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A Low Power Wireless Sensor Network for Gully Pot Monitoring in Urban Catchments

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***Abstract* —Sewer and gully blockages are the main cause of residential sewer flooding in the UK. A low-cost and power efficient wireless sensor mesh networking communication system has been designed, developed and implemented to provide adequate warning on potential blockage incidents to prevent sewer failure. By monitoring the water level of the gully pot at each residential property, the water company will be proactively informed of the best course of actions to eliminate the causal problem, i.e. blockage and leakage within the sewer infrastructure. Hence, the number of residential sewer flooding and pollution incidents can be reduced. The prototype system consists of eight Zigbee based wireless sensor nodes and a GPRS enabled data gatherer. Each Zigbee sensor node comprises of a radio transceiver, a data acquisition board and an acoustic sensor probe. Field trials were carried out in an outdoor scenario to cross-validate the theoretical and practical performance of the prototype system. The results in terms of durability of sensors, sensor nodes and gateways and reliability of communication under real operational conditions and within a typical inner city urban environment are discussed. The problems encountered and solutions to tackle these problems were addressed.**

Index Terms — **Wireless mesh networking, Zigbee, GPRS, residential sewer flooding**

I. Introduction

The UK's sewer network is around 300,000 km long and is the largest asset within the water industry. The deterioration of this ageing and primarily underground system has presented significant challenges to water companies. Moreover, the imposition of the 1999 Water Industry Act [1] and the Water Act of 2003 [2] by the government places a legal responsibility on the water companies not only to maintain the structural and operational reliability of the sewer system, but also to reduce progressively its risk of failure. In order to meet these obligations and to become more operationally efficient, the UK's water industry is currently investing in excess of £200 million per annum [3]. As a result, significant efforts have gone into research and development activities in all water companies seeking more advanced and cost-effective methods to properly monitor, maintain and rehabilitate their sewer infrastructure.

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Sewer flooding and pollution incidents are the most problematic issues encountered by water companies. Their performance is regulated by the Office of Water Regulation (OFWAT) via a number of performance indicators. Failure to meet these indicators can result in severe financial penalties. One of these indicators "DG5" deals with the number of properties that suffer from or are at the risk of sewer flooding. Given the significant impact on customers that suffer sewer flooding OFWAT requires companies to take action to reduce the number of residential flooding incidents. Last year, 4348 residential properties in England and Wales suffered sewer flooding [4]. Sewer and gully blockage are the major causes of both flooding and pollution [4]. Traditionally, water companies adopt both proactive and reactive approaches to tackle this problem. In the proactive approach, manual regular checks are carried out. In the reactive approach, a service support team is called upon in response to a customer's report on problems associated with a sewer blockage, which may eventually lead to flooding. Current monitoring involves mainly Closed Circuit Television (CCTV) inspection and is expensive and limited in its frequency. It should be remembered that around 24.5 millions properties are connected to the public sewer network and only 0.0177% suffer flooding [4]. A key issue with blockage formation is its intermittent nature so that current inspection technology may not be efficient enough to detect sudden incidents or serious blockage which may have accumulated before the routine check and which may lead to a flooding incident.

Currently, many water companies have deployed telemetry systems to replace some of the manual operations involved in data collection. These systems require extensive cabling for Public Switch Telephone Network (PSTN) and power. As a result, telemetry systems cannot be deployed widely over a large catchment area because of the cost. If dispersed, infrequent faults are to be monitored then it is imperative to find alternative economical methods to perform the data collection and transmission.

Low cost wireless sensors may be the only cost-efficient option to replace traditional visual CCTV inspection which is infrequent and costly. These wireless sensors could be deployed over an extensive part of the network and provide early warning of impending failure offering time for maintenance teams to prevent service or regulatory failure.

Wireless Sensor Network (WSN) has been used by numerous researchers due to its successful implementation in a wide range of government, military, commercial, transportation and healthcare applications [5-10]. Research literature on sensor networks, architectures, protocols, signal processing and hardware, is extensive [10-14]. The rapid development of wireless sensor technologies indicates the possibility to change radically the existing methods of data collection and monitoring that are used by sewer network operators. This can be achieved via the deployment of massive, self-organised sensor networks that able to convey real or near real-time data to managers who can then respond appropriately.

This paper presents the development and validation of the deployment of sensors at pilot scale within a residential urban area. The aim of the study was to demonstrate that water level data collected at gully pots (the most basic entry to the sewer network at a residential property level) can be used to reduce residential flooding incidents. Both Zigbee based transceiver and acoustic sensor probes, were installed in residential gully pots in a high density residential environment to regularly monitor the water level and so provide warning of damage or potential flooding.

