What Does Quality-aware Data Collection Really Achieve in Energy Harvesting Wireless Sensor Networks?

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Abstract: Energy is the major bottleneck for wireless sensor networks. Although energy harvesting sensor nodes have emerged as a solution, new challenges in energy management arise due to the intermittently available energy. We also observe that many applications can tolerate certain levels of data inaccuracies. Here, we exploit the application's tolerance for data inaccuracy to achieve an equilibrium between energy consumption and availability while satisfying application's accuracy needs, thereby improving network lifetime. Performance studies indicate that our method outperforms other data collection methods. Moreover, our comprehensive energy consumption analysis of quality-aware data collection on different sensor node arrangements reveals the limitations on energy savings when quality-aware data collection is used. We show that a tighter cooperation between MAC layer and Application layer, that is achieved through an Application-driven control mechanism can unlock the full potential of quality-aware data collection.

Keywords: Quality of data; Energy harvesting; Wireless sensor networks; Sensor mode transition; Network lifetime.

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1 Introduction

One of the main problems we face today when deploying wireless sensor networks (WSNs) is the limited energy availability. Generally, battery power supply is insufficient for running busy WSNs for longer time periods. Energy harvesting sensor networks, which are able to harvest energy from the surrounding environment, have emerged as a solution for this problem. Energy harvesting WSNs are generally known as energy neutral systems. These systems use abundantly available environmental energy sources to get the required energy to fulfill system requirements. Infinite lifetime is the goal of an energy neutral system. However, due to the uncertainty of the amount of harvested energy (thus the energy availability), we must manage energy consumption to achieve uninterrupted operations, while providing adequate communication with applications. Poor energy management can lead to the shutting down of those nodes with critical energy levels. In this paper, we introduce the integration of energy harvesting and consumption predictions, and sensor operation mode changes along with energy efficient communication patterns to balance energy usage.

Since communication is the major source of energy consumption in a wireless sensor node, the most effective way to extend the lifetime of a node is to reduce communication. We also observe that many applications such as landslide monitoring, groundwater quality monitoring, and oil pipeline monitoring can tolerate some imprecision in sensed data values. For instance, in subsurface contaminant monitoring Illangaskare et al. (2008), a subsurface transport model that takes continuous sensor readings as input provides a similar prediction of the evolution of the contaminant plumes as long as sensor readings do not significantly deviate from the ground truth. In this paper, we exploit an application's tolerance of data imprecision to avoid unnecessary transmission of sensor readings, thereby reducing communication. New readings transmission can be suppressed when the application can be satisfied using already available data. Theoretically, quality-aware data collection should give maximum energy savings while fully satisfying the applications. In this paper, we investigate how much energy savings can be achieved using quality-aware data collection in various network topology. Further, we show that tight cooperation between the MAC layer and the application layer can unlock full potential of quality-aware data collection.

Furthermore, as detailed in section 3, fair amount of previous work has studied energy harvesting sensor networks, prediction of harvested energy and quality-aware sensor data collection as separate problems. In contrast, there are very few studies that have considered these issues jointly. An our work presented here studies the joint problem. We aim at satisfying application accuracy requirements while ensuring uninterrupted sensor operation.

In this paper, we investigate the use of quality-aware data collection and, develop an algorithm to achieve a balance between energy consumption, network lifetime, and data accuracy. In particular, we model how a wireless sensor node can dynamically change its modes of operation while adhering to energy constraints and still maintaining acceptable level of communication and data quality to satisfy the applications. We theoretically determine conditions that must be satisfied to achieve maximum energy efficiency while using quality aware-data collection and operate the sensors accordingly. We propose different modes that a sensor node can operate to control energy consumption, and design an algorithm to trigger mode changes according to energy availability and energy consumption. In this way, the sensor network will provide uninterrupted service, and accurate data without introducing much latency.

