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A NOVEL DUAL MODE GATEWAY FOR WIRELESS SENSOR NETWORK AND LTE-A NETWORK CONVERGENCE

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A NOVEL DUAL-MODE GATEWAY FOR WIRELESS SENSOR NETWORKS AND LTE-A NETWORK CONVERGENCE

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Abstract

In recent years, the number of machine-to-machine (M2M) networks, which do not require direct human intervention, has been increasing at a rapid pace. Meanwhile, the need for a wireless platform to control and monitor these M2M networks, one with both a vast coverage area and a low network deployment cost, continues to be unmet. Mobile cellular networks (MCNs) and wireless sensor networks (WSNs) are emerging as two heterogeneous networks that can meet the challenges of M2M communication through network convergence. In this paper, a model for network convergence between a Long Term Evolution-Advance (LTE-A) cellular network and a WSN is proposed. Quality-of-Service (QoS) issues are assessed by a comparative study of the network delay in tight coupling and loose coupling LTE-A configurations. Simulation results indicate that the network delay in this proposed converged network is acceptable for various M2M applications. Additionally, it is demonstrated through simulation that the energy consumed by the implementation of the proposed protocol is suitable for resource-constrained devices.

Introduction

The authors envision a future where millions of small sensors, actuators, and other devices form self-organizing wireless networks. This vision relies heavily on the emerging *Internet of Things* paradigm, where millions of embedded systems (machines) are able to communicate with, and control, each other without human intervention. These machines should merge seamlessly into people's daily lives resulting in an enhancement of humans' well-being. Various aspects of people's lives will be affected. Major areas of impact will include:

- Healthcare: wireless body area networks will collect health data, for example, vital sign readings, and transmit this to healthcare providers. Healthcare provider computers will process the data and automatically request an ambulance to be sent to a patient's address, as needed.
- Emergency response: wireless sensor networks will collect data about the status of buildings, bridges, and highways. Emergency personnel will be notified if the data collected indicates a potential bridge collapse, a highway collision, etc.
- Supply chain and inventory management: raw material can be tracked from source to retail market in an automated manner. Sensors can determine when raw material is low, and communicate to other machines to initiate the supply chain for restocking, with little, to no, human intervention.

Currently, there is no universal platform that facilitates smooth end-to-end M2M communication via a widely accessible network. This paper attempts to fill this need by proposing a dual-mode gateway for WSN and LTE-A network convergence. The concept of a dual-mode gateway is not novel, and has been proposed in several works [1], [2]. However, a new dual-mode gateway for end-to-end communication between WSN and LTE-A cellular networks is proposed in this paper. The proposed model provides a wireless platform for the convergence of wireless sensor networks and LTE-A cellular networks, which can provide a cost effective and pragmatic solution for M2M communication.

This paper's main contributions are:

i) Exploring the challenges of developing a broad coverage, low cost solution for M2M networks.

ii) Proposing a novel dual gateway interface for WSNs and LTE-A networks.

iii) Demonstrating the feasibility of the proposed dual mode gateway.

Related Work

4G technology was meant to provide what is known as "ultra-broadband" access for mobile devices. LTE advanced was submitted as a candidate for the 4G system to the International Telecommunication Union- Telecommunication Standardization Sector (ITU-T) in 2009. It was approved into International Mobile Telecommunications (IMT) Advanced, and was finalized by the 3rd Generation Partnership Project (3GPP) as a major enhancement of the Long Term Evolution (LTE) standard in March, 2011[3].

Lee et al. [4] discuss the current state of standardization efforts in M2M communication and provide an overview of the network architecture and features of M2M communications in 3GPP, and identify potential issues including physical layer transmissions, the random access procedure, and radio resources allocation. They also proposed a solution to provide QoS guarantees to facilitate M2M applications with hard timing constraints. Attwood et al. [6] proposed a mobility architecture, IoMANETS, for wireless M2M networks. The design provides a fault tolerant solution to the mobility issue by allowing mobile nodes to seamlessly connect to M2M-Internet of Things infrastructure. The assumptions are that fixed nodes are connected to the internet with either IPv4 or IPv6, and that the mobile nodes have IEEE 802.15.4 adapters operating a 6LowPAN IP stack. IoMANETs facilitates the reachability of the device using indirections based on the original global address. The approach proposed in this paper does not focus on fault tolerant connectivity of mobile nodes, but rather on QoS issues in connecting WSN to 4G devices.

