Discrete Model to Estimate Lifetime of a Wireless Sensor Network for Audio Storage

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***Abstract*— Wireless sensor networks (WSNs) can be used to record and store audio data at remote and inaccessible places. However, audio data adds an additional concern to the design of the WSN; the motes need a larger amount of memory resources to be able to store the collected data. In this paper, we evaluate the ideas already presented, specifically the EnviroMic, for data collection and storage and apply a realistic power consumption model to estimate the lifetime of an audio sensor network.**

I. Introduction

Wireless sensor networks have been an area that has been used for the collection of data, and monitoring of different values including temperature and humidity. These values are easy enough to collect and transmit to the base station for instant analysis and charting due to the small size of this information. Audio is a useful tool for monitoring areas, and can give more information to the user, which can be used to increase the understand of the environment and inhabitants of that area if deployed in the outdoors, or if deployed in a controlled environment like an engine room of a ship to detect problems earlier. Audio has been a problem before now though due to the increased data size, but now with large amounts of memory being available for cheap it is now at a point where it can be used in a normal wireless sensor network. This does add another factor to determine the system lifetime of a wireless sensor network and that would be the amount of storage left in the network, especially if data is unable to extracted from the network for long periods of time.

Luo et al. [1] introduces EnviroMic for the collection and storage of audio stream in habitat monitoring. EnviroMic is designed for the collection of audio from both stationary and mobile sources. The protocol is designed to collect as much data as possible from the surrounding areas, and its goal is to maximize lifetime based on data being extracted from the network when the experiment or monitoring period is over. The protocol works as follows: 1) various nodes hear a sound in the surrounding area, 2) a group is then formed and a leader is elected, and 3) the leader collects data for certain periods of time. This is done to reduce the redundancy of data collection so that the network can have more data collected than if each sensor recorded the whole sound. The data is stamped with a file ID so that upon data extraction the sound can be fully heard. The other main component of EnviroMic is the data storage method, where the data collected by various nodes in the network can be transmitted to other nodes that are in less active parts of the network. This is based on the time for each sensor to live for both storage and energy requirements, storage being the more important.

Rajendran et al. [2] investigate collisions when transferring data between nodes. For energy efficiency, a wireless sensor network should minimize collisions in order to reduce the retransmission of data amongst nodes. While using the EnviroMic protocol a scheduled protocol should be used that provides the ability to interrupt the schedule so that a group can be formed to collect data. The Traffic-adaptive medium access protocol (TRAMA) would appear to be more appropriate for our scheme as it creates a schedule and adapts to the traffic between nodes, so that nodes that communicate frequently would have more slots available to transmit. However, the problem with TRAMA is the introduction of the nodes being in a low power sleep state, which could mean parts of the network not being active on hearing the new sound signal. The EnviroMic protocol does not really benefit with a sleep cycle due to the approach taken to store data, where a group is formed. A sleep cycle could be used by the EnviroMic protocol using the same techniques that were used in EnviroMic when a sound source is moving, so when nodes become active they are added to the group, and when they sleep they are removed from the group, just like nodes are added or removed from the group for when a node is moving.

The complete coverage of the monitoring region can be ensured when no sound within the monitoring area is missed. This can be done as follows: if all the nodes are in different positions, it is ensured that the perimeter of each sensor's sensing radius is covered, and also that the perimeter is covered. This method can be used to ensure that the network is covered by k sensors at all times, and if a sensor is ignored, increase all areas covered by the ignored sensor's radius by 1. The problem can be run on networks where the sensing range of the sensors is either unit disks or non unit disks, for non unit disks the protocol is the same, just the calculations are done based on the sensing range of each individual sensor rather than a common value . This information could be combined with a protocol like TRAMA to make sure that the network is always k-covered, as shown by Huang and Tseng in [3].

Smeaton and McHugh [4] use event detection in audio based wireless sensor networks. For instance, the sensors can be used with surveillance cameras to increase the monitoring capability of the cameras. The detection can occur based on the volume level in the surrounding area being above a certain threshold, the mean volume level. Further, the event can be based on the Zero Crossing Frequency rate (ZCR), the amount of times the signal amplitude passed through 0 in a given amount of time. This differs from the planned usage of EnviroMic, which stores data for future analysis.

The rest of the paper is organized as follows, Section II introduces the realistic energy model, Section III introduces the design of the simulation, Section IV provides the simulation results, and Section V concludes the paper.

