Using Sensor Technology to Monitor and Report Vandalized Pipelines

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Abstract— **Pipelines transporting gasoline, diesel, crude, and natural gas are periodically subjected to acts of vandalism and sabotage in Nigeria. Unfortunately, vandalized pipelines are not quickly detected; leading to major environmental degradation, and in case of gasoline, to explosion and attendant loss of lives and properties. Since it is nearly impossible for security operatives to monitor large sections of Nigerian national pipelines, it becomes imperative to propose smart solutions which allow monitoring of pipelines using wireless sensors. This paper proposes the use of wireless sensors to monitor acoustics, vibrations and lights emanating from or around targeted pipelines. Sound detection process automatically triggers verification, which involves turning on the sensor to detect pipeline vibration. A night-time mode allows the sensor to equally scan for bright lights which may connote a pipeline on fire. The paper strives to lay a solid foundation for full deployment of actual motes. We propose the use of linear clustering to ensure energy conservation.**

Keywords—Pipelines; Motes; Wireless; Sound; Acoustic.

I. INTRODUCTION

Various environmental monitoring projects using wireless sensors successfully demonstrated the ability of sensors to monitor changes in their deployed environment (such as ambience, movement, and stress in concrete) and report findings [6][7][12]. While designing wireless sensors monitoring systems, it is imperative to painstakingly gather environmental data which forms the parameters on which the algorithm controlling each mote will operate. Parameters gathered for our pipeline monitoring project include: (1) pipeline - material (iron, steel etc.), (2) thickness, (3) diameter, (4) normal vibration while conveying crude, gasoline, diesel or liquefied gas, and (5) topography and settlement type through which the pipeline passes (swamp, rivers, forests, underground, villages, towns etc.). Each parameter directly affects the distance, vibration and acoustic velocity, which are important parameters in our proposed project.

Wireless Sensor Networks (WSNs) are made up of a great number of sensors. These sensors are called sensor nodes, whose main purpose more often than not are to sense, process, and transmit information about the deployed environment or surrounding [5][6][7]. These sensors are usually dispersed in an environment or different location for the purpose of information gathering [3][6]. The acquired information is transmitted to a central sink node so that users could have access remotely through a gateway. A sensor node comprises of either one or more sensors, a signal conditioning unit, an analog to digital conversion module (ADC), a central processing unit (CPU), Memory, a radio transceiver and an energy power supply unit as depicted in Fig. 2 [5][12]. Subject to application or deployment environment, sensors are often protected to guard against physical, chemical, etc. damage.

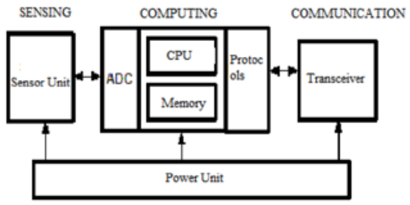

Figure 1. Wireless Sensor Node Architecture

Sensors nodes can be obtained off-the-shelf in two forms: 1. Generic (general-purpose) nodes and 2. Gateway (bridge) nodes [4]. A generic (general-purpose): the function of this kind of sensor node is to obtain measurements from the environment being monitored [5]. It is often equipped with different mechanisms which are capable of measuring various elements or environmental traits such as light, temperature, humidity, barometric pressure, velocity, acceleration, acoustics, magnetic field, etc. Gateway (bridge): the function of this type of node is to collect information from generic sensors and transmit to the base station. Gateway nodes are equipped with greater processing capability, stronger battery power, and a longer transmission (radio) range [3]. A mixture of generic and gateway nodes are usually set up to create a WSN [3][4].

Our proposed wireless sensor motes can function in two ways:

- As full function device (FFD): The FFD is a midway router whose function is to relay data collected from other devices. It does not require large memory which makes it less expensive to develop. It can function in all WSN topologies and can operate as a coordinator.
- As reduced function device (RFD): This device only transmit its host's or environment' physical attributes that is, it just transmits to the network coordinator only; it does not convey data from other devices. It in fact requires less memory than FFD (very little RAM and ROM, no flash); this makes it even cheaper to develop than an FFD. RFD is easier to implement on star topology.