The work most similar to the one presented in this paper was proposed by Zhang et al. [2], who examined network convergence between mobile cellular networks and wireless sensor networks. They proposed that the mobile terminals in MCN act as both sensor nodes and gateways for WSN in the converged networks. Comparatively, a separate device to serve as a dual mode gateway and protocol converter (adapter) is proposed in this paper. Additionally, LTE-A is specifically addressed, while Zhang et al. [2] did not specify the cellular technology involved, and they do not guarantee end-to-end connectivity as is done in the proposed converged network. They did, however, provide a useful framework, the current research proposes specific mechanisms, with current technologies, that can be pragmatically implemented and tested.

Igarashi et al. [7] proposed node and network models for achieving internet protocol (IP) based direct communication in M2M networks. Their proposal makes several assumptions, yet it cannot be implemented in its current form. The protocol proposed in the current work makes use of the current state of art WSN technology and LTE-A to implement what is believed to be a feasible end-to-end connection between wireless sensor nodes and LTE-A devices.

LTE Network Architecture

One of the major goals in 4G systems is to provide convergence between all IP-based networks. The appropriate platform for this purpose should integrate network management, security, and QoS. LTE-A satisfies most of the requirements for being a primary platform as a converged networks enabler. It is backward compatible with previous versions of 3GPP standards, non 3GPP networks, and most of the important IP-based networks, such as the Internet. Considering the technical features of the LTE network, elaborated on later in this section, and the potential capabilities of network convergence that LTE-A possesses, it is the authors' belief that LTE-A will play a major role in the future of M2M communication. Although other 4G technologies, such as 802.16m, may be an alternative, the vast majority of subscribers use LTE for wireless communication. As such, there would be little cost for additional deployment, thus making LTE a logical choice.

The LTE system architecture is all IP-based, and, therefore, is designed to support packet-based transmission. A simplified illustration of the LTE system architecture is shown in Figure 1.

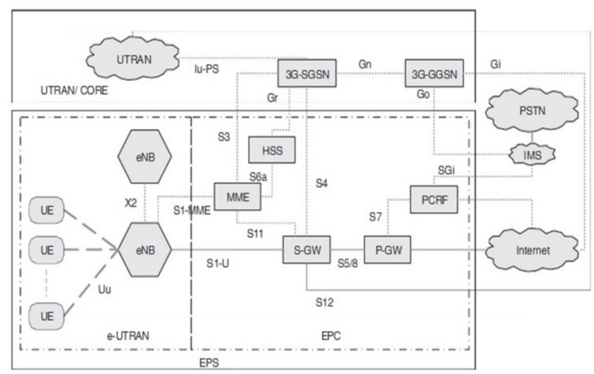

Figure 1. Simplified LTE System Architecture [8]

The two main blocks of the LTE system architecture are the Evolved Universal Terrestrial Radio Access Network (E -UTRAN) and the Evolved Packet Core (EPC). The E-UTRAN is responsible for managing radio access, and provides User Plane (U-Plane) and Control Plane (C-Plane) support to the User Equipment (UE). The U-Plane handles a group of protocols used to support end user data transmission through the network, while the control plane contains a group of protocols for managing the connection between the UE and the networks, and for controlling the user data transmissions. Some of the connection-management functions include handover, service establishment, resource control, etc. The E-UTRAN consists of only the evolved Node Base stations (eNodeBs) or eNBs, where eNB is the LTE terminology for a base station. The EPC is a mobile core network, and its main responsibilities include policy management, security, and mobility management. The EPC consists of the Mobility Management Entity (MME), the Serving Gateway (S-GW), and the Packet Data Network Gateway (P -GW).

M2M Networks

M2M is the concept of connecting machines for enabling the exchange of data. The major goal of the M2M network is both the interconnection of the individual machine nodes and the handling of data transport between the nodes. Regardless of the type of device or data, information typically flows through the network in the same general way: it is gathered from a machine over a link, and received by a controlling system where it can be processed and acted upon.