II. Realistic Energy Models

Received Signal Strength Indication (RSSI) is used to determine which power level setting is needed to transmit directly between two nodes. To estimate the RSSI we can use one of the existing radio models, which can be isotropic or anisotropic. Since the main goal of this work is to increase realism of our model, an anisotropic model is used to estimate the RSSI. The model chosen for our implementation is the Radio Irregularity Model (RIM) [5] because of its ability to simulate differences in sending power amongst different pieces of hardware and anisotropic path loss. The RIM model builds upon the simple isotropic models that use Equation 1 by adjusting the Sending Power and Path Loss variables. For Path Loss they introduce a degree of irregularity (DOI) parameter to assign unique path loss in each direction. RIM also adjusted the sending power variable for each node to account for differences in hardware. The Path Loss calculation performed in RIM can be based on several existing isotropic models such as the Free Space Propagation model, Two-Ray Model or the Hata model[6]. Mallinson et al. [7] investigate the combination of several techniques into a single model that is more realistic and useful for simulations.

$$RSSI = SendingPower - PathLoss + Fading \quad (1)$$

For simulation, we use modified energy consumption formulas based on the Radio Irregularity Model (RIM). These two formulas calculate the energy costs in joules based on the voltage left in the node, the cost based on power level, Startup time, and to get the Radio on and the Oscillator on, and the size of the packet being sent divided by the transmission rate of the node, as shown in Equation 2, where P_T is power for consumption, V is voltage left in the node, P_{ROON} is Power on, Oscillator on, $T_{Startup}$ is startup time for Power on, Oscillator on, $CPlevel$ is cost to transmit for the specific power level, and L is the length of packet being sent, while $Trate$ is the transmission rate of the node.

$$P_T = V \times (P_{ROON} \times T_{Startup} + C_{Plevel} \times (L/T_{rate})) \quad (2)$$

The formula for receiving a packet of data is based on the Voltage left in the node, the Cost to receive data, which is a constant cost and does not change based on power level, and also the packet length divided the transmission rate of the node. The following formula is for power consumption for reception and V stands for voltage, C_R is reception energy cost, L is packet length, and T_{Rate} is that rate of transmission for the node, as shown in Equation 3

$$P_R = V \times C_R \times (L/T_{Rate}) \quad (3)$$

III. Simulation Design

In the simulation, the nodes are initially given 1 joule of energy, along with 512K bits of storage space. Each audio signal is to be converted to a wav format with data at 22.05 kHz; it is a 16 bit signal and is stored at 43K bits per second. There are 100 nodes deployed randomly across 100 $\times$ 100 m^2 network, with 5 sound sources randomly placed around the network. Each source transmits for a random interval of time between 1 and 20 seconds. All nodes that hear the sound, within 10 meters in any direction, are added to a group of nodes, from which the storage space in each node is compared, and the one that has the most storage space hears the seconds worth of data. The storage space is compared after each data transmission, and a node for the next second is determined. The process continues until the given time for that signal expires. The process was run at 3 different power levels, level 3 which uses 8.5 mA, level 11 which uses 11.2 mA and level 23 which uses 15.2 mA. The cost to receive a packet was constant at 19.7 mA. The maximum transmission rate for the node is 250000 bits per second.

The data is distributed across the network after a sound source finishes transmitting. Each node is assumed to be able to transmit to a distance of 10 meters, so for each node in the network the nodes within 10 meters are calculated and placed in a group. Out of these nodes, a possible node is selected based on the greatest difference between time to live based on energy and the time to live based on storage. Then, for the selected node, if the quotient of time to live based on storage for the receiving node and the time to live based on storage for the transmitting node is greater than a value B, a packet of data is exchanged between the two nodes. This is done for each node in the network. The simulation continues until the storage or energy of a node reaches 0, or if a source is unable to fully transmit to the network for two rounds. A source is unable to transmit based on either energy costs being too expensive, or there is not enough storage space left on the node.

Further, for a series of tests, the addition of different base stations throughout the network is considered. Tests were conducted with either 5 or 10 base stations throughout the network which could collect data and remove it from the network, freeing up storage space. The calculation for transmission of data to a base station is just if a base station is within the range of a node. If a node is in range of a base station, it is able to transmit data to the base station. The data is transmitted to the base stations at the very end, after the data has been transmitted from the sound sources and also transferred amongst the nodes in the network.

IV. Simulation Results

The simulation experiments were conducted with all three power levels we were testing: level 3, 11, and 23 of the CC2420 mote. The energy available on each node, storage space, transmission and receiving range, and the number of nodes were common across all tests. First, we present the results when base stations are not a factor, followed by the results when base stations are included, and then finally the results are presented when the B value (threshold), when comparing time to live based on storage, is changed.