Further, we also observed that different sensor node arrangements show different levels of improvements in energy consumption. In any single-hop node arrangement (i.e., an arrangement where sensor nodes are always one hop away from the sink node) the application can be allowed to directly control the antenna states (i.e., switching off and on the TX/RX antennas) without affecting the communication channels of the other nodes. In contrast, in a multi-hop network, arbitrarily switching off the antennas of an intermediate node will break the communication channels of the nodes positioned towards the edge of the network. Therefore, a fully compliant MAC protocol must be used to control antenna states for the multi-hop networks. Our analysis and results show that the application-driven control along with single-hop networks (or cluster based network arrangements) and quality-aware data collection shows much improved energy saving than the quality-aware data collection in a multi-hop network. We show that an application-driven antenna state controlling can unlock the full potential of quality-aware data collection.

2 Problem Formulation

The scenario we consider is graphically presented in Figure 1. Here, the sensor nodes will sense some parameters from the surrounding environment and send that data to the sink node where the applications can access them. All the application queries are submitted to the sink node. Some applications will need the exact values and others may be satisfied with a certain level of imprecision. Therefore, each application (or user) query is associated with an acceptable level of imprecision of W_{req}. The sink node always has to satisfy the W_{req} when answering a query. Further, the sink node and the sensor nodes negotiate on the imprecision level (which we call W) to be maintained for the data of each sensor node. This value is then stored in the sensor nodes as well as in the sink node. Sink node has a separate entry for each sensor node in its database comprised of the last reading received from each sensor along with the W maintained for that particular sensor node. Each sensor node maintains its imprecision level independent of the others. If the current sensor reading is not updated to the sink node, then the current data imprecision is the absolute difference between the current reading at the sensor and the previous value updated to the sink, and this will always be less than W. When the threshold W is reached, an update will be triggered. In this work, we are not attempting to address how to schedule queries. Instead, we aim at answering all the application queries with required accuracy and minimum latency while performing energy management to achieve a longer network lifetime.

In the following part we show how to vary the actual W in order to satisfy W_{req} while minimizing energy consumption.

- If all the sensor data stored in the sink node satisfies the application query requirement (i.e., $W \leq W_{req}$ for each sensor node), that query will be immediately served from the database in the sink node without querying sensors explicitly.

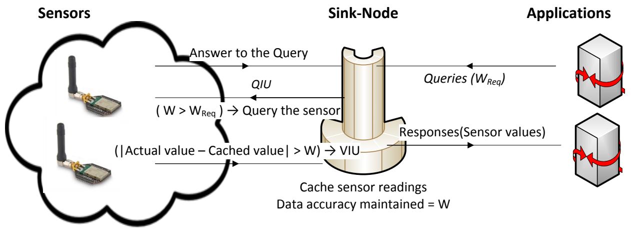


Figure 1: Proposed framework for quality of data assurance

However, if $W > W_{req}$ for any sensor node, then it explicitly queries the exact readings from the sensor network to meet the application requirement. Sensor nodes that are not satisfying the accuracy requirement will answer the query by sending the current reading and the newly calculated W(calculation of W is discussed in section 4). This process is referred to as a *Query Initiated Update (QIU)*. If more than one request of the same type simultaneously arrives at the sink node to be submitted to the sensor nodes, we construct one QIU with the lowest W_{req} (i.e., the highest accuracy). This will satisfy the accuracy requirements of all other pending queries.

- If any time the sensor node itself detects that its current reading exceeds the previous value updated to the sink node by more than a W amount, it will initiate an update and send the new reading along with the newly calculated W to the sink node while saving that in its own memory. This is referred to as a *Value Initiated Update (VIU)*.

So, any message sent from a sensor node to the sink node will look like (current reading, W).

By using these two update mechanisms, we are able to maintain the sensor value database in the sink node and accurately satisfy application queries. We adapt W according to the number of QIUs and VIUs. It should be noted that the number of QIUs and VIUs reflect the amount of communication happening in the network. To provide a holistic approach to dynamically adjust sensor data accuracy in energy harvesting sensor networks, we specifically address the following issues in this work:

Data accuracy management: Many WSN applications are able to tolerate some level of imprecision in data, and we can exploit this to minimize communication required in data gathering. However, we must do this carefully, so as not to assume a very high degree of data imprecision and to make the data unusable or incur additional delays in responding to application queries. In section 4 we discuss how to maintain data accuracy via updating W while minimizing energy consumption.