M2M communication typically is used on four network platforms: smart grids, building automation, healthcare, and automotive. The smart grid is an integration of a power network and an information network, designed to improve the efficiency of power transmission, to enhance the quality of service, and to reduce economic and environmental costs [9]. The primary purpose of home networking is media distribution. However, it can include elements of the smart grid network as described previously. Media distribution systems consist of media storage (media server), media transportation (Wi-Fi, Bluetooth), and media consumption (laptops, smart phones, tablets) [10].

Healthcare M2M networks are used to monitor health conditions, and inform monitored patients, as well as their doctors, of any abnormal conditions that may occur. In some cases, in order to measure health parameters, such as blood pressure, cholesterol, blood sugar level, etc., miniature sensors are implanted inside the human body to form a wireless body area network (BAN). Body sensors are all connected to an on-person gateway, such as a cell phone, which also acts as the collector for all sensor data. Sensors forward data to the cell phone, which in-turn sends it over the cellular network to health monitoring servers.

In recent years, research has been conducted on M2M communications support for vehicular networks. In an automotive application, an M2M network is utilized as a controlling part of the vehicle, known as a controller area network (CAN). In this application, M2M communications are divided into four different categories: traffic management, vehicle telematics, safety & collision avoidance, and entertainment [11].

There are two main restrictions in M2M communications: power consumption and computational capability. In most of the M2M networks, machine type nodes do not have access to a permanent energy source. A battery is the most common power source for a machine type node. Therefore, long distance wireless communication is not practical in M2M communication, since the high power transmission energy needs cannot be supplied with a miniature battery. Also, depending on the application, the computing capability of the sensor nodes may be extremely limited. For example, an implantable body sensor node has very limited memory and processing capability.

M2M and LTE-A Network Convergence

As the demand for M2M is increasing rapidly, M2M communication has become one of the focus areas of the LTE-A project. Within the next several years, M2M communications are expected to exceed the number of H2H (human-to-human) communications. Among other causes, one driver for the replacement of H2Hs by M2M communication is that there are almost 50 billion machines in the world, in comparison to 6 billion people.

In this research, other alternatives, including GPRS/UMTS, were considered. Indeed, there are some applications in GPRS/UMTS networks for the express purposes of metering and security alarm systems that are based on cellular M2M networks [12]. However, in general, current solutions that are based on general packet radio service (GPRS), have been proven to be inadequate for supporting the M2M system. On the other hand, LTE-A, with its higher data rate and larger network capacity, is able to cater efficiently to M2M communications.

The Proposed Dual Gateway Model

In this paper, a tight coupling, dual mode gateway is proposed. Employing a dual mode gateway, for the merging of two networks, enabled the use of specific features and protocols for each individual network. The WSN network employed the IEEE 802.15.4 standard and 6LoWPAN protocol stack, which enabled all the nodes to have distinct addresses. Therefore, the nodes could be addressed individually using the IPv6 protocol. This also facilitated power efficient connections among the resource-constrained nodes in the WSN. The WSN network was connected to the LTE-A network via the dual mode gateway, so that all of the nodes could be controlled and monitored by the LTE system via the gateway.

Merging Network Techniques

There are two major techniques for multiple network integration: loose coupling and tight coupling. In the loose coupling method of inter-networking, networks are interconnected to each other independently. For instance, the first network is connected to the IP network to obtain an indirect link with the second network. Figure 2 depicts the topology of the loose coupling method. In the tight coupling inter-networking method, the first network is connected directly to the second network. In such an inter-networking scenario, the first network's gateway is connected directly to the access layer of the second network. For the LTE-A/WSN model specifically, the WSN gateway can be merged to the UE (User Equipment), resulting in the creation of a dual mode radio. This method is quite efficient in terms of end-to-end latency. However, to the best of the authors' knowledge, prior to this work no dual mode gateway had been designed for LTE-A/WSN convergence. Hence, this dual mode gateway using tight coupling to connect LTE-A cellular and WSNs is proposed. The topology of the tight coupling, dual mode gateway is shown in Figure 3.

