Energy Latency TRADEOFF Stochastic Performance Evaluation In Wireless Sensor Networks

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ABSTRACT
The future Internet of Things era's fundamental network is made up of wireless sensor networks (WSN). These networks are made up of wireless nodes that are placed wirelessly with the goal of detecting a physical parameter and communicating the observed values to a base station. With the help of additional network nodes acting as routers, the transmission is completed. A microprocessor, a sensing device, and a radio for transmission make up a sensor node. Such a network encounters numerous deployment applications, which poses difficulties for network designers. The network lifespan and latency are the most important parameters that need to be optimised. The fact that wireless nodes are frequently prone to failure and are frequently deployed in large numbers in hostile and difficult environments is one of their most important characteristics. The nodes are also battery-powered and run on LR-WPAN protocols, which were created so that even a single lithium ion battery may last for roughly 6 months. These factors necessitate careful protocol design in order to ensure uniform energy usage across all nodes and enhance network lifetime with a minimum amount of packet loss. The Real Time WSN is a specific type of wireless sensor network that is used to manage time-sensitive requirements. This study makes two contributions. In terms of the number of Guaranteed Time Slots (GTS) in the superframe structure, it examines the real-time features of the network at the MAC Sublayer level. It is important to choose the ideal amount of GTS for the superframe in order to guarantee the lowest latency and longest network lifetime. In addition, it discusses the relationship between data aggregation and latency in the context of network lifetime at the application layer.

Keywords: Stochastic Modeling, WSN, Latency, Data Aggregation, MAC Sub-layer, Superframe, Network Lifetime.

INTRODUCTION
A network of sensing devices, referred to as "motes," known together as a wireless sensor network (WSN) [1-6], measures some quantitative measurements and transmits the measurement to a centralised computer for further processing. These items serve as nodes in the wireless data network, as their name suggests. These networks have a wide range of uses in the business, scientific, and academic sectors. [7-9] Fire sensors, temperature monitoring, heat detectors, radiation detectors, moisture sensor, pressure transducers, etc. are common wireless sensor network installations. In
recent years, there has been a steady increase in the applications of detectors for automation and other daily tasks. The modern internet is referred to as the internet of things by cloud and big data analysts [10–12], in which physical devices can interact with one another depending on the parameters measured and other variables.

If a refrigerator is properly programmed to send a request in the event that it runs out of milk on a Sunday morning, it might, for instance, ask a dairy stand or a milk supplier for assistance. [13] There are countless possibilities for WSN to transform modern living to a greater extent, transforming the current internet into the Internet of things. Figure 1 depicts the WSN in a general way.

The basic architecture of a WSN node is depicted in figure 2. The major components of a wireless sensor node or mote are:

- A microcontroller unit for managing the overall operation of the Node Unit.
- A sensing device (sensor).
- Analog to digital convertors for conversion of measured value to variable values.
- Battery for power supply
- Radio circuitry for transmission.
This is the most important component of practically all WSN deployment types. Since WSNs are used in locations where sensor nodes must continually monitor a certain quantity for an extended period of time without running out of energy, the nodes must be built with low battery consumption in mind. [14] For instance, a fire sensor in a hallway of an office building needs to continuously monitor for fire situations for a year or more so that, in the event of a fire, the message about the same may be sent to a central computer to turn the alarms on and to automatically dial the fire rescue team. WSN nodes are created with very low power consumption in mind. Low power consumption techniques include wireless sensor network protocols.

The term "latency" describes the interval of time between the occurrences of noticing something and the point at which the necessary action occurs. Low latency is a requirement for the majority of WSN deployments. For human rated systems, such as radiation level sensors [15] in nuclear power plants and temperature sensors in thermal power plants, a low latency requirement is essential. In IoT systems and applications, latency that exceeds a specific threshold is completely prohibited. The requirements for running a wireless sensor network with low energy and low latency are incompatible.

THROUGHPUT COMPUTATION OF THE GTS ALLOTMENT PROCESS IN THE CFP

The abstract view of the superframe at MAC layer of IEEE 802.15.4 can be depicted as shown in figure 3.