It is well-known that high radio signal attenuation can be experienced when the radio transceiver is operated in a lossy urban environment. To alleviate this problem, low power adaptive mesh network topology was implemented to enhance the radio coverage and establish a reliable communication link. Throughout the field trial, the performance of the proposed system in terms of durability of sensors, sensor nodes and gateways and reliability of wireless communication under real operational condition was characterized. Problems encountered and lessons learned from the sensor deployment process are discussed. The results of this field trial give sufficient information to the collaborating water company to evaluate the success of the system based on cost-benefit criterion so that planning for future large scale sensor deployment could be made.

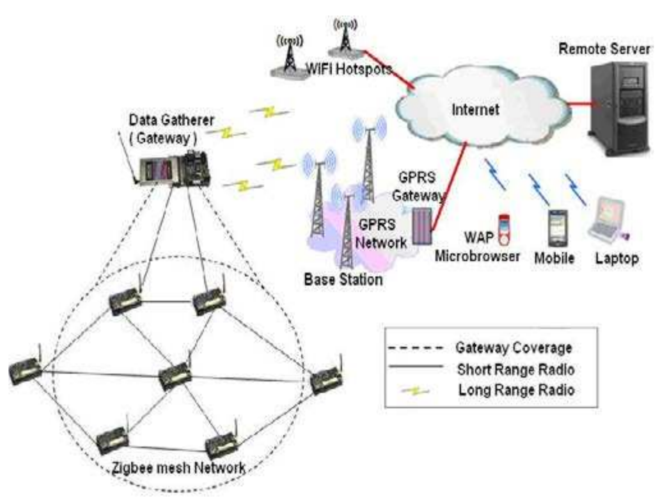

Fig. 1: Wireless Sensor Network System Architecture.

II. System architecture and Design methodology

Fig. 1 describes the architecture of the proposed low power mesh network wireless sensor system. This system is designed to monitor the water level in gully pots connected to the sewer network. Zigbee based short ranged WSN was selected for this application because of its low cost, low data rate, low power consumption, simple communication infrastructure, low latency and capability to support one master and up to 65000 slave control units [15-17]. The system consists of sensor nodes, a data gatherer and a remote user terminal. Each sensor node comprises of a radio transceiver, data acquisition board and acoustic sensor probe. Communication between the sensor nodes and the data gatherer is via the Zigbee protocol. The data gatherer communicates with the remote user terminal via either the Ethernet connection or WiFi/GPRS access, depending on the type of user terminal being used. Apart from providing the interface between the sensor nodes and the user terminal, the data gatherer also acts as a web-server. Once the sensor nodes received the digital sensor signal via the interface circuit board, by implementing a mesh network communication configuration, this WSN allows for continuous connections and reconfigurations around blocked paths. This results in hopping from sensor node to node until a connection can be established with the data gatherer. It should be noted that the mesh networks posses the self-healing capability that will operate even when a node breaks down or a connection fails. As a result, it forms a very reliable network. As soon as the data arrived at data gatherer, it is stored in the web-server database. The data is then retrieved by the user terminal and a graphical output of the water level and the battery level are displayed through an application interface.

A. *Crossbow Mica2 Sensor Node*

A number of commercial Zigbee compliant wireless sensor platforms have emerged in recent years [18]. Not all of them are suited to this work due to the inclusion of proprietary communication protocol and the lack of Ethernet IP connection from the gateway node in some of these sensor platforms. The advantages associated with employing such a commercial wireless sensor system include immediate “out-of-the-box” operation, availability of technical support from the platform manufacturer, and low unit costs. Nevertheless, constructing and distributing a wireless sensor networks over a large scale monitoring application has only become possible with some fundamental advances in the enabling technologies. The most important advance has been the miniaturization of hardware. Smaller feature size in chips has driven down the power consumption of the basic components of a sensor node to a level that means that the construction of battery powered WSNs can be contemplated. This is particularly true for the microcontrollers and memory chips, but also, the radio modems which are responsible for the wireless communication. Reduced chip size and improved energy efficiency is accompanied by reduced cost, which is necessary to make the deployment of large numbers of redundant sensor nodes affordable.

By comparing the existing Zigbee-compliant wireless communication system manufactures [18], it was found that Crossbow [19] is the only supplier which is capable of furnishing the most complete wireless communication system for this monitoring application. In terms of hardware, a Zigbee transceiver offered by Crossbow consists of a radio module onto which different types of sensor can be attached through a standard 51-pin expansion connector. In terms of software, Crossbow motes run on an open source operating system called TinyOS [20]. TinyOS is an event driven operating system that handles power consumption and radio networking. It is built to enable the user to focus on writing applications to acquire and react to sensor data. It distinguishes itself from other operating systems by its explicit support of ad-hoc networking and multi-hop data transmission. The concept behind TinyOS is to minimize power consumption and extend battery life. This was seen as a very important consideration in this study. In this work, the Mica2 mote [21] from Crossbow, which consists of CC1000 radio, Atmega 128L processor, 128kB Flash, 4kB RAM and 10 bits ADC, is used.