This paper proposes the use of wireless sensors to monitor pipelines by observing parameters such as pipeline acoustics, vibrations and ambience lights around pipelines. Our proposed project conserves energy by eliminating recording of detected acoustics and predictively control mote's wake up and radio usage functionalities. To further conserve energy, we adopted network segmentation through linear clustering [8][10][11][13]. Linear clustering was adopted based on

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research work by Alnuem [13], who demonstrated higher energy consumption when nodes are widely spaced.

Figure 2 below illustrates the diverse terrain (swamp, villages, towns, forests, roadside etc) through which Nigerian pipelines are deployed.

Figure 2. Nigerian Pipelines Network

The remainder of this paper is organized as follows: Section II discusses the state of the art which explores various methods used to monitor pipelines for vandalism, natural disaster, and leakages, while the proposed work, which comprises the system architecture, the mote configuration, the mote deployment, the mote security and the mote/Gateway messaging are discussed and illustrated in Section III. Section IV presents and discusses the simulation results. Finally, Section V concludes the paper and points out open research issues and further research works.

II. STATE OF THE ART

Several methods have been devised in order to monitor and report pipeline status. The most common and popular ones includes Acoustic Sensors – this employs acoustic or vibration measurement for pipeline monitoring [2][17][18]. Vision based systems – this is based on PIG (Pipeline Inspection Gauge) which must be inserted into the pipe. It works like image processor or laser scanner which main function is to detect leakages [2][18]. Ground penetrating radar (GPR) based systems – this is best suitable for use on environment with dry soil, but is not good for large network of pipes monitoring [2][17][18]. Fiber optic Sensors - this is suitable for present day pipeline monitoring systems, it can handle most present day pipelines issues, some of its drawbacks is the probability for redundancy and some challenges with deployment [2][13]. Multi modal underground wireless system – this uses low power, as the name implies it is meant for an underground installation, it has the advantage of camouflaging, but one of the disadvantages is that it has to be buried underground, that is a trench has to be created [2][18]. Every single Sensor has a distinctive feature and typical operating condition. Choosing a sensor for pipeline monitoring to a large extent depends on the environment to be deployed and the deployment method.

This research work recommends wireless motes from both *MICA series and IRIS* (to monitor pipelines and report either ongoing attempts to vandalize sections of a pipeline or to quickly report ruptured pipelines.

Ismail et al. [1] demonstrated the ability of IRIS and MICAz mote to detect and record sounds while eliminating ambient noise levels. Their paper allow a parent mote to assign recording tasks to motes within their cluster.

Lou et al. [17] demonstrated the ability of MICAz to detect and record environmental acoustics using the Microphone on MTS310CA sensor boards.

Kim et al. [18] also show the feasibility of using MICA based mobile wireless sensor with attached RFID in pipe line monitoring and maintenance.

This paper differs from [1][17][18] in the following areas : (1) Detected sound is not recorded. (2) Only very loud sounds triggers verification of sound source. Verification of detected sound is necessary due to the likelihood that certain persistent ambient sounds can trigger sound detection, hence the project introduces additional layers of checks, such as checking for pipeline vibration, detecting temperature and measuring magnetic flow around the pipeline. Finally, a night-time mode of operation allows base station to activate light sensors on deployed FFD motes. This enable FFD motes to detect and report fire around the pipeline. (4) Motes are deployed using "Linear Clustering". Figure 3 below represents our proposed test environment.

