Heterogeneous Wireless Sensor Networks Using CoAP and SMS to Predict Natural Disasters

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Abstract—Even in the 21st century human is still handicapped with natural disaster. Flood is one of the most catastrophic natural disasters. Early warnings help people to take necessary steps to save human lives and properties. Sensors can be used to provide more accurate early warnings due to possibilities of capturing more detail data of surrounding nature. Recent advantages in protocol standardization and cost effectiveness of sensors it is possible to easily deploy and manage sensors in large scale. In this paper, a heterogeneous wireless sensor network is proposed and evaluated to predict natural disaster like flood. In this network CoAP is used as a unified application layer protocol for exchanging sensor data. Therefore, CoAP over SMS protocol is used for exchanging sensor data. Furthermore, the effectiveness of the heterogeneous wireless sensor network for predicting natural disaster is presented in this paper.

Keywords—CoAP; IEEE 802.15.4; 6LoWPAN; SMS; Belief Rule Base Expert System

I. INTRODUCTION

Natural Disaster like flood will cost up to \$1 trillion per year by 2050 for coastal cities [1]. Furthermore, among different types of natural disasters (e.g. earthquake, hurricanes, tornadoes and other geologic process) flood is considered as the most devastating natural disasters [2]. Typically flood and its aftermath causes the highest number of human casualties and economic damage in comparison to other natural disasters. As for example, due to the overflow of water from Huang Hu River a terrible flood occurred in China in 1931. This flood is recognized as one of the most destructive flood of twentieth century, which is known as Yellow River flood. This flood caused eighty-eight thousand square km of land to be completely flooded with water, eighty million people were rendered homeless and around four million people died. Recent floods in Germany and France during June 2016 caused one billion euros worth of damage. Therefore, an efficient and effective flood prediction is required to provide a better flood warning system. Flood prediction is performed using several types of data. These are: the amount of rainfall, the rate of change in river flow,

rainfall duration, river water level, the features of a river's drainage basin and human activities. These data can be characterized into two groups. One is quantitative in nature and another is qualitative in nature. Henceforth, Belief Rule Base Expert System (BRBES) [3], a single integrated framework for processing both qualitative and quantitative data, is used for predicting floods from sensor data in this research work.

Different types of data those are necessary for predicting flood can be easily collected from the nature by using sensors and send these data to a server for predicting flood. Nowadays, due to the low cost and protocol standardization [4], low-powered sensors are easily deployed in large scale for different systems. Nevertheless, as sensors are deployed in harsh environment an efficient wireless sensor network (WSN) is needed for collecting and transmitting data to the servers.

In this paper, a heterogeneous WSN is developed based on the WSN architecture proposed in [5]. The heterogeneous wireless sensor network is based on standard protocols like, IEEE 802.15.4, IPv6 over Low Power Wireless Personal Area Networks (6LoWPAN), Constrained Application Protocol (CoAP), 3G and SMS. For the physical layer connectivity among sensors IEEE 802.15.4 protocol is used. In network layer 6LoWPAN is used, as it provides support of IPv6 and better resource management for resource constrained devices. Furthermore, UDP or SMS is used in transport layer. CoAP is used for exchanging data between sensors and server, as it is one of the popular application layer protocols for resource-constrained device. Moreover, the WSN network needs to be resilient to sustain harsh environment and support remote locations. Therefore, mobile networks were also included as backhaul connectivity in corporation with typical WLAN and LAN.

This paper studies performance of the WSN in an Arduino [6] based platform and is organized in the following way. Section 2 covers related work, while Section 3 describes standards and technologies. The proposed WSN system architecture is described in Section 4. The experimental setup

and the results are reported respectively in Sections 5 and 6. Furthermore, Section 7 concludes our paper and indicates future work.

II. RELATED WORK

Flood prediction systems are in use in many parts of the world. Most of them are not able to predict flood accurately as well as they are unable to generate warning or alert long time before the flood occurrence [7]. However, using WSN the flood prediction system becomes easier to design with high accuracy and faster response [8].

Sakib et al. [9] proposed a flood alert system based on neuro-fuzzy controller using WSN where IEEE 802.15.4 protocol used as the WSN protocol. The sensor information is sent to the Raspberry PI based gateway, which is later sent to the central server. The flood alert is generated based on historical and sensor data using neuro-fuzzy controller method in the central server and the alerts are showed in a GIS Map. However, the suggested WSN do not take into account of the redundancy of connectivity between Raspberry PI based gateway and central server. Moreover, the connectivity between gateway and the central server needs to be resilient and stable. It also needs to be easily deployable.