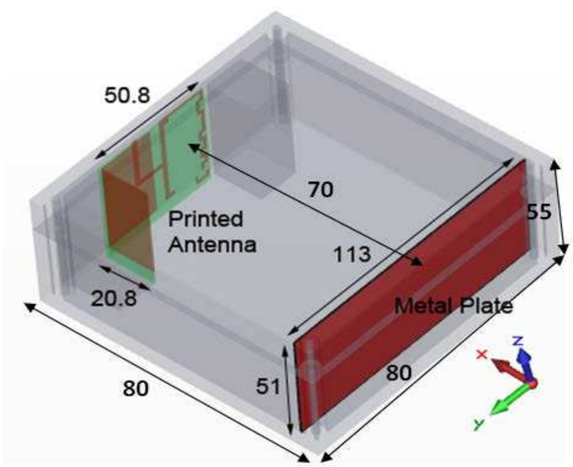

Fig.2: Proposed embedded antenna module. (Dimensions are in mm)

The open source Xmesh reliable route protocol [22-23] was employed for this application. By implementing this protocol, the sensor nodes are time synchronized within ±1 msec. They wake up eight times per second, time synchronized, for a very short interval to signal over the noise background. In order to keep the minimal power consumption in the sensor nodes, a low power listening (LPL) mode was enabled on the radio module (CC1000) of the Crossbow transceiver [24]. The LPL mode forced the radio module to go into sleep (extreme LPL) mode, instead of turning off the radio completely. This will ensure that the sensor node has high latency when it is activated by a neighboring node. Moreover, the route update interval is also set at a lower rate so as to conserve significantly the power and extend the battery life in this implementation.

B. Embedded Antenna design

Conventional low power mesh network of wireless communications sensors suffers from limited communication range. In order to achieve an optimum reasonable communication distance with minimum power consumption, the antenna plays an important role in implementation of the wireless sensor network (WSN). In this application the transceivers were located at or slightly below ground level and the urban environment had a number of physical obstacles, e.g. property boundary walls.

Antenna design is one of the most challenging tasks for electronic device manufacturers in order to develop a miniaturized antenna module within the available volume of the mobile terminal casing. In this application the whole sensor unit had to be “hidden” within the gully pot, so that there was a functional need to minimize the casing volume. It is expected that all new generation antennas are capable of providing a wide impedance bandwidth, acceptable gain and consistent radiation patterns throughout the existing wireless communication frequency spectrum. Due to its attractive features including low cost, intrinsically light, low profile, and compatible with the integrated circuit environment, printed monopole antennas [25-27] are becoming popular for wireless communication applications. Bandwidth enhancement and size reduction techniques on this type of antenna are well documented [25-26]. The most effective methods to improve the impedance bandwidth of this type of antenna are to modify the geometry of the radiating element structure [25] and defected ground plane [26]. By fine tuning both of these geometric features, the impedance bandwidth can be broadened to accommodate all the frequency bands. Antenna size reduction can be achieved by introducing high dielectric substrate, shorting pins, slits or slots on the geometry structure [25-26]. However, this type of antenna suffers from the back radiation and instable ground plane [27].

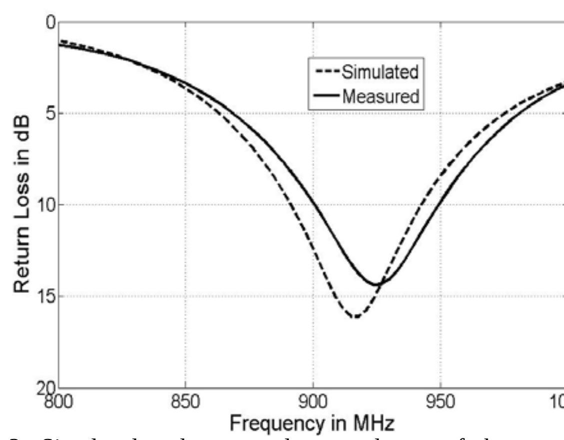

Fig.3: Simulated and measured return losses of the proposed antenna within the enclosure.

In this application the proposed transceiver is expected to operate in a harsh environment, with high radio signal attenuation (lossy and watery) surroundings and out of line-of-sight. A standard antenna is therefore not suitable for this application. It was necessary to redesign an aerial to satisfy the demands of the proposed WSN. The proposed antenna had to provide the following characteristics: (i) good impedance matching over the 902 MHz - 928 MHz frequency band, (ii) consistent radiation patterns and good front-to-back (F/B) ratio (iii) high gain, (iv) robustness, (v) low cost and profile and (vi) small size.