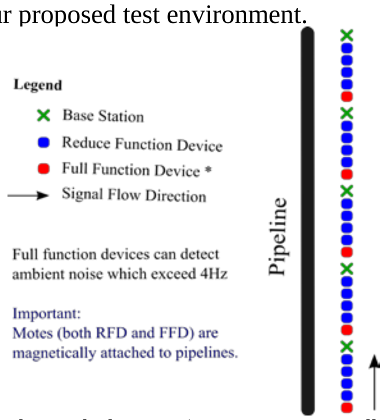

Figure 3. Proposed mote deployment (motes are magnetically attached to pipeline)

III PROPOSED WORK

This paper recommends using wireless motes to (1) sense ambient sounds, (2) confirm the type of sound by testing pipeline vibration and magnetic flow around monitored pipeline, (3) if operating under night-time mode; check for fire using both temperature and light sensors, (4) finally, the mote sends it's ID to designated base station or sink. MICAz and IRIS are compatible and can use similar sensor boards, since both are equipped with similar 51 pins sensor connector module. However, MEMSIC IRIS has better radio range and a larger memory capacity when compared with previous MICA motes [14].

Figures 4, 5 and 6 below depict deferent kinds of motes for the proposed project.

Figure.4. MICA2

Figure 5. MICAz

Figure 6. IRIS

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Each mote has a 51 pin connector interface which allow MTS310CA sensor boards to connect to the mote. The sensing capabilities [14] of MTS310CA sensor board are (1) light detection (2) temperature detection (3) sound detection (4) acceleration and vibration sensing and (5) magnetic field detection [14].

A. *Proposed Mote Configuration*

Two kinds of motes will be deployed to achieve proposed objectives, namely motes equipped with MTS310CA sensor boards (also known as full function devices or FFD), and those without the sensor board (known as Reduced Function Devices or RFD).

B. *Sound Sensing*

Sound sensing triggers other sound verification events in quick succession. This process avoids false alarm and stabilizes system credibility. Hence sound sensing motes must be properly configured to detect sounds above topographical ambience levels. However, setting a high frequency level can force the device not to detect certain frequencies, for example, a large explosion has a frequency of between 20Hz to 50Hz, however, when explosions rips through metal, the frequency increases and can be detected by a sound sensing mote. Another interesting fact about sound is the fixed distance within which generated wavelength can propagate; depending on the velocity. Sound velocity is determined either by environment (temperature) or the composition of the material through which the sound propagates (such as air, water, iron and steel). For example, Given the following values, let us calculate the distance covered by a large explosion through an empty steel pipe:

$$Given: \ Sound\ velocity\ through\ empty\ steel\ pipe\ (v) = 5960$$
$$Given: Explosion\ frequency\ (f) = 50\,Hz$$

$$formula: \ \lambda = \frac{v}{f}$$

$$therefore: \ \lambda = \frac{5960}{50}$$

$$= 199\,meters \ \text{ or } \ 391.08\,feets$$

A knowledge of the distance covered by each sound wavelength influences placement of sound sensing motes. The Table.1 lists the various ambient sounds common along the route of Nigerian pipelines:

TABLE 1. AMBIENT SOUNDS COMMON ALONG THE ROUTE OF NIGERIAN PIPELINES

Source	**Decibel**	**Frequency (Hz)**
Chain Saw	100 db	2000 Hz
Chirping Bird	5 db	7000 Hz
Rustling Leaves	>2 db	1500 Hz
Gunshot	>120 db	2000 Hz
Festive Band	110 db	800-1500 Hz
Crying, talking, barking dog	30 – 60 db	250 – 700 Hz

C. *Proposed Motes Deployment*

The proposed Motes are deployed in such a way that Full Function Devices are positioned to prevent simultaneous sensing of same sound (due to sound propagation) Figure 3 above. However, in the rare event that it does happen, operators will be able to locate the actual sound source by examining transmitted ID of motes that reported the sound within a linear cluster.

"Linear Clustering" allow a group of Full and Reduced function devices to be either "linearly attached" to surface pipelines or to trees, rocks and other naturally occurring feature over an underground pipeline. Each group/cluster of FFDs and RFDs relay monitoring results to a base station as shown in Figures 7 and 8 below.