A. No Base Stations

In this series of tests, all nodes and transmitters were randomly placed in a 100 $\times$ 100 m^2 area. As described above, the nodes and transmitters could each transmit and receive in a distance of 10 meters. For each power level, five simulations were done, and the average along with the minimum and maximum time for the network, along with how many rounds that were involved are presented. For the tests conducted for power level 3, the longest the network was active was 912 seconds for two different tests, with both 84 and 79 rounds of transmissions. The minimum lifetime was 769 seconds, the test being conducted for 82 rounds. The average for the network was a lifetime of approximately 849 seconds, with an average round total of 81 rounds.

When conducting tests on power level 11, the maximum lifetime was 1029 seconds, with a round total of 99 rounds, while the minimum was 786 seconds with a round total of 71. The average for this power level is a lifetime of approximately 910 seconds with a round total of approximately 86 rounds. This is an increase of 7.2% in the average lifetime category compared to the result with level 3 despite the increase in power consumpation. The tests were then conducted on power level 23 of the nodes, and the maximum result was 1015 seconds, with a total of 102 rounds, while the minimum was 702 seconds with a total of 69 rounds. The average lifetime for this power level is approximately 869 seconds, with an average round total of roughly 82 rounds. This is a difference of 2.3% compared to average of power level 3, and a difference of -4.7% compared to average of power level 11.

The difference between power levels 3, 11, and 23 is unexpected, considering power level 11 and power level 23 consume more power than level 3. The result is more understandable when factoring in the reason for the network failure. The limiting factor was the storage space remaining in the possible receiving nodes, while the amount of energy was still sufficient being above 0.8 joules for all nodes in all the tests conducted, which explains the difference in lifetime for power level 11 and power level 23 compared to power level 3. For further investigation, the tests were conducted including the use of base stations spread amongst the network. All nodes that would have failed in all tests, had 32K bits of data left. In table I, the results for Maximum, Minimum and Average lifetime for each of the three power levels are presented.

TABLE I
Simulation Results for No Base Stations

PA_LEVEL	Max Lifetime [seconds]	Min Lifetime [seconds]	Avg Lifetime [seconds]
3	912	769	849
11	1029	786	910
23	1015	702	869

B. Base Stations

Base stations were included after the results from the previous series of tests were conducted. Base stations were distributed randomly amongst the network with a series of tests including 10 base stations, and a series of tests involving 5 base stations. These tests were done at all three power levels. A base station was able to accept data from any node within 10 meters of its radius. The results are presented, including the maximum, minimum, and average for 5 simulations at each power level.

First, we consider power level 3 with 5 base stations. The maximum result for this round of tests was 5805 seconds, with a total of 534 rounds, the minimum amount was 4417 seconds with a total of 415 rounds. The average for this group of tests was approximately 5067 seconds, with approximately 475 rounds. The next test was power level 3 with 10 base stations throughout the network. The maximum result was a lifetime of 5452 seconds, with a total of 505 rounds, while the minimum was a lifetime of 5186 seconds, with a round total of 512. The average was a lifetime of approximately 5323 seconds, and approximately 511 rounds. These results represent an increase in average lifetime by roughly 597% for 5 base stations, and roughly 627% for 10 base stations compared to the average of power level 3 with no base stations. The data also shows that both energy and storage cause the network to fail, the energy that remains is much lower with nodes having as little as 0.00052 J left when the network is deemed to have failed, when the cost of receiving a packet of data is roughly 0.01 J, and storage amounts of 32K bits.

Next, the power level 11 with 5 base stations was tested, and the maximum was 4784 seconds, with a round count of 470, while the minimum was 3705 seconds with 358 rounds. The average for this test was 4368 seconds, with roughly 422 rounds. For 10 base stations, the maximum lifetime was 5873 seconds with 565 rounds, while the minimum was 5280 seconds 526 rounds. The average for this series of tests is a lifetime of roughly 5600 seconds and 542 rounds. The average lifetime, when including base stations, is an increase of roughly 480% with 5 base stations, and roughly 615% with 10 base station. The power level 11 has a shorter lifetime than power level 3, as should be expected, at the 5 base station level; however, at the 10 base station level, it still has a performance edge. This can be explained by looking at the reason for failure of the network at this power level. At this power level failure is apparently caused by the lack of energy remaining in the nodes because upon failure only a small fraction of nodes during the 5 base station test would be unable to store an additional second worth of data, while during the 10 base station test all nodes were unable to handle additional data. This is in contrast to power level 3, where at failure, for both 5 and 10 base stations, the vast majority of nodes were unable to handle anymore data, so with better optimatization of base stations or nodes placement, power level 3 can have a better lifetime as should be expected.