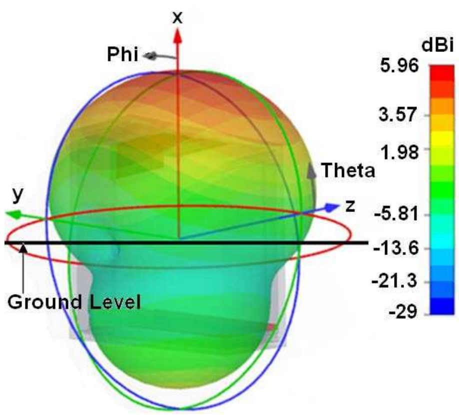

Fig.4: Simulated 3D radiation pattern of the proposed antenna at 915 MHz.

For the proposed system, an embedded printed antenna was designed, tested and implemented within a 80 x 80 x 55 mm^3 IP68 enclosure, as shown in Fig.2. The antenna consists of a meander line radiating element and a defected ground plane. Both of them are printed on two sides of double layer FR4 epoxy substrate with thickness of 0.8 mm and the dielectric constant (ε_r) is approximately equal to 4.4. The total length of the radiating element is around 160 mm and this corresponds to a half wavelength ($\lambda_0/2$) at 915 MHz which is the centre frequency of the operating band. By optimizing the size of the ground plane, good impedance matching can be attained over the design frequency band. Due to the limited space inside the enclosure, the flat printed antenna is modified and formed into a L-shape structure. It is positioned on the face of the enclosure at a location nearest to the ground surface for optimal radio signal reception. To improve the radiation patterns front-to-back (F/B) ratio, a 113 x 51 mm^2 metal plate which acts as a reflector element, is placed inside the enclosure to prevent back radiation by the antenna.

By using an existing electromagnetic modeling tool [28], the performance of this antenna module is predicted and later the obtained results are cross-validated by the measurement. Fig.3 shows the computed and measured return loss of the antenna. As can be seen, both results occupy the required operating frequency spectrum from 902 to 926 MHz at return loss better than 10 dB. It should be noted that there is a 10MHz frequency shift between the simulated and measured results; this can be attributed to the manufacturing and alignment errors of the antenna prototype. Fig.4 depicts the predicted 3D radiation pattern of the selected antenna at 915 MHz. As can be observed, the radiation direction is pointed upwards which indicates the signal penetrates from below to the above ground level. This predicted result is confirmed by measured data acquired in an anechoic chamber. Moreover, both simulated and measured maximum gains of this antenna in the broadsight direction are in a good agreement, which is 4.4 and 4.2 dBi respectively. The proposed antenna is believed to have a high potential and feasibility to be adopted in underground water infrastructure monitoring. More descriptions of this antenna can also be found in [29].

C. Acoustic sensor probe and Data Acquisition Board (DAQ)

There are a number of water level sensors available in the market [30]. But, many of these sensors are expensive, unreliable, are large in size and consume too much power to be used in the hostile gully pot environment. In order to reliably and effectively measure the water level of a gully, a novel and low cost, low power acoustic sensor was designed and developed. This sensor makes use of how sound waves radiate in water in the gully environment. In general, there are two ways of using a sonic transmission to detect the water level [30].

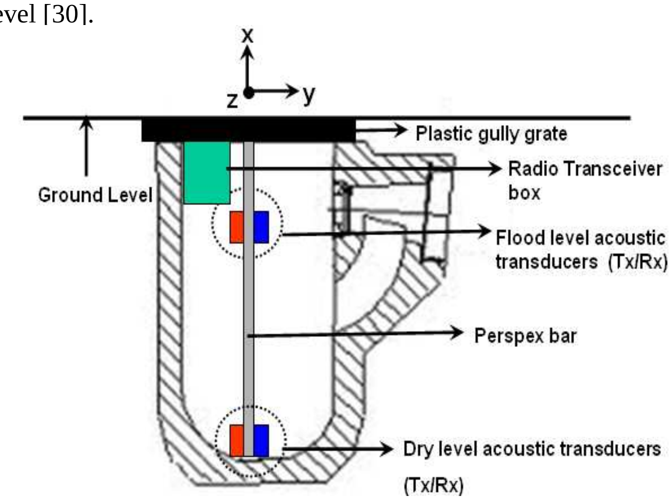

Fig.5: Installation of the sensor within the gully pot.

The first method is to use an echo-sounder which measures the time between the beginning of a pulse of sound and return of the echo. Due the acoustic impedance mismatch between air and water, sound waves reflect from the interface, so that the time of flight from transmitter to receiver can be measured and converted into the water level. The second method is to evaluate the level of received signal strength when the transmitter and receiver are either both under water or in the air. This method makes use of the better coupling between the acoustic transducer in water, so that the amplitude of the signal measured in the receiver is significantly higher if the transducer and receiver are submerged under water. However, both of these methods of detection require a driver for the acoustic transmitter and an amplifier for the received signal. The first method suffers from potential effects of debris that cover the transducer which are likely to cause a false alarm and it takes longer time for measurement, whereas the second method does not suffer from interference of debris and requires shorter time for measurement. Therefore, the second method was adopted in this project.