Energy management: For a WSN, the main source of energy consumption that can be controlled is the communication between nodes. On one hand if we reduce the communication, it may introduce significant delay in answering queries and will make data useless in some scenarios. On the other hand, more communication results in a higher energy consumption and the system will die out sooner. Hence, it is desirable to optimize communication considering both the application requirements and the energy availability. When taking energy harvesting into account, we will get a new energy source apart from the battery, so we can afford to more communication. However, since there is no guarantee on the amount of energy that can be harvested over a given period, we must be careful in making decisions on what to do with the available energy. Section 5 presents a method to predict energy harvest and consumption.

Sensor operations: We believe it is better to reduce communication of data to the sink node than to shutdown the sensor nodes due to energy limitations. Therefore, it is critical to have an effective state management strategy that will allow us to do this while operating the sensor nodes in a maximum capable mode. Section 6 proposes modes of sensor operation, derives energy consumption for each mode, and presents a strategy for sensor nodes to switch between different modes of operation.

To address all of the above issues, we present a detailed description, analysis, and simulation results of the approach we have developed to optimize communication and power consumption of energy harvesting sensor nodes taking into consideration both energy availability and application requirements.

3 Related Work

Our work is related to several areas of research: quality of data management, energy harvesting WSNs, and MAC protocols for energy harvesting sensor networks.

Quality of data management in sensor networks is to conserve energy consumption by exploiting application requirements for data quality such as tolerance for data imprecision or latency. For instance, Yu et al. (2004) explores energy-latency trade-offs to achieve energy savings, Olston et al. (2001) investigates how to adapt accuracy levels of data so that the cache data values can be used to answer application queries successfully in large computer networks, Han et al. (2007) develops a method that integrates data accuracy tolerance and management of sensor operating state for improving energy efficiency and lifetime of WSNs. However, none of the above mentioned work was not done in the context of energy harvesting.

The problem of efficient energy management for energy harvesting sensor nodes introduces a whole new dimension. Previous work like Kansal et al. (2006), Sudevalayam et al. (2011) and Viigorito et al. (2007) gives some insight about energy management in these networks. Prediction of the harvested energy is an important problem in this area. Unreliability of the energy sources makes it hard to accurately predict the energy availability and Ali et al. (2010) presents one of the better approaches to predict future energy harvest based on previous data and current environment conditions. We use the method presented in Ali et al. (2010) in our work to get the predicted energy harvest.

During our study of related work we only came across a very limited amount of work done considering quality of data management and energy management of energy harvesting WSNs together in one problem. As the most related one, Dang et al. (2011) (QuARES) aims to minimize average actual error margin while adhering to energy constraints in energy harvesting WSNs. In other words, QuARES uses application imprecision tolerance and data caching to reduce energy consumption while keeping maximum possible accuracy in the data cache. In contrast, our work aims at efficient management of the energy consumption for a longer network lifetime while satisfying accuracy needs of application queries, a dual problem of QuARES.

In our work, we demonstrate how to use accuracy tolerances and mode transitions of sensor nodes to realize energy savings while supplying accurate and timely data to the applications. We strategically use cached data values, Query Initiated Updates, and Value Initiated Updates as well as prediction of harvested and consumed energy to realize this.

Model driven data acquisition as in Deshpande et al. (2004) and Raza et al. (2012) provides frameworks for optimizing the acquisition of sensor readings. Generally with model driven data acquisition, sensors are only used to acquire data when the statistical model itself is not sufficiently rich to answer the queries with acceptable confidence, thereby reducing the amount of communication needed in data acquisition. For example, Raza et al. (2012) introduces a model driven data acquisition method that shows 99% data suppression in sensor data collection. Normally we would expect the network lifetime to show an increase in the same order due to reduced communication. However, they found that the network lifetime extension achieved was comparatively less. When a CSMA based MAC protocol is given the control of the antenna state, antennas may become actively receiving data which are not intended to them. Any communication occurring in the contention domain triggers the receiving antennas. This is the main reason that Raza et al. (2012) can not achieve the expected life time extension even with high data suppression. TDMA based MAC protocols switches off the receiving antennas when the sensor nodes are not supposed to receive any data. However, maintaining a schedule in a large multi-hop sensor network is impossible. Furthermore, in a multi-hop network, an intermediate node can not switch off receiving antennas arbitrarily. Doing so can disconnect the communication paths to the other nodes. However, for a single-hop network, we can safely switch off receiving antennas when sensor nodes are not supposed to receive data. In this paper we show that for one-hop networks and cluster based network arrangements, higher energy savings can be achieved by allowing the application layer a greater control over the radio state management which may switch off the receiving antenna when it expects no data.