![Fig 3 IEEE 802.15.4 MAC superframe frame structure](http://www.webology.org)

It is evident from the figure that there exist frame beacons followed by CAP which is followed by the inactive interval. The inactive period is again followed by a beacon signal. This structure is particular to the application which uses slotted time. In the case of un-slotted (or pure) time, the beacon signal may or may not be present.

In the case of Real time applications, the CAP is optionally followed by a CFP consisting of Guaranteed Time Slot (GTS) which are reserved for the devices that have the time critical data to send to the base station or to the coordinator. A more detailed illustration of the superframe structure in such deployments is depicted in figure 4.
PERFORMANCE ANALYSIS OF DATA AGGREGATION, LATENCY AND ENERGY CONSUMPTION IN CLUSTER BASED WIRELESS SENSOR NETWORKS

Relationship between Data Aggregation, Latency, and Energy Consumption Analytical Model

The requirements for Data Gathering and Latency are shown to be incompatible in Figure 5, and one must choose an ideal location in the horizontal plane of Figure 5 for the deployment of the particular type of sensor network. The purpose of this research is to develop a generalised model of the WSN that takes into account data aggregation and grouping strategies, and then to tie that model to energy usage as precisely as possible. This research utilises the first order radio energy consumption model and primarily examines the network at the application layer. The most popular LEACH (Low Energy Adaptive Clustering Hierarchy) protocol is utilised to cluster the network. From a straightforward calculation like the one below, it is possible to determine the significance of data aggregation. Take into account the values for the energy consumption of the transmission and processing circuitry:

Analytical Model of Clustering and Data Aggregation

The specification for the model parameters are given in table 4.1.

Parameter Values/Specifications

Hardware ATMEGATMega60
System Software Tiny OS version 2.x
Energy Dissipation Model First Order Radio Energy Dissipation
Clustering Mechanism LEACH
Number of Nodes N
Number of Clusters K
Mean Number of Data Packets transmitted by each sensing node per unit time $\lambda$
Data Packet Size R bits
Physical Dimension of the Placement Area of the sensing nodes $a \times a$
Initial Battery power in each sensor node P

The network model can be analyzed in its three variants:
1. Network with no Clustering, no data aggregation.
2. Network with Clustering, No data aggregation.
3. Network with Clustering and Data Aggregation.

The goal of this work is to analyze all the above three and derive an exact relationship curve for the three parameter as shown in figure 4.1. More exactly, we need to derive the relationship between latency and energy consumption for various values of the system parameters.

In each of the configurations described above, it is assumed that the sink is externally powered and all other nodes of the network, viz, the sensor nodes and the cluster heads are battery powered.

4.4 Network with no Clustering and no data aggregation

The energy Consumption per unit time in the network is given by

\[ E = E_t + E_d + E_r \]

where

- \( E_t \) = Energy Consumption in processing Circuit at Transmitting Nodes
- \( E_d \) = Energy Consumption in transmission of data packets (all transmitting nodes)
- \( E_r \) = Energy Consumption in processing Circuit at Receiving Node(s)

Here,

\[ E_d = E(\lambda \ast R \ast N, d) \]
and
\[ E_r = E(\lambda \ast R \ast N) \]

where \( N \) is the number of nodes in the network, \( R \) is the data packets size, and \( \lambda \) being the mean number of packets sent per unit time by each node. Thus the energy consumption per unit time is given by:

\[ E = et1 \ast \lambda \ast R \ast N + ed1 \ast d2 \ast \lambda \ast R \ast N + er1 \ast \lambda \ast R \ast N \]

\[ E = ed1 \ast d2 \ast \lambda \ast R \ast N + 2 \ast et1 \ast \lambda \ast R \ast N \]

The last term is due to the fact that both the processing circuitry at transmission and the reception consumes equal amount of power.