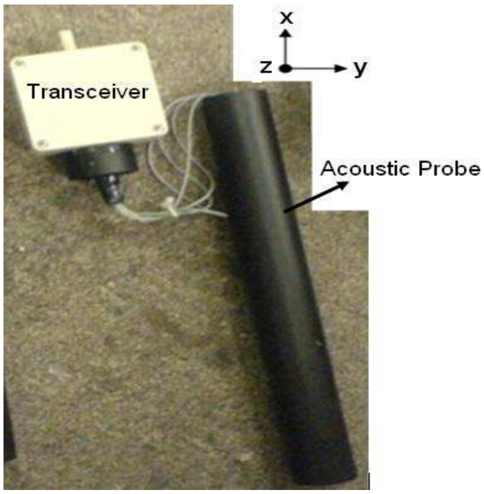

Fig.6: Typical gully pot monitor unit.

The developed acoustic probe comprises of two pairs of piezoelectric transducers as shown in Fig.5, which are able to convert electric signals to acoustic waves or vice verse. The lower pair of transducers is designated to determine the dry (leakage) condition of a gully, while the upper pair of the transducers is used to detect the high fluid level (flood condition). In both pairs of the piezoelectric transducers, one of them plays the role of a transmitter, while the other acts as a receiver. An electrical pulse at the resonant frequency of transducer is sent to the transmitter to generate sound, whereas the receiver detects the sound field and converts it to the electric signal fed back to the interface circuit board. Due to the high acoustic impedance mismatch between air and water the level of fluid in a gully can be easily identified from the amplitude of the response between the acoustic transducer pair. A suitable prototype of the acoustic sensors has been designed and constructed to generate signals to indicate three different conditions, i.e. Normal, Leaking and Flooding. In the case of the normal fluid level the high and low acoustic responses between the lower and upper transducer pairs are recorded, respectively. In the case of low fluid level (leaking condition), the low acoustic responses between the lower and upper transducer pairs are recorded. In the case of high water level (flooding condition), the high acoustic responses between the lower and upper transducer pairs are recorded.

The DAQ board is designed to drive the piezo-transducers by using a pulse. It then examines the difference between the amplitude of the received sound wave and interprets this information in a form understandable by the radio transceiver. Each sensor probe is calibrated prior to be installed in the gully pot due to the manufacturing variability. Owing to the different depth of the gully pot, the positions of the two piezo-transducer pairs inside the plastic tube are adjusted accordingly. Throughout the calibration process, the water level alarm trigger points will be saved in the microcontroller on the DAQ board. Based on these trigger points, the water level condition can be determined. It should be noted that the DAQ board was designed to operate in low power consumption mode and considerably extend the life time of the sensor module.

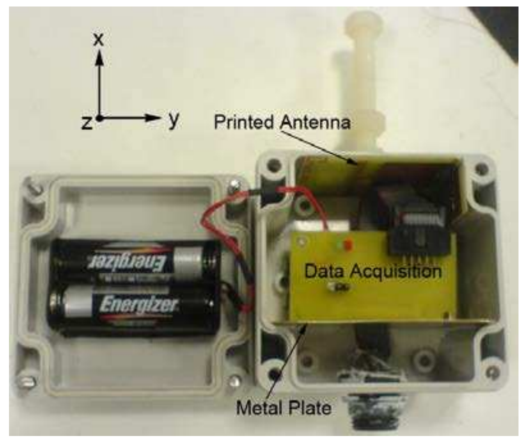

Fig.7: Internal view of the gully monitor unit.

Fig. 8: Deployment of wireless sensors in gullies and data gatherer on lamppost.

D. Data gatherer/Hub

Due to its compact, low-profile, easy to program and compliance with common wireless standards including Wifi, GPRS, Wimax and GSM, the Stargate platform [30-31] is adopted as the data gatherer for this work. The Stargate platform is a licence-free Linux operating system for mini computers. In this present application, it is used as a data

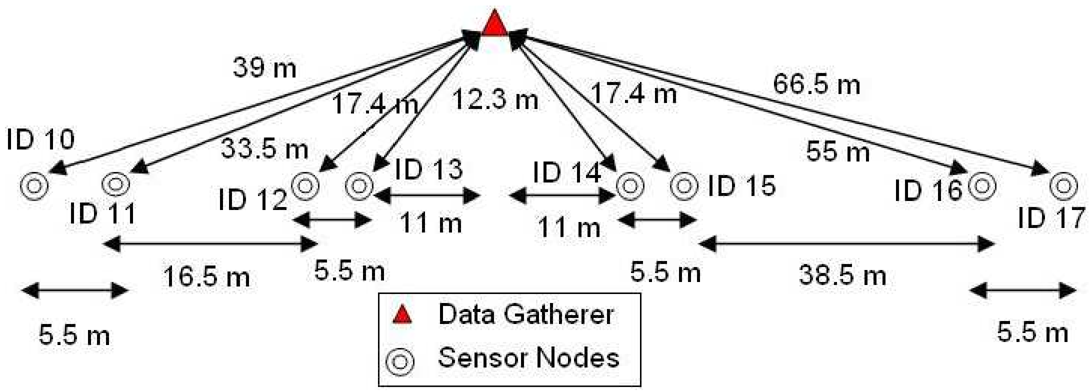

Fig. 9: Wireless Sensors Distribution on field trial.