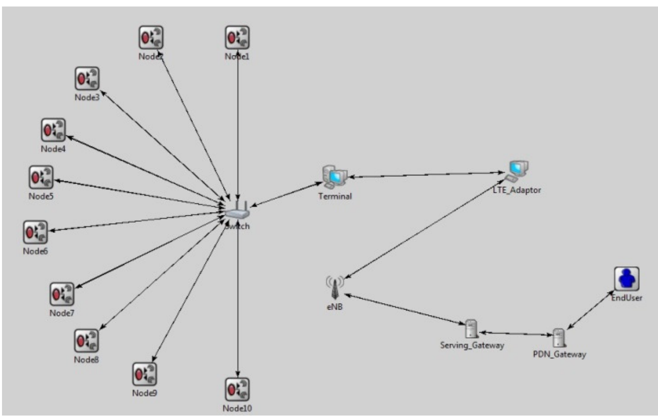

Figure 2. Loose Coupling Topology

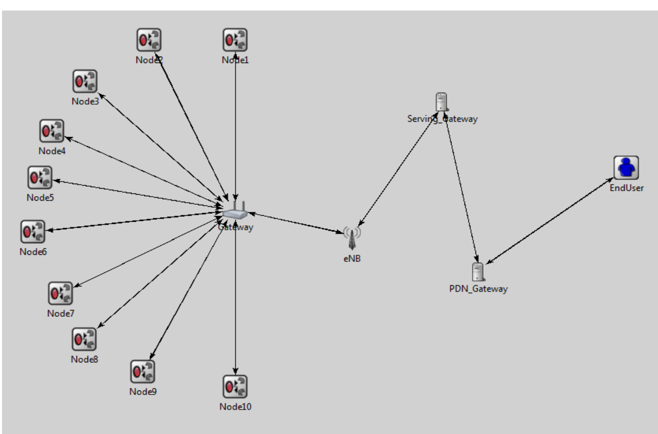

Figure 3. Tight Coupling Method with Dual-Mode Gateway

Protocol Conversion

The main effort of this research work was to establish bidirectional communication between the WSN and LTE-A devices. The protocol stacks of 6LoWPAN and the User Equipment (UE), which is the last node in the access layer of E-UTRAN, are not the same. Therefore, protocol conversion needs to occur in the gateway to make the receiving packets (packets coming from the WSN) compatible with the LTE-A network, and vice versa. The protocol stacks of 6LoWPAN and UE are shown in Figure 4.

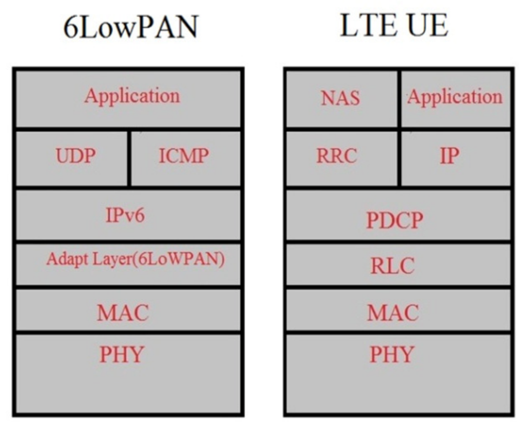

Figure 4. 6LoWPAN and LTE UE Protocol Stack

6LoWPAN technology has defined encapsulation and header compression mechanisms, which allow IPv6 packets to be sent and received over low-power wireless networks, specifically those using the IEEE 802.15.4 standard. The specification developed by the 6LoWPAN IETF group is RFC 4944, and the problem statement document is RFC 4919. IPv6 expands the IP address space from 32 to 128 bits. Also, IPv6 increases the Maximum Transmission Unit (MTU) from 576 to 1,280 bytes. In the IEEE 802.15.4's standard, the maximum packet size is 127 bytes, which perfectly fits in the IPv6 packet. The frame structure of 6LoWPAN is shown in Figure 5.

In addition to the increase in address space that IPv6 has in comparison to IPv4, and the ongoing depletion of available IPv4 addresses, there are several other reasons to prefer IPv6 implementations for resource-constrained devices. First, IPv6 reduces the size of routing tables, and makes routing more efficient and hierarchical. Second, in IPv6 networks, fragmentation is handled by the source device, rather than the router, using a protocol for the discovery of the path's maximum transmission unit (MTU). This technique increases the data transmission speed [13]. Third, in IPv6 the packet header is simplified, which makes packet processing more efficient. Compared with IPv4, IPv6 has no IP level checksum, so the checksum does not need to be recalculated at every hop. This results in comparatively reduced end-to-end latency in multi-hop networks.