Mitra et al. [10] proposed a flood forecasting system by using WSN. The proposed system uses ZigBee for the WSN while Artificial Neural Network (ANN) is used to support forecasting of flooding in the river basin. The WSN is based on mesh topology of ZigBee to provide alternative routes to the sensor nodes. Proposed network architecture uses GPRS for transmitting data to the central server. However, GPRS connectivity might not be available in remote locations, which might hinder the connectivity. Moreover, the sensor nodes are built using MSP430 that are comparatively costly device and ZigBee is a proprietary protocol, which hinders the interoperability.

Han et al. [11] proposed a hydrology monitoring system using ZigBee technology with a star topology. Authors propose to use ZigBee for communication among sensors and GPRS technology for transmitting data to data receiving center. However, any flood prediction mechanism is not presented in their work. Ancona et al. [12] described a flood monitoring system with energy efficient sensors for measuring amount of rainfall and river gauges. They took into more consideration of the new IoT paradigm like cloud computing and data streaming.

Ahmed et al. [13] described Ad hoc WSN architecture for disaster survivor detection. According to the authors, this WSN architecture is energy efficient and sensors are easily deployable.

Moreover, most of the discussed WSN networks did not propose any application layer protocol. Nenad et al. [14] presented an implementation and evaluation of CoAP over SMS as M2M communication. The research paper shows that the increase traffic of SMS leads delaying in SMS delivery time. However, sensors data are not always time critical therefore, delay in delivery time is not very important. Moreover, SMS provides more network coverage of locations, as the mobile network is available in remote areas.

From the above discussion, it is evident that researchers have proposed different protocol based on WSN networks. These WSN architectures mostly concern on redundancy on sensor communication. However, redundancy in backhaul communication is not considered [9], [10], [11], [12] and [13]. Therefore, our proposed architecture considers two types of backhaul communications. These are Wi-Fi/LAN and SMS based backhaul communications. Moreover, the proposed architecture also uses CoAP as an application layer protocol.

III. STANDARDS AND TECHNOLOGIES

This section describes technologies and standards necessary for a heterogenous wireless sensor network. Different protocols of each network layer are discussed below.

A. IEEE 802.15.4

In Wireless Sensor Networks one of the most accepted protocols for Medium Access Control Layer (MAC) is IEEE 802.15.4. The main characteristics of IEEE 802.15.4 are low power, low cost, short distance. 802.15.4 provides specification for physical layer and MAC layer. It operates on one of three possible unlicensed frequency bands:

- 868.0–868.6 MHz for Europe
- 902–928 MHz for North America
- 2400–2483.5 MHz for worldwide use

IEEE 802.15.4 defines two types of network nodes. The first one is the full-function device (FFD). It works as the coordinator of a personal area network or function as a common node. Second one is the reduced-function device (RFD). These devices have very low capability and usually act as an end node in WSNs. They communicate with FFDs only.

Accordingly, IEEE 802.15.4 WSNs can be configured as either peer-to-peer or star networks. However, every WSN should have at least one FFD, which work as the coordinator of the WSN.

B. 6LoWPAN

Internet Protocol (IP) is the most used and adopted protocol in the networking. At the beginning WSN community wanted to develop separate protocols. However, nowadays WSNs community is more interested to use IP protocol for the WSN. Therefore, a new standard was introduced to facilitate IPv6 to WSN, named "IPv6 over Low Power Wireless Personal Area Network" or 6LoWPAN. It uses IEEE 802.15.4 as physical and MAC layers. The advantages of 6LoWPANs are their popularity, applicability, bigger address space, and stateless address configuration [11]. The MTU size of IPv6 is 1280 octets, which is higher than the IEEE 802.15.4 frame. Therefore, fragmentation was introduced. A routing protocol is also defined for the low-cost devices named RPL. It allows easy configuration and maintainability for dynamically formed network.

C. CoAP

The Constrained Application Protocol (CoAP) is an application layer protocol designed for low resource devices with low computation, low memory and low power requirement. The main feature of this protocol is less overhead

and easy parsing. It also provides support for Uniform Resource Identifier (URI), content-type and resource discovery of known CoAP service. CoAP also has simple caching mechanism. It also provides subscription and push notification for a resource. Like the HTTP protocol, it uses a request/response infrastructure and supports web services. It operates over the UDP protocol with its own easy session control and retransmit schema. It has four types of messages. These are Confirmable, Non-Confirmable, Acknowledgement and Reset. It uses only a 4 bytes header.