gatherer/hub which collects the data from all the wireless sensors. These data are then processed and displayed on a webpage and stored in a SD memory card. For the optimum radio coverage of the monitored area, the data gatherer was mounted on a lamppost in order make it as visible as possible to the sensor nodes. The Stargate sends the recorded data back to the remote server once a day using a GPRS connection.

III. Field Trials

An area of terraced houses in a city in Yorkshire was selected for testing the practical viability of the proposed system. There are three main reasons why this area was selected for this sensor deployment. Firstly, this area has had numerous blockage incidents reported in the past. So, it was considered that there was a reasonably high likelihood that blockage incidents would occur during the field trial. Secondly, in this area, every single house has only one gully to collect all the wastewater, such as kitchen wastewater of different temperatures with fat and oil waste, bath water, and rain water. This single outlet point is exposed as the single failure point for the disposal of wastewater. Thirdly, the topology of the site allows the proposed Zigbee mesh network wireless sensor system to be tested. Since the site has a row of residential houses, the system will need to use a sensor network to relay information to the data gatherer. It is believed that if the system can work in this challenging environment, then it should subsequently work for most of the other urban scenarios.

Fig. 5 shows the installation of the wireless sensor inside the gully pot. As can be seen, a watertight enclosure which comprised of an antenna, a transceiver and a DAQ board is attached to the base of the gully grate and an acoustic probe is positioned in the centre of the gully pot. Fig. 6 shows the deployment of the prototype of the gully pot monitor unit, while Fig. 7 portrays the internal view of the enclosure. The practical implementation of the proposed system is illustrated in Fig. 8 and the system is constituted of eight gully monitor units and a data gatherer/hub. Fig. 9 schematically shows the distribution of the proposed sensor nodes and data gatherer. It shows, the sensor to sensor (STS) and sensor to data gatherer/hub (STH) distances. It can be seen that, the shortest and longest STS and STH distances were 5.5 m and 38.5 m, and 12.3 m and 66.5 m, respectively. An ID from 10 to 17 is assigned to each individual sensor to locate their position and the data they produce.

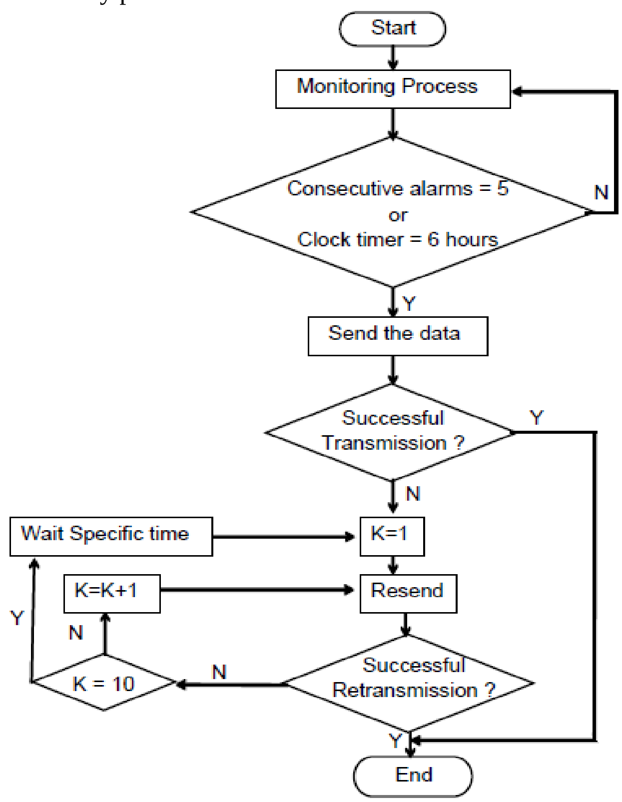

Fig. 10: Flow chart for basic operation of the sensor.