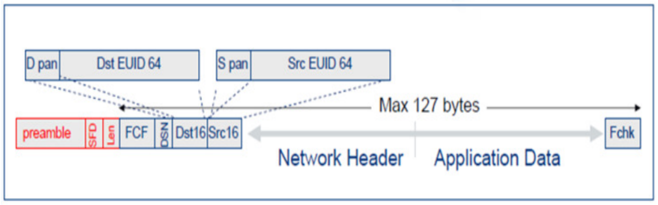

Figure 5. Frame Structure of 6LoWPAN [14]

Internet Protocols are used widely in different wired and wireless networks. Any two heterogeneous networks, regardless of the function, size, or topology, can have connection to each other through Internet protocols. WSNs employing 6LoWPAN over the IEEE 802.15.4 standard, have enabled connectivity to other networks (and the Internet) using IP routing protocols. Due to the restrictions on memory size, power consumption, and computing capability of WSNs, some type of data compression may be necessary. The distinct features of 6LoWPAN make it particularly suitable for use in IP-based M2M networks.

For the remainder of this section, the details of the protocol conversion mechanisms that are executed in the proposed dual mode gateway will be explained. First, consider data packets traveling from the WSN to the LTE-A network. Figure 6 illustrates the protocol conversion of incoming packets (outgoing from the WSN) to the LTE-A network. Since the connection is IP based, there is no need to reach the layers above the IP layer. IP tunnel encapsulation, which is illustrated in Figure 7, is employed to convert the IPv6 to IPv4 in the gateway. This is done in order to ensure the establishment of end-to-end connectivity, since IPv4 is compatible with all of the existing networks. The MAC layer of LTE UE consists of MAC header and RLC payload. The MAC header size is 42 bytes, and the RLC payload is 400 bytes. The maximum size of the packets coming from the WSN is 127 bytes, plus 20 additional bytes for the IPv4 header, which is added in the IP tunneling procedure. This makes the total maximum packet length 147 bytes. As such, the packet coming from the WSN network fits into the LTE MAC layer payload. As can be seen in Figure 1, in the user plane of the LTE network, the received packet from the UE is passed to the eNb. The LTE network's compatibility facilitated the transfer of the incoming packet from the WSN network to other IP-based networks. EUTRAN enabled the exchange of data through the SGW (Serving Gateway) and PGW (PDN Gateway), between the dual mode gateway and the IP-based network.

Second, consider data traveling in the reverse direction, that is, from the LTE-A network to the WSN. The packet frame structure is depicted in Figure 8. Here it is shown that there are three headers, namely the LTE, IPv4, and IPv6 headers. However, the LTE and IPv4 headers are not recognizable by the WSN. Therefore, the packet would be discarded by the WSN if it were delivered in this format. To deal with this issue, the LTE and IPv4 headers are discarded at the dual mode gateway. Both the LTE and IPv4 headers have constant size (42 bytes for LTE and 20 bytes for IPv4), and are easily recognized by the dual mode gateway. The dual mode gateway simple strips 62 bytes off the packets coming from the LTE-A network. The resulting packet frame is shown in Figure 9.