D. SMS

Short Message Service (SMS) provides text-messaging service for mobile handset. It originated from radio telegraphy in radio memo pager. Global System for Mobile Communications (GSM) first standardized SMS in 1985, which is now maintained in 3GPP as TS 23.040. A conventional SMS message can have 160 chars (encoded by 7-bit character set), 140 chars (encoded by 8-bit character set) and 70 chars (encoded by 16-bit for Unicode character set). Therefore, the size of SMS is 140 bytes. Messages bigger than 140 bytes are grouped into a 134 bytes message with 6 bytes of User Data header (UDH) for each message, which is called concatenated SMS. From sender, mobile handset the SMS is sent to a short messaging service center (SMSC) and later on delivered to recipient's mobile handset using a mechanism called "store and forward". If the recipient is not reachable the message is stored and queued in SMSC and later retried to deliver to recipient. Mobile Application Part (MAP) of the SS7 protocol is used for sending and receiving short messages among the SMSC and the user handset. SMS from mobile handset is called SMS-MO and SMS from SMSC to mobile handset is called SMS-MT.

IV. SYSTEM ARCHITECTURE

In this section, the proposed heterogeneous wireless sensor network architecture is described. The main aim of this architecture is to provide an interoperable, non-vendor-specific, and cost effective system for collecting data from the low-cost sensor nodes distributed over a vast geographical area and ensure the transmission of data from the sensor nodes to the central server. The proposed heterogeneous WSN uses IEEE 802.15.4 as physical and MAC layer, 6LoWPAN as network layer, UDP or SMS as transport layer and CoAP as application layer for communication among sensor and sink nodes. IEEE 802.15.4, 6LoWPAN and CoAP are interoperable, non-vendor-specific protocols. Moreover, these protocols are designed for resource constrained sensor devices. One of the main issues of sending data from the sensor nodes to central server is the non-availability of Wi-Fi/LAN connectivity in the remote places. Therefore, a combination of mobile network and Wi-Fi/LAN is used in proposed WSN network as backhaul connectivity. Moreover, the heterogeneous wireless sensor network system is developed using open source platforms and standardized protocols.

The proposed heterogeneous WSN is presented in Fig. 1. Sensor nodes are deployed over vast geographical near the river basin for collecting data using different sensors like water level, temperature and humidity sensors. Star topology is used for

communicating among sensors. Sensor nodes sense the environmental data after certain interval and send the data to sink node using CoAP messages. Here, sensor nodes act as CoAP client and sink nodes as CoAP server. Thereafter, sink nodes send the data to the central server based on the available backhaul connectivity. There are two types of sink nodes based on the backhaul connectivity. These are SMS sink node and Non-SMS sink node. SMS sink nodes send data using SMS over the mobile network to a SMS gateway. Non-SMS sink nodes use HTTP Rest protocol for sending data using IPv4 or IPv6 over traditional Wi-Fi/LAN networks to central server. CoAP message are sent over SMSs instead of UDP to a SMS gateway by the first type of sink nodes. Usually, a CoAP messages fits into one SMS of 14 bytes with 4 bytes of CoAP header and 10 bytes of payload containing sensor data. If sensor data are more than 10 bytes than the data can be distributed over several separate SMSs. In that case, CoAP options field can be used for sequencing the split sensor data. Henceforth, SMS gateway sends the data to central server by HTTP request using IPv4 or IPv6. Belief Rule Base Expert System collects data from the central server to predict floods for a specific geographical location.

Fig. 1. Architecture of heterogeneous wireless sensor network

Arduino based popular open source hardware platform is used for developing the WSN. Four main hardware components were used to develop the scenario. These are Arduino Mega, XBee Shield, XBee Series 1 module, Arduino Ethernet Shield, Adafruit FONA 808 Shield and DHT11 sensor.

Arduino Mega [16] is an ATmega2560 microcontroller based embedded device. It has flash memory 128 KB of which 4 KB used by boot loader, SRAM of 8 KB and EEPROM of 4 KB. Arduino Mega has fifty-four input/output pins. Among these pins 14 can be used as PWM outputs, 16 analog inputs, 4 UARTs. It also has a USB connection, a power jack, an ICSP header, and a reset button.

XBee Series 1 [18] is a RF module to communicate with other nodes using 802.15.4. It operates on 2.4 GHz frequencies with 250 kbps data rate. Indoor coverage range is up to 100 ft. (30 m) and outdoor range is up to 300 ft. (90 m) for the module. It uses 802.15.4 with ACK in MAC mode. The module uses three retries as default while transmitting.