As there is no clustering, it can be assumed that the sink is at an optimal location and almost equidistant from all the nodes. For a square area of side \( a \), the average distance of all the nodes from the sink can be assumed to be \( a/2 \). Thus, the energy consumption per unit time is given by:

\[ E = ed1 \ast (a/2)^2 \ast \lambda \ast R \ast N + 2 \ast er1 \ast \lambda \ast R \ast N \]

The network lifetime in this case is given by:

\[ \text{Network Lifetime} = N \ast P \]

\[ \text{Energy Dissipated per unit time in the WSN by all nodes} = N \ast L \]

where \( P \) is the energy (initial battery power) of every node and \( N \) is the number of nodes in the network. Thus

\[ N \ast L = \]

http://www.webology.org
This is the best case analysis of the Network lifetime as it implicitly assumes evenly energy consumption in all the nodes of the network. Even if the sink node is externally powered, the nodes in the field can transmit data unevenly due to which the energy dissipation in the nodes takes place at an uneven rate. At the time of realization of the sensor mote, the transmission range is defined. Thus, the network lifetime is independent of transmission distance. However, the mean number of data packets transmitted by each node is uneven which leads to more rapid battery depletion in some of the nodes as compared to the others leading to a reduction in network lifetime. It is important to mention here that network lifetime is defined as the time since the network is operational till the moment at which the first node of the network runs out of the battery. In the above equation, the power dissipation is uneven due to the uneven transmission of the data packets by the nodes. Assuming that the sink node is externally powered, the network lifetime can be well modeled by the following equation:

\[ \text{Network lifetime} = N * P \]

\[ ed1 * \frac{a}{2} * \lambda * R * N + 2 * er1 * \lambda * R * N \]

Let L1 be the latency caused by the A/D converter at the transmission and L2 be the latency caused in the receiving circuit. In this case, no latency is induced apart from these two as all nodes are connected to the central gateway in star topology. Thus, the overall latency induced in the WSN is:

\[ L = L1 + L2 \]

Assuming the equivalence of operations stated previously, the latency \( L2 = N * L1 \) as the receiver has to process data packets received from each of the node in the WSN. Thus, the latency in this configuration is given by:

\[ L = (N + 1) * L1 \]

### 4.5 Network with Clustering and no data aggregation

Consider the same physical situation of WSN having n nodes and K clusters. Thus, the average number of nodes per cluster is N/K. The processing of information in each of the cluster takes the following parameters:

1. Let EE be the energy consumption overhead in each of the cluster for Cluster Head election using LEACH. If the frequency of election is one in T time units, the per unit overhead of leader election is EE/T.
2. For a square having side a, if the complete area is partitioned into K blocks corresponding to K clusters, then a direct measure would suggest that the side of each of the partition (possibly rectangle) is 2a/K. Thus the average distance of all the
nodes of the cluster from the cluster-head is a/K.
3. On the basis of the results 1 and 2 as stated above, the Energy Consumption in each of the cluster is given by:

\[
E_K = \frac{e_t 1 \times \lambda \times R \times N}{K} - 1 + \frac{ed1 \times a}{K} - 1 + \frac{ed1 \times a}{K} - 1 + \frac{er1 \times \lambda \times R \times (N - 1)}{K} + \frac{ed1 \times a}{K} - 1)
\]

The first term represents the energy consumption in the transmitted circuit of N/K-1 nodes of each cluster. The second term represents the energy consumption in the antenna circuit of all the nodes of the cluster. The third term represents the power consumption in the CH circuit in processing all the data packets arriving from all the Cluster members. The fourth term represents the power consumption in antenna circuit in transmitting all the data packets arriving at the cluster head. This result can be explained in a simple way as for each cluster, the mean number of nodes transmitting at any time in the cluster is N/K and the mean distance is a/K. It is assumed that after the election of the cluster head in any of the cluster, all the cluster members are informed to operate in the low transmission range mode of the order of cluster head while the cluster head itself operate in mode of high transmission range to enable it to transmit data to the sink node.

The overall energy dissipation in the WSN per unit time is:

\[
E = K \times E_K + \frac{EE}{T}
\]

The Latency involved in this network topology is more than the previous mode due to clustering. Apart from the latency L1 and L2 stated previously, the latency involved due to clustering is LK = (N/K)*L1

The overall latency in the WSN is L = L1 + N
The parameter specification is same as given in the table 4.2 for MICA motes running Tiny OS 2.x.

