network, a large amount of wireless communication is performed by a single node (the coordinator node) and this results in retransmission attempts and missed traffic when

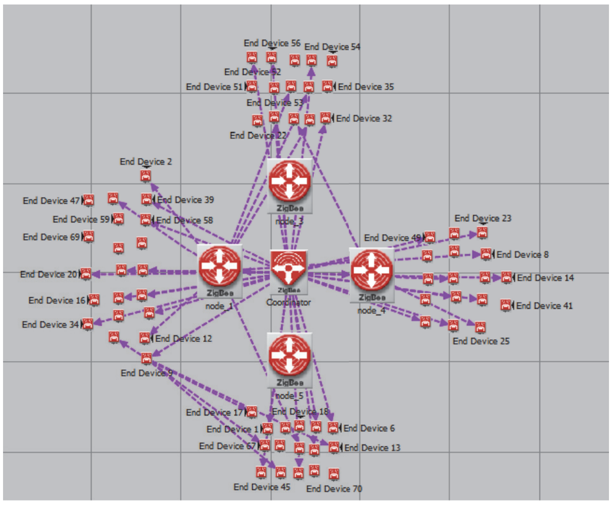


FIGURE 7: The mesh topology simulated in Riverbed Modeler.

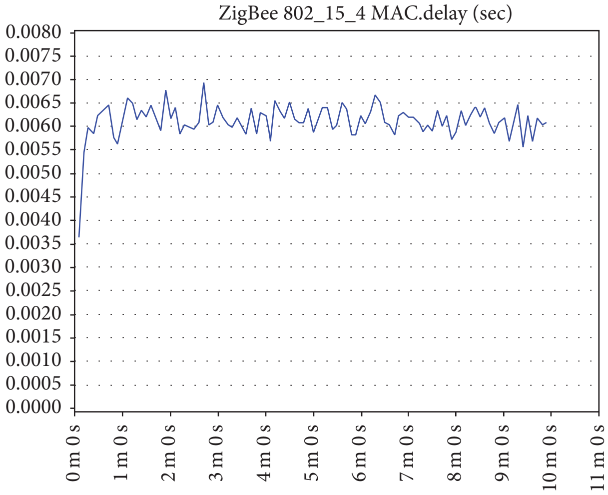


FIGURE 8: MAC end-to-end delay in a 40-end device star network.

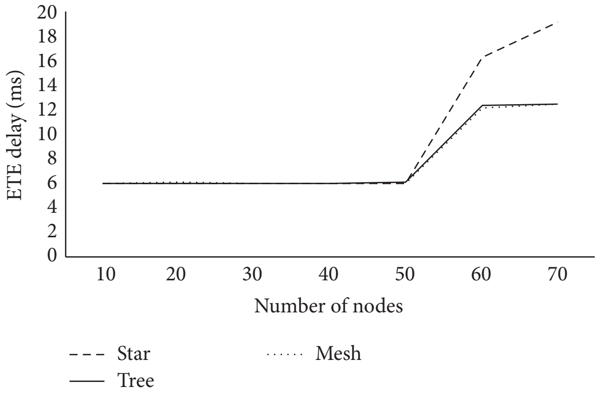


FIGURE 9: MAC end-to-end delay experienced by the coordinator node for 3 different network topologies.

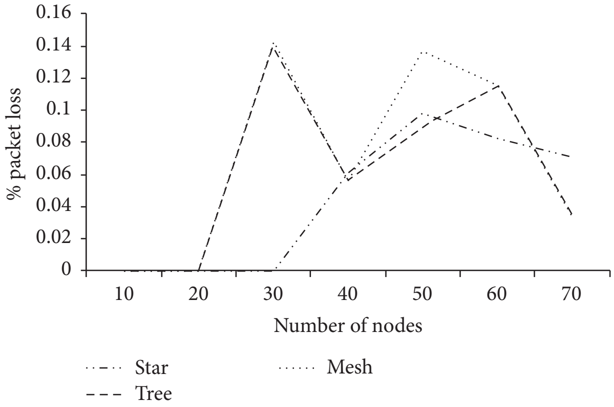


FIGURE 10: Packet loss (%) in the network for 3 different network topologies.

the simulation setting children position is changed from logical to meters. When this setting is set to "logical" zero packet loss is experienced but when node distances are taken into account (setting to meters) this is no longer the case.