XBee Shield [17] is used to connect Arduino Mega and XBee Series 1 RF Module. The shield breaks out each of the XBee's pins to a through-hole solder pad. XBee Shield also

provides female pin headers for use of digital pins 2 to 7 and the analog inputs that are covered by the shield. The XBee shield has a switch, which determines the serial communication between the microcontroller and FTDI USB-to-serial chip on the Arduino board.

Arduino Ethernet Shield [19] permits Arduino Mega to use LAN connectivity. It uses Wiznet W5500 chip with 32K buffer, which provides a built-in support for TCP and UDP of Internet Protocol (IP). It also can maintain eight simultaneous socket connections. Arduino Ethernet Shield connects with Arduino Mega using SPI ports.

Adafruit FONA 808 Shield [20] helps in sending SMS from Arduino Mega. It uses SIM808L chipset for communicating with mobile network. Adafruit FONA supports Quad-band (850/900/1800/1900MHz) of global GSM network using any 2G SIM. It also has an onboard LiPoly battery charging circuitry and GPS tracker. AT commands are used for sending and receiving SMS.

DHT11 [21] is used as temperature and humidity sensors. It uses a capacitive humidity sensor and a thermistor to measure the surrounding air, and outputs digital signal. The sensor operating voltage is 3-5 V DC. Temperature measurement range is 0-50 °C (± 2 °C) and Humidity measurement range is 20-80% RH ($\pm 5\%$ RH). The DHT11 sensor has three pins, which are connected with the 5V, GND and digital PIN 24 of Arduino Mega.

A sensor node consists of Arduino Mega, temperature and humidity sensors (DHT11), XBee Shield and XBee Series 1.

Fig. 2. Sensor node

SMS sink nodes, which send sensor data to SMS gateway using SMS, consist of Arduino Mega, Adafruit FONA 808 Shield, XBee Shield and XBee Series 1 Module. It acts as CoAP server for the sensor nodes and CoAP client for the SMS gateway.

Non-SMS sink nodes are used to send data over LAN to the central server. The sink node is composed of an Arduino Mega, Arduino Ethernet Shield, XBee Shield and XBee Series 1 Module.

The deployments of these devices are not quite easy, as different standalone components need to be interfaced and configured to work with each other. Perhaps the biggest drawback is the power consumption as the Arduino is a multipurpose device for building prototype, not designed only to

operate in battery efficient conditions. However, the Arduino based devices are easily available and comparatively cheaper.

Fig. 3. Sink Node

In summary an interoperable, non-vendor-specific, and cost effective heterogeneous WSN is presented. The heterogeneous WSN uses multiple backhaul connectivity for transmitting data to central server. Moreover, the CoAP messages are ported into SMS for interoperability.

V. EXPERIMENTAL SETUP

For evaluating the proposed heterogeneous WSN, an experimental setup was created using two sensor nodes, one SMS sink node, one Non-SMS sink node, SMS Gateway and central server. Fig. 4 and Fig. 5 present the connectivity diagrams and the protocols used by different nodes. Sensor Node s1 and s2 periodically send data either to SMS sink node or Non-SMS sink node. One of the sink nodes was used at a time for the better understanding the behavior of the backhaul connectivity between sink node and central server.

Fig. 4. SMS based WSN architecture for experimental setup

An analysis of sensor data delivery time from sensor node to central server was performed to evaluate the performance of WSN. From each sensor node 30 CoAP put messages are sent to central server after certain interval through two different types of sink node (i.e. SMS sink node and Non-SMS sink node). Moreover, an analysis of round trip time of different sizes of packets was performed between sensor node and sink node. From each sink node 30 CoAP PUT messages were sent to both sensor nodes within interval 25 seconds. The message

Fig. 5. Non-SMS based WSN architecture for experimental setup

packet size started from 29 Byte to 84 Byte. The packet size was increased by 5 bytes after every 30 messages.

Arduino based IPv6 Stack; named μ IPv6 provided by Telecom-Bretagne [22] is used for performing the analysis. μ IPv6 is based on the Contiki IPv6 stack and implements 6LoWPAN, UDP, CoAP and RPL. A delay was introduced before the sensor nodes reply back to the sink node to emulate the real-life sensor deployment scenario.

VI. RESULT AND DISCUSSION

The main motivation of the proposed WSN architecture is to ensure connectivity and propagation of sensed data towards central server. Most of the previous works [9][10][11][12] proposed single type of backhaul connectivity based on either Wi-Fi or Cellular connectivity. However, our proposed architecture uses combination of Wi-Fi/LAN and Cellular connectivity, which ensures connectivity even in remote places. Moreover, the proposed WSN architecture uses non-proprietary protocols such as IEEE 802.15.4, 6LoWPAN and CoAP protocols and also uses CoAP as an end-to-end application layer protocol for sending sensor data.