### 4.6 Network with Clustering and Data aggregation

In this setting, the overall energy consumption in each of the cluster is given by:

\[
E_K = e_t 1 \times \lambda \times R \times (K - 1) + ed1 \times (a/K)2 \times \lambda \times R \times (N - 1) + C \times er1 \times \lambda \times R \times (K - 1) + ed1 \times (a/2)2 \times Z \times R
\]

The first term of the above equation relates to the energy consumption in the nodes sensing the physical parameter. The second term relates to the energy dissipation in the transmission of data packets over a/k distance in all the nodes of the cluster. The third term related the energy consumption incurred in data aggregation and compression. The variable to emphasize on the overhead in the compression/ aggregation algorithm is denoted by C. The fourth term relates to the data transmission from the cluster head to the central gateway computer. Here Z is the compressed number of data packets.

As stated previously, the overall energy dissipation in the WSN per unit time is:

\[
E = K \times E_K + EE / T
\]

The overall latency in the WSN is

\[
L = n + 1 \times L1 + LK + Lc
\]

where Lc is the latency involved in the data compression.

### 4.7 Results and Analysis

The results are computed for the mica motes running Tiny OS and the corresponding values of the variable are assumed for the analytical and simulation modeling. The tabular values of the variables as per the three network configurations__ Fig 4.3 The Network lifetime as a function of mean number of packets transmitted. The red curve shows the Lifetime without data aggregation whereas the green curve shows the network lifetime with data Aggregation.

Thus, it is evident that the network lifetime increases with the data aggregation. Also, not much improvement on network life time can be achieved with clustering without data aggregation. This is because in the absence of data aggregation, the cluster head has to forward all the data packets it has received from the cluster members, thus causing battery depletion at a very fast rate. With the use of suitable data aggregation / data compression algorithm at the cluster head (full functional device FFD), a substantial improvement in the network lifetime can be achieved. The computation of latency that is introduced in the network as a result of clustering is not straightforward. In the case
of clustering with no data aggregation, the latency involved is due to the fact that all the cluster nodes transmit the data to the cluster head and the cluster head transmits the data to the sink node. Latency is involved at A/D converter at CH, then the processing of the data and again in D/A Ckt at the CH for transmission to the WSN Sink. In the case of clustering with data aggregation, latency is involved at A/D converter at CH, then the processing of the data as per some compression algorithm with certain time complexity, and again in D/A Ckt at the CH for transmission to the WSN Sink. Moreover, the computation of Latency is also affected by the type of the hardware (e.g. Bipolar RTL or CMOS) for the realization of wireless motes.

4.8 Analysis of NP- CSMA
Without carrier sensing, each node has the liberty to send data packets as per the requirement. It is assumed that the transmission of the data packets and the time critical GTS requests by the node follows Poisson Distribution. As depicted in Chapter 3, the probability of k frame transmissions per unit frame time is given by:

\[ P_k = \frac{\lambda' k \cdot e^{-\lambda'}}{k!} \]

Here, \( \lambda' = N(P_1 + P_2) \). Here, \( P_1 \) is the probability that the transmitted packet is a data packet and \( P_2 \) is the probability that the transmitted packet is a GTS request. Substitution of value of \( \lambda' \) in the above equation yields:

\[ P_k = \frac{[N(P_1 + P_2)]k \cdot e^{-\lambda'}}{k!} \]

The plots for the above equation can be derived as shown in figure 4.1.