The project specification required the gully monitor to operate for up to two years. To achieve this, the Zigbee monitor was programmed to work in two modes. The microcontroller on the DAQ board is programmed to wake up from sleep mode to measure the water level condition every five minutes while keeping the transceiver in the sleep mode. Once it detects a low/high alarm, the transceiver wakes up to sense the Received Signal Strength Indicator (RSSI) from the hub as well as from its neighboring sensor's node. Then, it compares the RSSI and selects the best route to relay the data back to the data gatherer via the Zigbee mesh network. After that, the data gatherer enables the GPRS connection and sends the data to the remote server. Subsequently, the remote user can send an inspector to investigate the event. In the case of no occurrences of any event, the sensor broadcasts a health condition packet back to the hub to indicate its battery level and water level conditions every 6 hours. The hub establishes the GPRS service to send all the received data back to the remote server on a daily basis. To fully understand the activities of the installed sensors, Fig.10 provides a brief flow chart of the proposed protocol for the sensors.

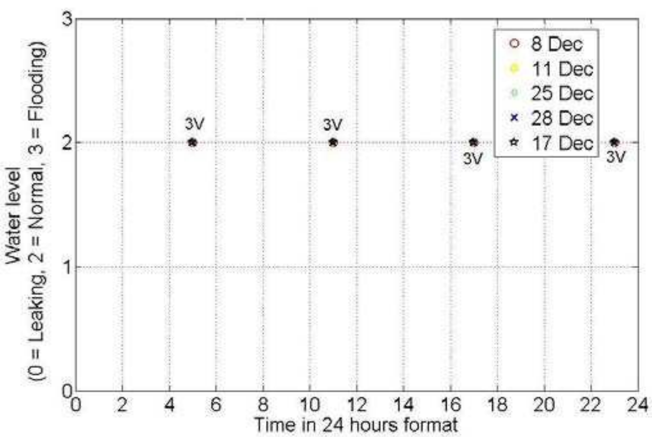

Fig. 11: Example of a working sensor node over selected days.

IV. *Results and Discussion*

This section reports on the outcomes of the three month field trial. By analysing the received data from the data gatherer, it is feasible to calculate the success rate of the system operation. The performance of the system is assessed based on two key elements: sensor reliability and communication reliability. The sensor reliability was calculated by finding the ratio of the number of correct data (right status of the water level condition) received to the total number of received data. Data was determined as correct based on the physical behavior of the gully pot as it was empty, filling and emptying. In order to verify whether the received data is correct, on-site investigation was carried out on a weekly basis in the case when no alarm was triggered. However, when an alarm was activated, a site survey was immediately conducted to check the sensor reliability. An example of the received data from a working sensor is plotted on Fig. 11. Due to a large amount of the received data from the hub, Fig.11 only shows data over three consecutive weeks starting from the 8 December to the 28th December to illustrate the reliability of the sensors. As can be clearly seen, the sensor node transmits a health packet reliably back to the hub every 6 hours. Each data indicates that the water level is normal and battery level is above the minimum voltage threshold (2.5 volt) of the sensor node.

A. Acoustic Sensor

Fig. 12 shows the reliability of the acoustic sensor only and its improvement over the full trial period. The results suggested that the acoustic sensor can achieve up to 85% reliability. During the field trial, modifications have been made to the program which controlled the DAQ board and acoustic probe at three different points in time (stages). The modifications enabled the water level condition of the gullies to be determined more reliably and to avoid false alarms. It was found that there were five factors affecting sensor reliability. Firstly, in the sensing mode, the sensing activity takes place every 5 minutes. If the water level is above/below the normal status, an alarm is triggered and a data package is sent to the hub. By using this sensing method, many false alarms were reported, as in stage 1. This can be attributed to the use of household electronic appliances such as a dish-washer, washing machine and showering activities lasting over 5 minutes. In order to remove these false alarms, consecutive alarms were counted; the sensor reliability can be improved. By optimizing this parameter, it was found that the sensor reliability can be progressively enhanced, as from stage 2 to 4. It was found that by using five consecutive alarms false alarm sensing issues were eliminated. Secondly, the position of the probe within the gully is another parameter that needs to be taken into consideration in order to accurately determine the water level condition. Thirdly, by using the onsite waste water to calibrate the sensing probe instead of the tap water in the laboratory can also improve the reliability of the system. Fourthly, the definition of normal, high and low water level on each individual gully pot is different. Therefore, it is important to define this parameter carefully for enhancing the accuracy of the sensor. Lastly, the consistency of manufacturing the sensor probe is another important issue for achieving good accuracy of the measurement.

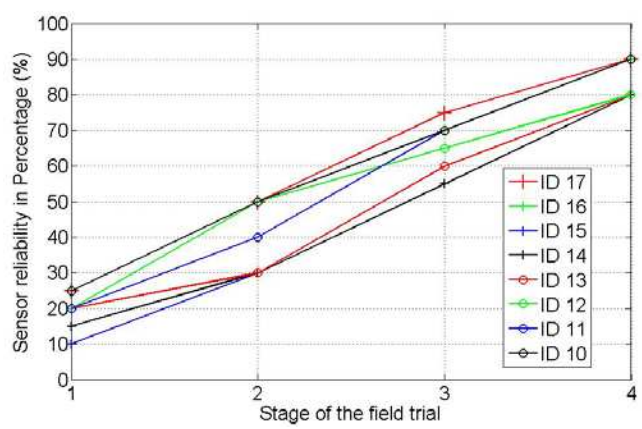

Fig. 12: Sensor reliability of the proposed system.