Figure 7. Cluster of FF and RF Devices on a surface pipeline. Cluster will be repeated along total distance of surface pipeline

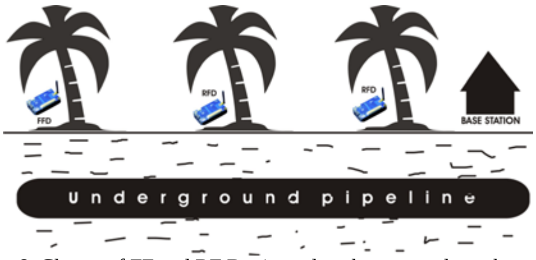

Figure 8. Cluster of FF and RF Devices placed on trees along the path of underground pipeline. Cluster will be repeated along total distance of underground pipeline

Distances between Full Function and Reduced Function Devices will be determined by both lowest acoustic worth detecting and the maximum range of wireless broadcast.

Monitoring underground pipeline against vandalism is achieved through constant monitoring of ambience acoustics along underground pipeline deployment route.

Emphasis is laid on monitoring attempts to excavate sections of top soil above underground pipelines. Motes saddled with monitoring these sections will be programmed to detect voices, excavating machinery, chainsaws etc.

As stated earlier, both surface and underground pipelines adopt linear clustering to both enhance communication and minimize power consumption.

However, a stolen or malfunction mote within a cluster will greatly affect transmission of verified attempts on a pipeline.

D. *Mote Security*

Motes will be required to periodically send identifying information every 72 hours to the base station. Failure to receive such information enable operators to know what motes to replace (either lost to theft, drained batteries, or simply damaged).

E. *Mote/Gateway Messaging*

Mote's ability to properly monitor pipelines can be jeopardized if sound sensing motes are not aware of changes in pipeline status. For example, is it empty or is it

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crude, gasoline or diesel flowing through it? Therefore, operators need to inform motes wirelessly when crude is being pumped along pipelines. This enable sound sensing motes to adjust their sound sensing algorithm. We equally propose a night-time mode for FFD sensors, this mode is trigger via a message received from the base station. It allows sensors to include temperature and light sensing during each pipeline monitoring cycle.

Base station operators remotely notify motes regarding both pipeline status and day time/night time status. Pipeline status notifies motes when liquid is being pumped through pipelines or when pipeline are empty. Such notifications enable motes to know what sensors to engage during each sampling process.

Similarly, night time/day time status notification determines the various sensors a mote will utilize during each predetermined round of ambience sampling.

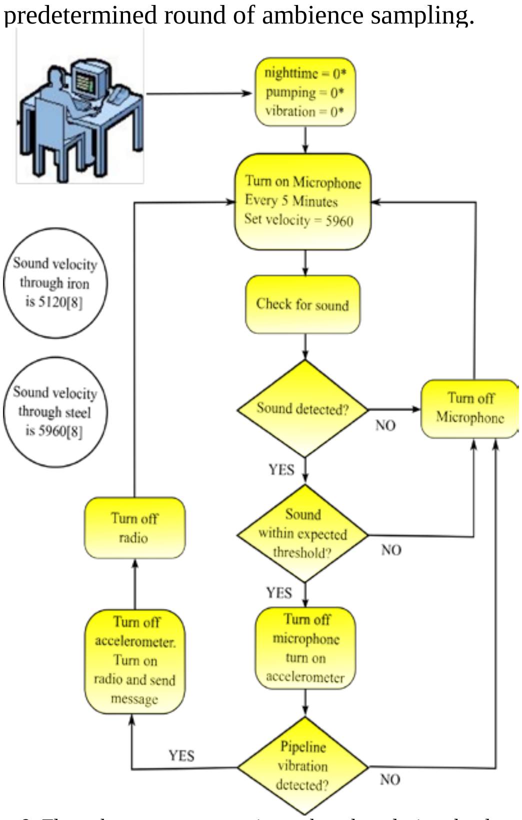

Figure 9. Flow chart represents action to be taken during the day when nothing is being pumped through the pipeline. In TinyOS 0 or false is 1

The process flowchart (above, Fig.9) represents actions to be taken by FFD motes during the day, when pipelines are empty (that is when nothing is being pumped through pipelines). The process flowchart eliminates false “alerts” caused by high frequency sounds such as the chirping of a bird by checking if detected sound lead to pipeline vibration.