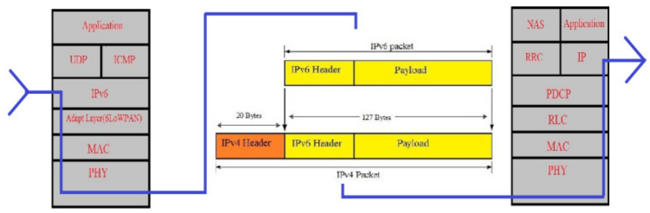

Figure 6. Protocol Conversion of Packets Traveling from WSN to LTE-A Network

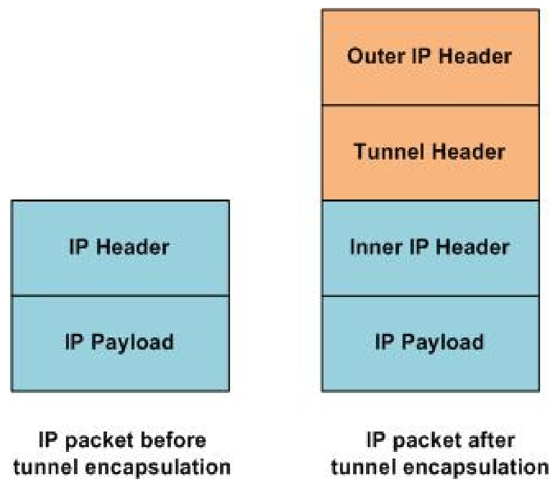

Figure 7. IP Tunneling

Figure 8. LTE-A Packet Frame

Figure 9. LTE-A Packet Frame after Protocol Conversion

In the interest of clarity, a high level, step-by-step description of the dual mode gateway operation is now provided. First, consider the packets traveling from the WSN to an LTE-A end-user. The sequence of events/processes is:

1. A wireless sensor node generates a packet containing the source IPv6 address, the destination IPv6 address, and the payload;
2. The incoming packet arrives at a port on the IPv6 side of the dual mode gateway;
3. The dual mode gateway adds an IPv4 header to the packet;
4. The dual mode gateway sets the IPv4 source and destination addresses;
5. The dual mode gateway adds the LTE header to the packet;
6. The packet is forwarded to the LTE-A cellular network.

Second, consider packets traveling in the reverse direction, that is, from the LTE-A end-user to a wireless sensor node. The steps are as follows:

1. The end user creates a packet containing IPv4 source and destination addresses, an IPv6 destination address, and the payload;
2. The dual mode gateway receives the packet from the IPv4 side interface;
3. The dual mode gateway extracts the LTE and IPV4 header;
4. The dual mode gateway identifies the destination IPv6 address from the IPv6 header;
5. The dual mode gateway sends the packet to the destination node.

Implementing the Dual Gateway Model

In this section, implementation details of the simulation model are presented. First, it provides a step-by-step description of how the M2M to end user connection is established. Second, the establishment of the end-user to M2M (in this case WSN) connection is explained.

The M2M to End User Connection:

i. An M2M node generates a packet;
    The packet includes the following information:
        SrcIPv6
        DstIPv6
        Payload
ii. The incoming packet arrives at a port on the IPv6 side of the dual mode gateway;
    Connection in OMNET++ is made with the following command
        Server.Out[0] -> Client.In [1]
iii. The dual mode gateway adds an IPv4 header to the packet;
    The header is encapsulated using inheritance (a feature of object-oriented programming).
iv. The dual mode gateway sets the IPv4 source and destination addresses;
    The dual mode gateway sets the IPv4 source and IPv4 destination addresses with the following commands:
        pkt->setSrcIPv4();
        pkt->setDstIPv4();
v. The dual mode gateway adds the LTE header to the packet.
    The header is encapsulated via inheritance.

The End User to M2M Connection:

i. The end user creates a packet containing IPv4 source and destination addresses, IPv6 destination address, and payload;
    The following commands are used:
        PKT-> SETSRCIPV4();
        PKT-> SETDSTIPV4();
        PKT-> SETSRCIPV6();
        PKT-> PSETDSTIPV6();
        PKT-> SETPAYLOAD();
ii. The dual mode gateway receives the packet from the IPv4 side interface;
iii. The dual mode gateway extracts the LTE and IPV4 headers;
iv. The dual mode gateway identifies the destination IPv6 address from the IPv6 header;

Modeling Energy Consumption

The proposed solution is feasible in real networks if it can be implemented efficiently on resource constrained M2M nodes, which in this case are wireless sensors. To assess the energy demands of this technique, a scenario is considered in which each wireless sensor node is powered by two AA batteries. This is a popular source of power for commercially available wireless sensor nodes. The length of the 6LoWPAN packet varies between 74 and 127 bytes, depending on the size of the payload. The amount of energy consumed during packet transfer was determined by evaluating the reduction in battery voltage using Equation (1):

$$V_{Battery} = V_{Initial} - \frac{E\left(\frac{J}{B}\right) * Bits(bit)}{C(mAh)} \quad (1)$$

where E is the energy consumption of the node per bit, and C is the capacity of the AA battery. In accordance with

Aslam et al. [15], it is assumed that the value of E was 50 nJ. The capacity of the AA battery typically varies between 400-3000 mAh, depending on battery characteristics. For this research, a value of C=500 mAh was chosen. This was an arbitrary value selected from the typical range.