The final tests occurred at power level 23. First, using 5 base stations, the maximum lifetime was 4876 seconds with a round total of 454. The minimum was a lifetime of 3224 seconds and 310 rounds. The average was 3859 seconds and 367 rounds. This is an increase in average lifetime by 444% compared to no base stations. The results show that there are more nodes that would be unable to accept more data and it appears to be due to the increase power level, which means that the transmission power costs is increased, bringing about quicker failures. During the 10 base station tests, the maximum lifetime was found to be 4780 seconds and 472 rounds, while the minimum was 4544 seconds and 411 rounds. The average was a lifetime of roughly 4663 seconds and 442 rounds. There was an average increase in lifetime of roughly 537% compared to the earlier results of no base station. As discussed earlier, the reason of failure is that the data is not being transferred to base stations due to the increase in the energy cost to transmit, as most nodes seem to be close to full.

TABLE II
SIMULATION RESULTS FOR BASE STATIONS

PA_LEVEL	Base Stations	Max Life [seconds]	Min Life [seconds]	Avg Life [seconds]
3	5	5805	4417	5067
3	10	5452	5186	5323
11	5	4784	3705	4368
11	10	5873	5280	5600
23	5	4876	3224	3859
23	10	4780	4544	4663

The base station tests provided insight to the maximum possible lifetime for the network using very basic energy protocols and the EnviroMic protocol is expanded to include multiple base stations. At all three power levels, the networks achieved hundreds of times better lifetime compared to when no base stations were deployed in the network. Power level 3 was restricted based on the amount of storage throughout the network because most of the nodes could still transfer data amongst nodes. However, power level 11 was the level that contained the most energy usage amongst the nodes and it can perform better. Power level 23 is restricted by the energy demands to transmit data between two nodes, as most of the nodes were full at the end of the simulation. In table II the maximum, minimum and average lifetime for each power level while having either 5 or 10 base stations are presented.

C. B Threshold

The simulation experiments were conducted to see the effect changing the value of B. If we set the B value too high, the transmitting node has to be almost full before data is transferred. However, if it is set too low, the receiving node will need to have a small amount of time left to live. The experiments were done with the same settings as the tests with no base stations, and at power level 11. B was set to three different values, 2, 3 and 4, where each B level has 5 simulation runs. When B was 2, the maximum lifetime was 1029 seconds and 99 rounds, while the minimum was 786 seconds and 71 rounds. The average for this power level is a lifetime of approximately 910 seconds and 86 rounds.

When B was 3, the maximum lifetime was found to be 923 seconds and 90 rounds, the minimum was 744 seconds and 66 rounds, and the average was roughly 855 seconds and 83 rounds. These results show a roughly 6% decline in terms of average lifetime between the results when B was 2 compared to when B was set to the value of 3. When B was 4, the maximum lifetime was 969 seconds and 85 rounds, the minimum was 632 seconds and 61 rounds, and the average 832 seconds and 77 rounds. This average lifetime was roughly 9% worse than the value with B of 2. The experiments were not conducted on the values where B was less then 2 because of the fact that decreasing the value would mean that nodes receiving the data would have a smaller time to live than the transmitting node, and the goal of distrubting data across the network was to maximize lifetime. In Table III the results for the various B values, in terms of Maximum, Minimum and Average Lifetime are presented.

TABLE III
SIMULATION RESULTS FOR DIFFERING B VALUES

B Value	Max Lifetime [seconds]	Min Lifetime [seconds]	Avg Lifetime [seconds]
2	1029	786	910
3	923	744	855
4	969	632	832

V. CONCLUSION

Audio wireless sensor networks is an area requires a lot of research to maximize the potential, especially with current energy and memory limitations. A simple wireless sensor network with very basic energy saving methods and using the very basic EnviroMic protocol could be able to stay active for approximately 14 minutes on the lowest power level on modern day sensor nodes. However, with the addition of base stations and some changes in the protocol, the network could be active for 88 minutes. The addition of audio, especially the ability to store data across the network is important as it allows for more intense data collection and analysis to be conducted. At higher power levels, the storage is a huge restriction especially due to the cost to transmit data at that level. The realistic energy consumption models, based on the actual available power levels, provide more accurate evaluation of network lifetime and energy consumption.

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