B. Communication

This section discusses the feasibility of using a Zigbee based mesh network sensor topology for the gully monitoring system. It was interesting to find in the field trial that the gully monitor can relay the data to its neighbour within a 10 meter communication range. The wireless communication range can be extended over 100 meters if a reliable mesh network is established. These observations are in good correlation with the results presented in [29]. However, it was observed that when it was raining or snowing the STS and STH communication distances can be reduced up to 30 %, which correspond to 7 and 70 meters respectively. During the field trial, even with these reduced levels, no drop in the warning capabilities of the system was observed.

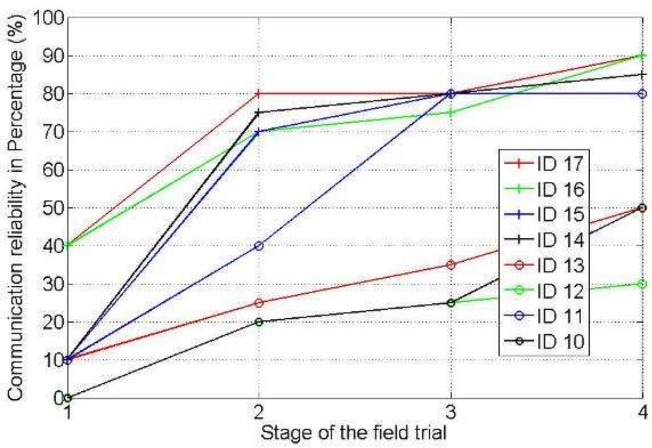

Fig. 13: Communication reliability of the proposed system


Fig. 14: Wireless link enhancement methods; (a) Adding relay point, (b) Using high gain antenna on the data gatherer

Fig. 13 illustrates the communication reliability of the proposed WSN system for each individual gully monitoring unit over each stage of the field trial. In general, this field trial has been divided into four stages. In the first stage, eight sensors and one data gatherer were installed, but it was found that the communication reliability was relatively low. An investigation was carried out to pinpoint the reasons why the radio communication on those gully monitoring units were blocked. It was discovered that the blockage was due to water leak issues in the transceiver enclosures and third party interferences including covering the sensors with objects. In order to improve the radio coverage signal strength, significant efforts have been made to tackle this problem. These included remedial works to change the orientation of the aerial of the hub, adding relay points (i.e. repeaters) which were installed at 40m to 70m away from the hub. In addition, a high gain aerial was installed at the hub, as shown in Fig. 14. These works corresponded to stages 2, 3 and 4 in Fig.13. As a result, the efficiency of the proposed system was improved considerably. It should be noted that adding relay points to the system is not always a feasible solution to this problem because the performance of the system is heavily dependent on the location of lamppost. A possible alternative is to implement multiple-input multiple-output (MIMO) antenna on the data gatherer to improve the communication signal coverage. This will be studied in future. It was observed that 5 out the 8 of the sensors achieved a working reliability of around 80%. The poorer performance of sensors (ID 10, 12 and 13) can again be attributed to the water leaks into the enclosure.

V. Conclusions and Recommendations

This paper presents the development of a novel Zigbee based WSN communication system and the results obtained from a field trial deployed in an urban residential area to provide warning of flooding at a single property scale. The presented work has led to the development of knowledge and expertise in four areas of research: a) wireless communications and distributed wireless sensor networking; b) embedded antenna design; c) sensors and instrumentation for use in water industry assets; d) remote monitoring of water related assets. These technologies formed a reliable wireless system that was able to transfer and process data effectively from a number of gully pot sensors in a typical residential setting. The results indicated that providing suitable rules were used to determine alarms and a high quality enclosure was possible then a large number of diverse sensors could be distributed within a sewer network. These sensors could provide reliable information in order to reduce significantly flooding events. Outcomes from the field trial enabled the researchers to gain expertise in the issues associated with the practical monitoring of the performance of elements of the urban sewerage infrastructure managed by a water company. The problems encountered and associated solutions to these problems have been addressed and discussed. The field trials have resulted in a system that can be adapted, modified and extended for use in the sewer network under different operating conditions. The approximate cost is around $150 for crossbow transceiver and data acquisition board, $10 for the water level probe and

$500 for the data gatherer/hub. To further improve the communication and sensor reliabilities of this system, it is suggested that a commercial manufacturer is needed to develop a more robust prototype of the proposed gully monitor unit. Such a wireless communication system could also be used to collect condition data on other civil infrastructure given appropriate sensing technology.

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