Results and Discussion

Two sets of simulation studies were conducted. For the first set of simulations OMNET++ was utilized. The main issues investigated were: (i) the reliability of the connections, and (ii) the end-to-end delay in the proposed converged network. The approach consisted of a comparative study of both loose coupling and tight coupling. The network setups for loose coupling and tight coupling are shown in Figures 2 and 3, respectively. In the second set of simulations, analytical estimates of power consumption in wireless sensor networks were used. Additionally, MATLAB was utilized to demonstrate the rate of energy consumption.

Evaluating Reliability and End-to-End Delay

In the simulation, a dual mode gateway that separates the heterogeneous WSN and LTE-A cellular networks was modeled. For simplicity, only 10 nodes were deployed in the WSN. Network size was limited because the main consideration was the establishment and feasibility of end-to-end connections. The reliability of the converged network was limited by the low power, lossy channel of the WSN. IEEE 802.5.4 and 6LoWPAN are among the best options for the low power, lossy network, and both were utilized in these simulations. The researchers were cognizant of potential bottlenecks at the dual mode gateway. This, however, was an issue of scalability, and could easily be addressed by providing multiple gateways. Nonetheless, issues of scalability were not the focus of this research, and, therefore, were not addressed in the simulations. The delay at the dual mode gateway, as a result of buffering and protocol conversion processing, was negligible with respect to the delay caused by the noisy channel of the WSN, and was not taken into account.

The simulation parameters were: end-to-end delay and number of transmitted packets. The bit error rate, the result of collision, was not included, since the main focus was to ensure that the connection was established, rather than to evaluate the noisiness of the channel. The objective was to achieve successful protocol conversion, which is indicated by the ability of packets to travel between the M2M and LTE-A networks.

Figures 10 and 11 depict the end-to-end transmission delay time in loose coupling and tight coupling, respectively. The graphs imply that by using the proposed tight coupling method, the end-to-end delay time can be decreased significantly, from a maximum of 900 milliseconds to 500 milliseconds, which would be a significant enhancement for real time networks or systems with low latency restrictions. Also, this would meet the requirements for various applications of real-time M2M networks [16].