A 70-end node wireless tree network with the coordinator node as the end device traffic destination was therefore compared to a network where end nodes transmit their data to their nearest router node. This transmission of the received data from the router nodes to the coordinator node was excluded in the simulation as the focus of the simulation was on the successful transmission of end node data to its destination. The connections between the router nodes and the coordinator node were assumed to have no packet loss and endless capacity.

The data loss at MAC layer level due to failed transmissions or packets exceeding the retransmission threshold was recorded. The amount of application level packets sent and received was also recorded and the results are shown in Table 4. The coordinator node's maximum children were set to 30 nodes and the network was spread out in this simulation to ensure end nodes transmit data via their nearest router node.

The transmission success rate for a 70-node tree network is presented below in Table 4.

Table 4 shows that more packets are successfully transmitted when end nodes transmit their data to their closest router when compared to transmitting their data directly to the coordinator node. In designs where these routers are connected with a high capacity data connection this approach can be followed to achieve higher transmission success rates. Transmitting data to router nodes instead of direct transmission improved the ratio of application layer packets received versus sent from 23% to 48%.

4.5. Packet Size Evaluation. Table 4 shows packet success rates of 23% and 48% for the different data destination approaches. Both these rates are quite low and therefore the fourth performance evaluation was created where the packet success rate was evaluated against packet sizes. The successful

Table 4: 70-end node tree network with single versus distributed data destinations.

Measured	Data destination	
	Coordinator node	Nearest router node
Data dropped at MAC layer (bits/sec)	1032	70
Application layer packets sent (packets/sec)	75	75
Application layer packet received (packets/sec)	17	36

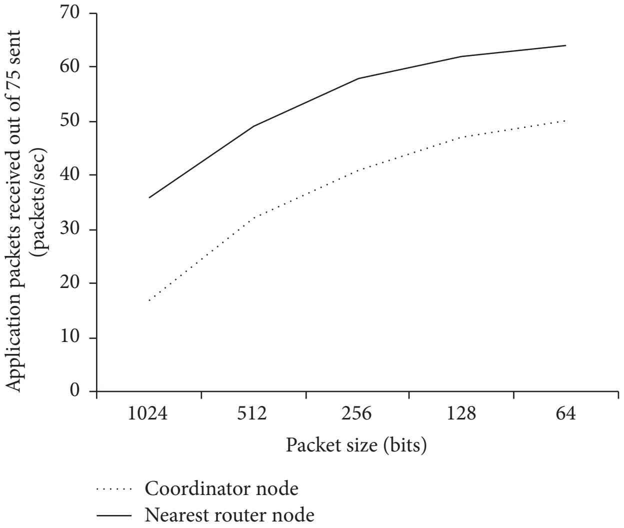


Figure 11: Application layer packet reception rate versus packet size.

received application layer packet rate for various packet sizes is given in Figure 11.

Figure 11 shows that packet size is one of the main contributing factors of the application layer packet reception ratio. By reducing the packet size with a factor of 16 the number of successfully received packets can be improved from 17 to 50 (nearly a 300% increase) or from 36 to 64 (a 156% increase). This shows a dramatic increase in the success rate regardless of whether data is transmitted to the coordinator node or to the nearest router node. For a packet size of 64 bits data transmission to the nearest router node achieved a success rate of 64 packets per second out of the possible 75 (85%). The line slopes shown in the graph indicate that as the packet size is halved the success rate increases but that diminishing returns will occur for low packet sizes. The difficulty in reducing the packet size must be weighed against the improvement it would provide to determine if the improvement would outweigh the significant design efforts required to achieve a smaller packet size. Reducing the packet size also reduces the amount of application data transmitted per packet so more packets would have to be transmitted as packet size reduces.

5. Conclusions

This paper investigated some of the challenges faced when creating scalable smart water meter networks. Three of the identified design considerations are the water flow sensing method, chosen network technology (star, tree, or mesh), and the scalability of the network due to its topology.

Network simulations performed showed that network performance is heavily influenced by the number of nodes in a network as well as the packet size. The simulations were limited to only a small number of nodes but the resulting graphs show that a network has a number of nodes threshold (50) after which a sharp increase in delays will be experienced. Using the mesh network topology decreases this delay increase therefore providing the best scalability of the three simulated network topologies. The percentage packet loss for all three networks remained below 0.14% for $n = 10$ to 70 nodes.