A detected pipeline vibration triggers the next action which involves turning on the radio and transmitting sensor's ID to the base station. Transmitted ID is used by base station operators to identify sensor's coordinate along the pipeline.

The next process flowchart (Fig. 10) represents algorithm to execute during the day, when pipeline is in use (that is when crude or related products are being pumped through pipelines).

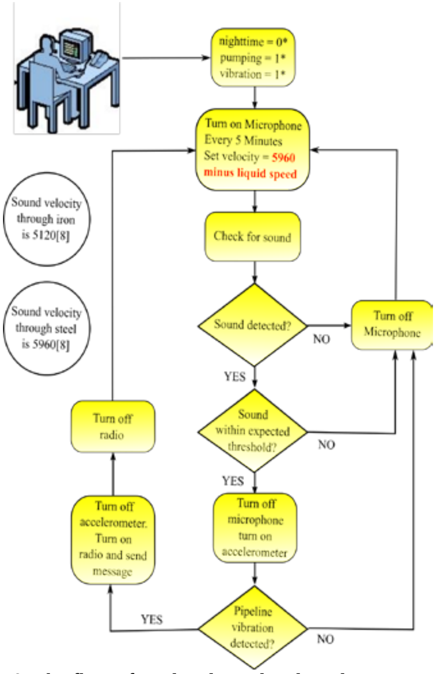

Figure 10. The flow of crude oil or related product triggers slight vibration

Finally, the next two process flow chart uses light and temperature sensors (in addition to acoustic and accelerometer, (Figures 11 and 12) during **nighttime** mode to detect acts of vandalism against the pipe.

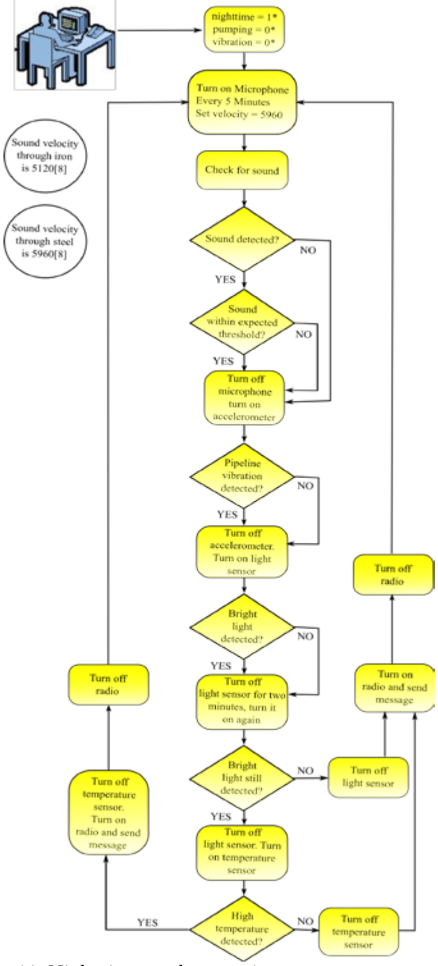

Figure 11. Night time mode operations use up more resources

The process flowchart above (Fig. 11) represents actions to be taken by FFD motes during the night, when pipelines are empty (that is when nothing is being pumped through them). The process flowchart also eliminates false “alerts” caused by high frequency sounds such as the chirping of a bird by checking if detected sound lead to pipeline vibration. Detecting pipeline vibrations triggers the next action which involves turning on the radio and transmitting sensor's ID to the base station. But this uses light and temperature sensors.