Among MAC protocols developed specifically for energy harvesting WSNs, Seah et al. (2009) investigates performance of different MAC layer protocols in harvesting only (i.e.,nodes without a battery) wireless sensor nodes, and Vigorito et al. (2007) develops an adaptive duty cycling mechanism for energy harvesting WSNs that allows sensor nodes to maintain their power supply at sufficient levels by adapting to changing environmental conditions. However, these methods do not specifically consider application's requirements, whereas our approach adapts node's operation according to application requirements while adhering to energy constrains.

4 Sensor Data Accuracy Maintenance

There is always a trade-off between accuracy of the sensor data maintained in the sink and the communication overhead. On one hand, if higher accuracy (i.e., smaller W) data is maintained, there will be more VIUs and less QIUs (because sensor readings have higher probability to vary beyond the smaller accuracy range). On the other hand, if lower accuracy data (i.e., higher W) is maintained in the system, there will be more QIUs and less VIUs (because there is a higher probability that the accuracy expected by the application query to be higher than the low accuracy level maintained in the sink node database). However, increase of either QIUs or VIUs increases the energy consumption. Therefore, a balance must be found between these two types of updates (i.e., QIU and VIU) in order to minimize the total number of updates and reduce energy consumption.

4.1 Modeling Energy Consumption

A wireless sensor node consumes energy mainly for sensing and communication.

Energy consumed for sensing: This source of energy consumption is constant if a constant sampling rate is maintained.

Energy consumption for communication: The amount of energy consumed for communication varies depending on the amount of VIUs and QIUs.

In a multi-hop network, we can categorize the energy consumed for communication by a sensor node into two. The first one being for receiving messages destined for itself and messages originated from itself and the second one being for forwarding messages destined for others (i.e., serving as a relay node for others). The first category is totally dependent on the amount of QIUs and VIUs incurred. Thus, it is dependent on the W value maintained by the sensor node. In contrast, the second category is not controllable by the sensor

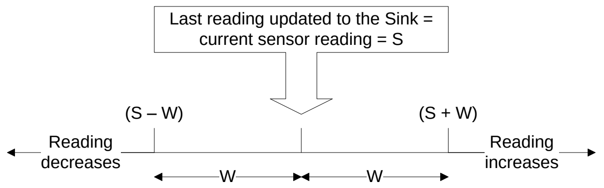


Figure 2: The value of a sensor node right after an update

node, no matter how W is maintained, the second part is related to the amount of messages injected by other sensor nodes to the network. Therefore, from the perspective of a particular sensor node, this is uncontrollable by changing parameters like W associated with itself. It must be noted that by individually controlling the amount of communication, the sensors collectively reduce the energy consumption of the whole network. This fact enables us to do computations in a distributed manner individually by the sensor nodes to reduce their own energy consumption, thereby reducing the energy consumption of the whole network.

We denote the energy consumption of a sensor node per time unit for sensing as E_{sense}, for QIUs as E_{QIU}, for VIUs as E_{VIU}, and for being a relay node as E_{relay}. Further, if the probability of QIUs per unit time is P_{QIU} and the probability of VIUs per unit time is P_{VIU}, then the total energy consumption per unit time E_{total} can be modeled as follows,

$$\begin{aligned} E_{total} &= E_{sense} + E_{relay} + P_{QIU} \times E_{QIU} \\ &\quad + P_{VIU} \times E_{VIU} \end{aligned} \tag{1}$$

4.2 Modeling Probabilities of QIUs and VIUs

If a smaller W (i.e., higher accuracy) data is maintained in the system, there will be a higher probability of sensor readings varying beyond the small accuracy range. However, there will be a lower probability of application queries requesting an accuracy that can not be satisfied by the data stored in the sink node. Thus, smaller W leads to higher P_{VIU} and lower P_{QIU}. In contrast, if a larger W (i.e., lower accuracy) data is maintained in the system, there will be a higher probability of application queries requesting an accuracy that can not be satisfied by the data stored in the sink node. However, there will be a low probability of sensor readings varying beyond the larger accuracy range. Thus, larger W leads to lower P_{VIU} and higher P_{QIU}. Therefore, it is evident that both update probabilities can be controlled using W.