Further simulations also showed that a 70-end node tree network becomes congested when all end nodes transmit data to the coordinator node. This congestion can be reduced by configuring the end nodes to transmit their data to their nearest router node and then using high capacity wired connections between the router nodes and the coordinator node to forward the received data. This configuration improved the number of application layer packet arrivals from 23% to 48%.

Follow-up simulations of this 70-end node tree network in which packet size was varied showed that the number of application layer packet arrivals can further be improved by reducing the packet size. In a network where end nodes transmit their data to their nearest router node a 16-fold reduction in packet size resulted in a 156% increased success rate. This reduction may however not be possible as any chosen technology will have a minimum packet size.

Competing Interests

The authors declare no conflict of interests.

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References

[1] M. J. Mudumbe and A. M. Abu-Mahfouz, "Smart water meter system for user-centric consumption measurement," in *Proceedings of the 13th International Conference on Industrial Informatics (INDIN '15)*, pp. 993–998, July 2015.

[2] T. Khalifa, K. Naik, and A. Nayak, "A survey of communication protocols for automatic meter reading applications," *IEEE Communications Surveys and Tutorials*, vol. 13, no. 2, pp. 168–182, 2011.

[3] V. C. Güngör, D. Sahin, T. Kocak et al., “Smart grid technologies: communication technologies and standards,” *IEEE Transactions on Industrial Informatics*, vol. 7, no. 4, pp. 529–539, 2011.

[4] V. C. Gungor, D. Sahin, T. Kocak et al., “A survey on smart grid potential applications and communication requirements,” *IEEE Transactions on Industrial Informatics*, vol. 9, no. 1, pp. 28–42, 2013.

[5] J. Zhou, R. Q. Hu, and Y. Qian, “Scalable distributed communication architectures to support advanced metering infrastructure in smart grid,” *IEEE Transactions on Parallel and Distributed Systems*, vol. 23, no. 9, pp. 1632–1642, 2012.

[6] P. Jokar, N. Arianpoo, and V. C. M. Leung, “Electricity theft detection in AMI using customers’ consumption patterns,” *IEEE Transactions on Smart Grid*, vol. 7, no. 1, pp. 216–226, 2016.

[7] N. A. Cloete, R. Malekian, and L. Nair, “Design of smart sensors for real-timewater quality monitoring,” *IEEE Access*, vol. 4, pp. 3975–3990, 2016.

[8] F. Benzi, N. Anglani, E. Bassi, and L. Frosini, “Electricity smart meters interfacing the households,” *IEEE Transactions on Industrial Electronics*, vol. 58, no. 10, pp. 4487–4494, 2011.

[9] H. Nicanfar, P. Talebifard, A. Alasaad, and V. C. M. Leung, “Enhanced network coding to maintain privacy in smart grid communication,” *IEEE Transactions on Emerging Topics in Computing*, vol. 1, no. 2, pp. 286–296, 2013.

[10] C. Rottondi, G. Verticale, and C. Krauß, “Distributed privacy-preserving aggregation of metering data in smart grids,” *IEEE Journal on Selected Areas in Communications*, vol. 31, no. 7, pp. 1342–1354, 2013.

[11] Z. M. Fadlullah, M. M. Fouda, N. Kato, X. Shen, and Y. Nozaki, “An early warning system against malicious activities for smart grid communications,” *IEEE Network*, vol. 25, no. 5, pp. 50–55, 2011.

[12] Y. Ren, J. Shen, J. Wang, J. Han, and S. Lee, “Mutual verifiable provable data auditing in public cloud storage,” *Journal of Internet Technology*, vol. 16, no. 2, pp. 317–323, 2015.

[13] F. Cuomo, S. Della Luna, E. Cipollone, P. Todorova, and T. Suihko, “Topology formation in IEEE 802.15.4: cluster-tree characterization,” in *Proceedings of the 6th Annual IEEE International Conference on Pervasive Computing and Communications (PerCom ’08)*, pp. 276–281, March 2008.