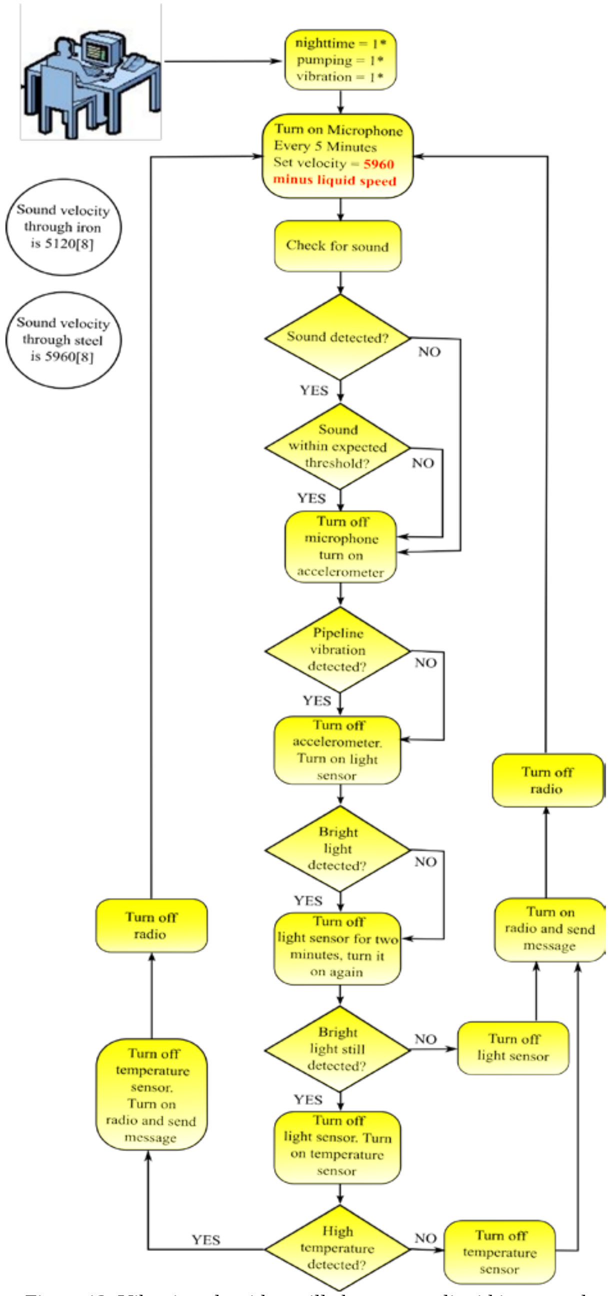

Figure 12. Vibration algorithm will change once liquid is pumped through pipeline

Figure 12 above represents algorithm to execute during the night, when pipeline is in use (that is when crude or related products are being pumped through pipelines). But this also uses light and temperature sensors.

IV. SIMULATION RESULT

The pipeline monitoring solution was developed using TinyOS 2.1.2 on Ubuntu 14.04 LTS. TinyOS Yeti2 plugin for Eclipse IDE was installed to enable TinyOS software development under Eclipse 3.8. During the course of testing, it was discovered that TOSSIM [9] (TinyOS Simulator), cannot simulate certain hardware features (such as microphone). Hence, Berkley University's Avrora [10] (The AVR Simulator and Analysis Framework) was downloaded and installed from [16].

Another limitation discovered during the course of simulating the solution is the inability of available simulators to use hardware available on the host computer to emulate certain features of the mote. For example, the computer's microphone should be used during simulation when a call is made to use Micaz's acoustic microphone. To overcome this and other limitations, flashing of Micaz's led was used to simulate the turning on and off of microphones and other sensors.

The solution does not seek to modify the behavior of B-MAC. Rather, it simply recommend keeping the radio on FFD turned off until needed.