Fig 5 Poisson Probability Distribution for various mean values of Packet Transmission Rates - Continuous time

In fig 5 it is evident that the Poisson Probability Distribution takes the maximum value at the mean value. Thus, each of the curve finds its maximum at the mean value for which the Distribution is plotted.
The plot in the figure 7 shows the case of ALOHA in continuous and in slotted time. In the absence of carrier sensing and any other policy for data transmission, each node is free to transmit the data packet as and when the need arises. The maximum throughput achieved in this case is 18 percent in case of continuous time. In the case of slotted time, the vulnerable period is reduced to half of its value, thus, the throughput achieves double the value as compared to that in the pure time. This value is 36 percent and still is very low. The plot in figure 4.3 shows the generic probability of packet transmission in Non Persistent CSMA. It is evident from the figure that the probability of packet transmission increase with the increase in the number of nodes in the network. Also, for any particular value of number of nodes in the network, the probability of packet transmission increases with the increase in the mean value of packet transmission (data packet traffic) in the network.
successful transmission and collision. It is evident from the figure 8 that the probability of getting into the idle state increases as the time duration of the slot decreases. Also, the probability of getting into the idle state decreases as the mean value of packet transmissions by the node increases. Both these results are consistent with the practical scenario of the state of the channel in IEEE 802.15.4 MAC.

Fig 8 Analysis of NP CSMA - Probability of Getting into the ideal state: right horizontal axis shows the Time Slot Duration in slotted time Variant and left horizontal axis shows the Mean Number of Data Packets/GTS Requests Transmitted per unit time Figure 4.5 shows the transition probability of the system for having successful transition state from any of the three state of the system, viz, being idle, being in collision state or being already successful transmission state. It is evident from the figure that there are various peaks for successful packet transmission as the max value depends upon the number of nodes in the network and the mean number of data packets transmitted by each node in the network.

The probability of successful packet transmission is given as per the equation given in chapter 3, namely; $P_k = aG * e^{−aG}$ repeated here for ready reference. It is important to note that the packet transmission is successful if and only if a single node transmits the packet and all other nodes in the network are silent. Thus, corresponding to the values of slot duration and the mean number of data/GTS packets, there are several maxima for the probability of successful packet transmission.
Probability of successful packet transmission: right horizontal axis shows the Time Slot Duration in slotted time Variant and left horizontal axis shows the Mean Number of Data Packets/GTS Requests Transmitted per unit time Figure 10 shows the probability of the channel being in collision state from any of the state viz; idle, collision or successful packet transmission. It is evident from the figure that the probability of collision increases with the increase in the mean traffic rates of packet transmission by the nodes as well as the slot length in IEEE 802.15.4 MAC.

![Fig 10 Analysis of NP CSMA - Probability of Packet Collision](image)

Fig 10 Analysis of NP CSMA - Probability of Packet Collision: right horizontal axis shows the Time Slot Duration in slotted time

Variant and left horizontal axis shows the Mean Number of Data Packets/GTS Requests Transmitted per unit time

In the case of Non Persistent CSMA, it is important to note that the transmission channel can only be any one of the three states of the system, namely:

1. Idle Channel
2. Successful Transmission
3. Collision State

Figure 11 shows the steady state probability of being in idle state, in normalized condition, with respect to all the three state of the system. In the similar ways, figure 12 shows the stated state probability of the system being in collision state and figure 13 shows the probability of the system in successful transmission state.

![Fig 11 Analysis of NP CSMA - Steady State Probability of being in Idle State](image)
4.9 Analysis of P Persistent- CSMA of IEEE 802.15.4 MAC Through SPN
The Petri Net Model of the state of transmission channel in IEEE 802.15.4 MAC is depicted in fig 14. The same is repeated here for ready reference.
The set of tangible states of the channel state space derived by the Stochastic Petri Net analysis of the system.

**CONCLUSION**

The current study focuses on the tradeoff between data aggregation and delay when first order radio energy dissipation modulus is taken into account, and it gives analytical equation for the same. This research can be used to decide the best network configuration for a specific WSN deployment. This study adopts a bottom-up methodology, starting with data link layer performance modelling and moving up through application layer clustering, Data transmission utilising a cluster head-specified schedule. The details of the underlying hardware technology must also be considered as part of the work's future scope because the power dissipation varies significantly depending on the kind of technology used to realise the sensor module. However, because the ratio of emery expenditure in transmission and processing remains the same in practically all IC technologies, the results of this analysis are qualitatively significant regardless of when they are realised.

**REFERENCES**