For evaluating the heterogeneous WSN architecture two types of evaluation were carried out. One is data delivery time and another is round trip time of different packet size data. In Fig. 6, a comparison of sensor data or message delivery time for different throughputs of messages is presented. Dotted and straight line show the average delivery time of sending messages from sensor s1 and s2 through SMS Sink node and Non-SMS Sink node respectively. It can be observed from the Fig. 6 that with the increase of throughput the message delivery time remains similar. Moreover, the time required for delivering of message to central server through SMS is higher than LAN due to the conversion of SMS to HTTP by the SMS gateway. Average message delivery time through SMS sink node and Non-SMS sink are twelve seconds and two seconds respectively. The increase of the message delivery time through SMS sink node was due to the longer time required by the SMSC and processing time of SMS Gateway.

Furthermore, the rate of success full message delivery decreases with the increase of the messages per minute as, it is evident in Fig. 7. The dotted line and straight line show the successful message delivery rate of sensor s1 and s2 through SMS Sink node and Non-SMS Sink node respectively. The success rate of message delivery through the Non-SMS sink node is comparatively higher than the SMS Sink node.

Fig. 6. Message delivery time vs throughput

The lower success rate of SMS sink node is due to the higher time required by the node to process and send SMS to SMS gateway and lack of threading or parallel processing in Arduino Mega. The processing time of received data from sensor node and sending messages to server on an average is five seconds at the SMS sink node where as Non-SMS sink node requires one seconds. However, the success rates of message delivery time through the both sink nodes are almost same for the two messages per minute.

Fig. 7. Message success rate vs throughput

Fig. 8 below shows the round-trip times vs. packet sizes. The straight line shows the result for sensor node s1 and the dotted line shows the result for the sensor node s2. The graph generally shows that the round trip increases with the packet size. It is seen in the graph that for first two packet sizes the round-trip times are varying. This might be influenced by the random radio traffic conditions. For larger packet size a linear growth is observed because of the increase of processing and transmitting time.

Furthermore, evaluations of the delivery time of concatenated SMSs were also carried out with two messages per second; as it is evident in Fig. 7 that SMS sink node has best success rate for two messages per second. The average time of sending two concatenated SMSs were thirty-one seconds. The delivery time of concatenated SMSs increased linearly with the number of concatenated SMSs.

In summary, an evaluation of the proposed heterogeneous WSN architecture is carried out in this research work. The WSN architecture was measured over message delivery time, message delivery success rate and round trip of messages. It is observed from the experiments that even though message delivery time is higher for the messages going through SMS sink nodes; the success rate is similar like the Non-SMS sink node and for specific two messages per minute.

Fig. 8. Round trip times vs packet sizes

The SMS based backhaul provides an opportunity to deploy WSNs in remote places where there is a lack of Wi-Fi/LAN based infrastructure. As for example, remote places of Bangladesh lack proper infrastructure of Wi-Fi/LAN. Therefore, the proposed SMS based backhaul connectivity approach will provide more flexibility to deploy than from other approaches mentioned in Section 2. Furthermore, a network resilient WSN architecture is proposed using low cost resource constrained devices for gathering data for flood prediction.

VII. CONCLUSION

Flood is one of the most catastrophic natural disasters. Predicting flood will help to prevent the loss of human life and economic losses. Low cost resource constrained sensor devices help us to gather more precise data for predicting flood. Therefore, a heterogamous WSN architecture is proposed here for deploying sensor and gathering data in remote areas based on non-proprietary hardware and protocols. Henceforth, the data received from the sensor are used by the BRBES for predicting flood. Moreover, an evaluation of performance of the proposed architecture is also carried out in this research work. The results showed that the delivery time of data through SMS sink node is higher than the Non-SMS sink node. However, the success rate of delivery of data was almost equal for two messages per second for SMS sink node and Non-SMS sink node. In addition to this, the variation of success rates and delivery time with increased throughput was unforeseen. Most likely this is due to randomness of radio traffic and lack of parallel processing in Arduino platform. As future work, we intend to further investigate the operation of the medium access control layer and how it might affect the performance of 6LoWPAN. More detail evaluation of the proposed WSN architecture needs to be carried out with large number of sensor nodes and different types of sensor hardware platforms.

ACKNOWLEDGMENT

This work has been supported by the Swedish Research Council under grant 2014-4251.

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