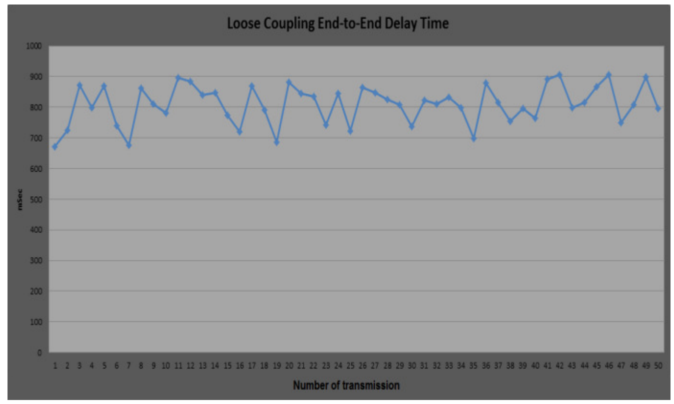

Figure 10. Loose Coupling End-to-End Transmission Delay Times

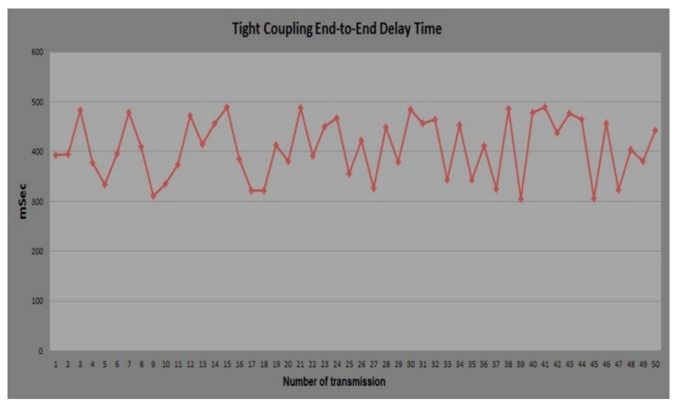

Figure 11. Tight Coupling End-to-End Transmission Delay Times

Evaluation of Power Consumption

Evaluation of power consumption for the protocol was achieved by using MATLAB simulations based on Equation (1). The WSN was configured primarily as a monitoring network, with sensors gathering and sending data via the dual mode gateway to LTE-A devices. The data rate was set at 250kps, as used in the IEEE 802.15.4 standard. A screen capture of the MATLAB simulation is shown in Figure 12. The simulation parameters are: battery voltage, battery threshold voltage, battery capacity, energy consumption, reception rate, and critical interval, which are user defined. In addition, the packet length was included, and its value is consistent with real networks. The MATLAB Graphical User Interface (GUI) simulator that was developed and utilized is shown in Figure 12.

Figure 12. Wireless Sensor Node's Battery Lifetime

Figure 13 implies that the node's operational lifetime is approximately 159 days. One solution to extend the short operational lifetime of the node is to reduce data throughput, and, thus, power consumption, by adding an interval time, for each transmission between the dual mode gateway and the nodes, once a critical battery voltage threshold is reached. The critical voltage threshold was set to 2.6 volts, while a node was considered dead if its battery voltage fell to 2.4 volts. In this scenario, after reaching the threshold voltage, a control packet, 'low life', is sent from the wireless sensor node to the dual mode gateway, indicating that the node's battery life is low. Upon receiving the 'low life' packet, the dual mode gateway adds an interval time between each transmission in order to extend the lifetime of the node's battery. This effectively lowers the data transmission rate of that particular sensor node. Also, it should be noted that, in this scenario, the interval time can be set by the LTE-A device (or end user). In this case, the interval time was set at 1000 milliseconds. Figure 14 shows that after inserting the proposed interval time in the transmission protocol, the node's lifetime was extended to 252 days.

Conclusion and Future Work

In this paper, a model for the convergence of WSN and LTE-A networks was proposed. In the model, a dual mode gateway facilitated end-to-end connection for M2M communication with access to a wide coverage network. The simulation results indicated that this is a viable option that meets the delay and power consumption requirements of various types of M2M applications. For future work, a comprehensive test-bed evaluation of this research project is recommended. Additionally, creating an end-to-end security solution is worth investigation.

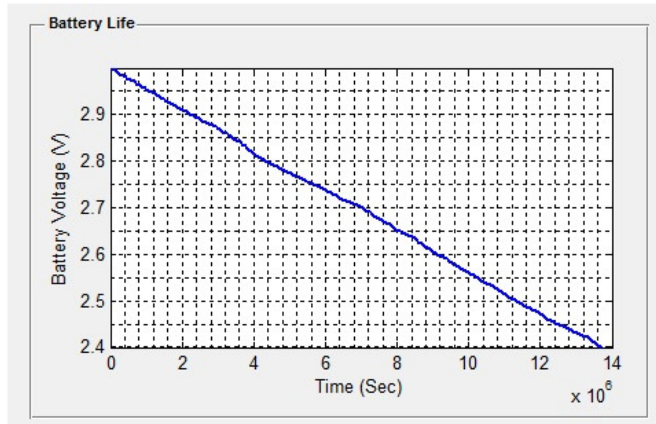

Figure 13. Wireless Sensor Node's Battery Lifetime

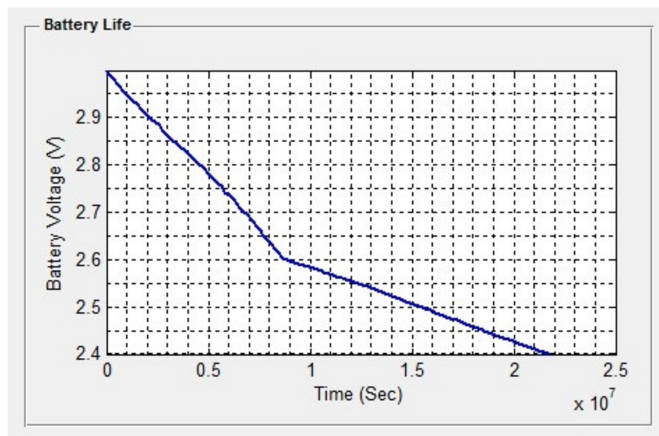

Figure 14. WSN Battery Lifetime after Employing Interval Time

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