[14] M. Y. Nayan, A. H. Primicanta, and M. Awan, “Hybrid automatic meter reading system,” in *Proceedings of the International Conference on Computer Technology and Development (ICCTD ’09)*, vol. 2, pp. 264–267, Kota Kinabalu, Malaysia, 2009.

[15] B. Zhang and J. Liu, “A kind of design schema of wireless smart water meter reading system based on Zigbee technology,” in *Proceedings of the International Conference on E-Product E-Service and E-Entertainment (ICEEE ’10)*, IEEE, Henan, China, November 2010.

[16] H. Dhaka, A. Jain, and K. Verma, “Impact of coordinator mobility on the throughput in a Zigbee mesh networks,” in *Proceedings of the IEEE 2nd International Advance Computing Conference (IACC ’10)*, pp. 279–284, Patiala, India, February 2010.

[17] S.-C. Hsia, M.-H. Sheu, and Y.-J. Chang, “Arrow-pointer sensor design for low-cost water meter,” *IEEE Sensors Journal*, vol. 13, no. 4, pp. 1281–1287, 2013.

[18] X.-P. Rui and X.-F. Song, “A character recognition algorithm adapt to a specific kind of water meter,” in *Proceedings of the WRI World Congress on Computer Science and Information Engineering (CSIE ’09)*, pp. 632–636, April 2009.

[19] Z. Zhang, Y. Li, and W. Yuan, “Research on pointer location of multi-pointer meter,” in *Proceedings of the IEEE International Conference on Automation and Logistics (ICAL ’09)*, pp. 911–914, Shenyang, China, August 2009.

[20] C. Schantz, J. Donnal, B. Sennett, M. Gillman, S. Muller, and S. Leeb, “Water nonintrusive load monitoring,” *IEEE Sensors Journal*, vol. 15, no. 4, pp. 2177–2185, 2015.

[21] S.-C. Hsia, Y.-J. Chang, and S.-W. Hsu, “Remote monitoring and smart sensing for water meter system and leakage detection,” *IET Wireless Sensor Systems*, vol. 2, no. 4, pp. 402–408, 2012.

[22] Y.-W. Lee, S. Eun, and S.-H. Oh, “Wireless digital water meter with low power consumption for automatic meter reading,” in *Proceedings of the International Conference on Convergence and Hybrid Information Technology (ICHIT ’08)*, pp. 639–645, Daejeon, South Korea, August 2008.

[23] R. P. Lippmann, “An introduction to computing with neural nets,” *ACM SIGARCH Computer Architecture News*, vol. 16, no. 1, pp. 7–25, 1988.

[24] X. Jin, J. Shao, X. Zhang, W. An, and R. Malekian, “Modeling of nonlinear system based on deep learning framework,” *Nonlinear Dynamics*, vol. 84, pp. 1327–1340, 2016.

[25] T. Triantoro, F. R. Batubara, and F. Fahmi, “Image based water gauge reading developed with ANN Kohonen,” in *Proceedings of the 1st International Conference on Electrical Engineering and Computer Science (ICEECS ’14)*, pp. 74–78, November 2014.

[26] Z. Zhang and Y. Li, “Research on the pre-processing method of automatic reading water meter system,” in *Proceedings of the International Conference on Artificial Intelligence and Computational Intelligence (AICI ’09)*, vol. 3, pp. 549–553, November 2009.

[27] S. Cai, S. Zhang, D. Huang, and S. Yu, “Remote gas meter reading system based on zigbee networks,” in *Proceedings of the Spring World Congress on Engineering and Technology (SCET ’12)*, Xi’an, China, May 2012.

[28] C.-H. Chen, C.-Y. Chen, C.-H. Hsia, and G.-X. Wu, “Big data collection gateway for vision-based smart meter reading network,” in *Proceedings of the 3rd IEEE International Congress on Big Data (BigData Congress ’14)*, pp. 266–269, IEEE, Anchorage, Alaska, USA, July 2014.

[29] K.-H. Chang and B. Mason, “The IEEE 802.15.4g standard for smart metering utility networks,” in *Proceedings of the IEEE 3rd International Conference on Smart Grid Communications (SmartGridComm ’12)*, pp. 476–480, November 2012.

[30] V. C. Gungor and G. P. Hancke, “Industrial wireless sensor networks: challenges, design principles, and technical approaches,” *IEEE Transactions on Industrial Electronics*, vol. 56, no. 10, pp. 4258–4265, 2009.