Project workability is the primary goal of using wireless sensors to monitor pipelines in Nigeria. Nonetheless, simulating energy dissipation rate of deployed motes goes a long way to guide future power pack design and deployment plans.

The energy dissipation graphs of the simulation are shown below (Figures 13 and 14). Both solutions dissipate equal energy during FFD transmissions. However, our proposed solution (Figure 14) will dissipate less energy overtime since radio usage (that is turning the radio on and off) is predetermined by the presence of sound.

Nonetheless, periodic turning on of mote’s microphone, accelerometer and temperature sensors will most likely negates intended energy gained from periodic usage of FFD’s radio.

Our proposed solution reduced collusion and lost as a result of delays which can be attributed to the need to verify detected sound before reporting.

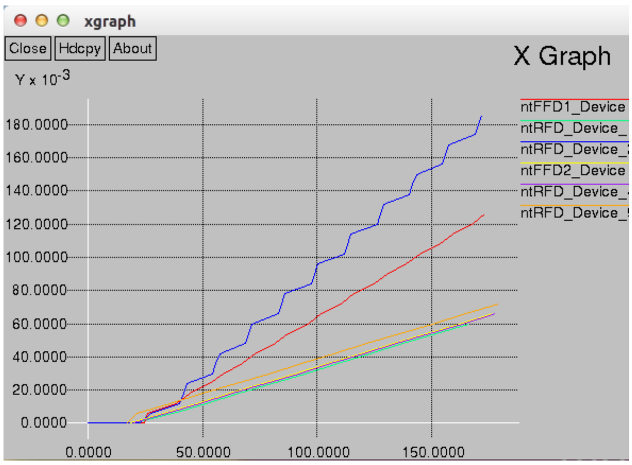

Figure 13. Normal transmission energy dissipation graph using short delays.

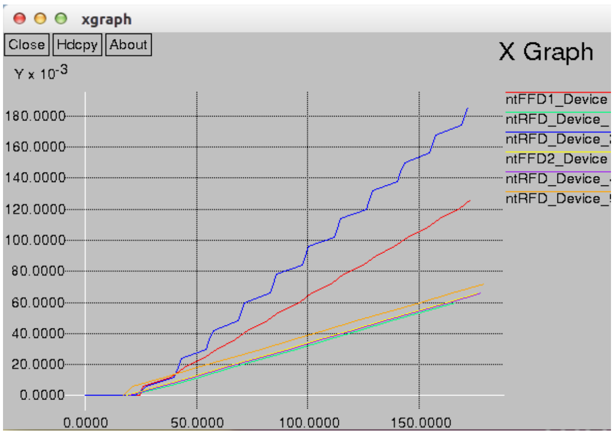

Figure 14. Energy transmission graph of our proposed solution

V. CONCLUSION AND FUTURE WORK

This paper has proposed the use of wireless sensors to monitor acoustics, vibrations and lights emanating from or around targeted pipelines. Motes are best positioned to achieve 24/7 surveillance of oil pipelines. However, this will only materialize through adequate planning and deployment strategy. Planning includes combination of hardware and software options, to boost performance and to ensure energy sufficiency.

We believe adding imaging ability will further enhance the project. This involves using concealed cameras which can communicate with Micaz, Mica2 and IRIS motes by capturing and sending low quality images of areas which Base station operators wish to see.

Moreover, additional work needs to be done on mote simulators. Especially in the area of emulating mote hardware by integrating into host's devices. For example, a call to a mote to turn on its microphone should equally turn on the microphone of the PC on which the mote is executing. Avrora simulator returns identical energy consumption values for yellow, green and blue LEDS during simulation, hence it was impossible to simulate light sensor using the three available LEDS. Finally, due to a tight budget, we could not deploy motes in a physical environment, we therefore, recommend that further research work on this experiment should be conducted using methods outlined in this project.

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