[31] J. Li, X. Zhu, N. Tang, and J. Sui, “Study on ZigBee network architecture and routing algorithm,” in *Proceedings of the 2nd International Conference on Signal Processing Systems (ICSPS ’10)*, vol. 2, pp. V2-389–V2-393, Dalian, China, July 2010.

[32] S. Xie and Y. Wang, “Construction of tree network with limited delivery latency in homogeneous wireless sensor networks,” *Wireless Personal Communications*, vol. 78, no. 1, pp. 231–246, 2014.

[33] D. Gislason, *Zigbee Wireless Networking*, Elsevier Science, Amsterdam, Netherlands, 2008.

[34] J. Sewook, A. Chang, and M. Gerla, “Comparisons of ZigBee Personal Area Network (PAN) interconnection methods,” in *Proceedings of the 4th IEEE International Symposium on Wireless Communication Systems (ISWCS ’07)*, pp. 337–341, October 2007.

[35] Z. Zheng, X. Zhou, and W. Z. Design, "Design and implementation of remote meter reading system," in *Proceedings of the 2nd International Conference on Software Technology and Engineering (ICSTE '10)*, vol. 2, pp. 247–250, San Juan, Puerto Rico, USA, 2010.

[36] M. Korkalainen, M. Sallinen, N. Kärkkäinen, and P. Tukeva, "Survey of wireless sensor networks simulation tools for demanding applications," in *Proceedings of the 5th International Conference on Networking and Services (ICNS '09)*, pp. 102–106, IEEE, Valencia, Spain, April 2009.

[37] I. S. Hammoodi, B. G. Stewart, A. Kocian, and S. G. McMeekin, "A comprehensive performance study of OPNET modeler for ZigBee wireless sensor networks," in *Proceedings of the 3rd International Conference on Next Generation Mobile Applications, Services and Technologies (NGMAST '09)*, pp. 357–362, September 2009.


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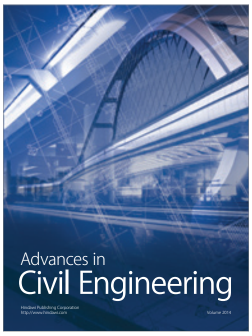
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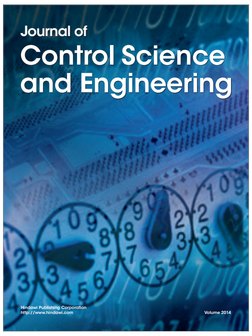
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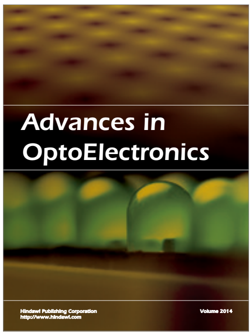
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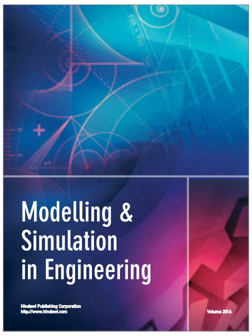
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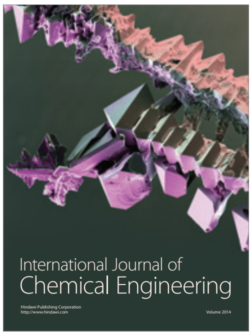
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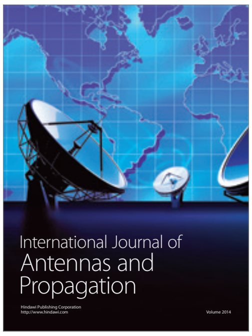
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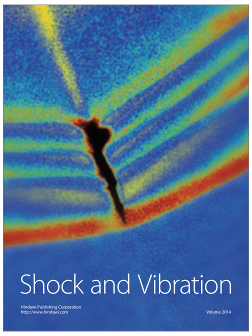
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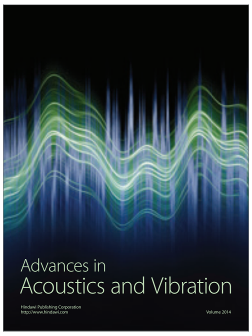
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