Consider the relationship between the current sensor reading at a time instance immediately after an update to the sink occurs (the update can either be a VIU or a QIU) and the current imprecision level W as depicted in Figure 2. At this time instant, the sensor reading updated to the sink (we denote it by S) and the current sensor reading are the same. However, starting from the next moment the current reading deviates from S according to the variations in the sensed parameter. For the purpose of this derivation, we assume that the change in the sensor reading during each time step is 1 unit. When the current reading increases by W units or decreases by W units from S, a VIU will be generated. Since the environment's behavior is unpredictable, we assume that the sensor reading can increase with a probability of p or decrease with a probability of q at given time step. Furthermore, A VIU will be triggered if the current sensor reading increases beyond $(S + W)$ or decreases beyond $(S - W)$. Take Y_W as the number of time steps until the next VIU and $E[Y_W]$ as the expected value of Y_W. Here, the subscript W of Y_W represents how far the current reading is from the lower boundary condition $(S - W)$. It is easy to see that Y_0 and Y_{2W} are the VIU triggering points, and $E[Y_W] = 1 + p \cdot E[Y_{W-1}] + q \cdot E[Y_{W+1}]$.

It should be noted that $E[Y_0] = E[Y_{2W}] = 0$. For the purpose of the derivation we assume the sensed variable behaves unbiased, and $p = q = \frac{1}{2}$ (our methodology works well even when $p \neq q$. For the simulation results presented later, we use $p = 0.55$ and $q = 0.45$). We can obtain the following relationship,

$$E[Y_W] = 1 + \frac{1}{2} \cdot E[Y_{W-1}] + \frac{1}{2} \cdot E[Y_{W+1}]$$

Which yields, $E[Y_W] = W^2$. Hence, $P_{VIU} \propto \frac{1}{W^2}$ or it can be written as,

$$P_{VIU} = \frac{K_1}{W^2} \tag{2}$$

where K_1 is a constant parameter.

By assuming that the queries arrive periodically (every T time units) and the accuracy requirement for the query varies uniformly in the range of $[0, W_{max}]$. Since a QIU occurs when $W > W_{req}$,

$$\begin{aligned} P_{QIU} &= \textit{(Probability of a Query is issued)} \\ &\quad \times \textit{(Probability of } W_{req} < W\textit{)} \\ &= \frac{W}{T \cdot W_{req}} \end{aligned}$$

Therefore, $P_{QIU} \propto W$. In other words,

$$P_{QIU} = K_2 \times W \tag{3}$$

where K_2 is a constant parameter. The results for P_{VIU} and P_{QIU} we derived here are the same as in Olston et al. (2001).

4.3 Finding the Right Data Accuracy

Lemma: In an environment with randomly changing sensing values and periodically arriving queries with accuracy requirements, maximum energy savings can be achieved by maintaining $P_{QIU} = 2 \cdot (\frac{E_{VIU}}{E_{QIU}}) \cdot P_{VIU}$.

Proof: By substituting the values for probabilities in Equation 1,

$$\begin{aligned} E_{total} &= E_{sense} + E_{relay} + K_2 \cdot W \cdot E_{QIU} \\ &\quad + \frac{K_1}{W^2} \cdot E_{VIU} \end{aligned}$$

To find the minimum E_{total}, we should have $\frac{dE_{total}}{dW} = 0$. In other words, $K_2 \cdot E_{QIU} - 2 \cdot \frac{K_1 \cdot E_{VIU}}{W^3} = 0$. Then by using Equations 2 and 3,

$$\frac{P_{QIU}}{W} \cdot E_{QIU} - 2 \cdot \frac{P_{VIU} \cdot W^2 \cdot E_{VIU}}{W^2} = 0$$

Therefore, for minimum energy consumption

$$P_{QIU} = 2 \cdot \frac{E_{VIU}}{E_{QIU}} \times P_{VIU} \tag{4}$$

Hence, if Equation 4 can be maintained during operation of a sensor node, the energy consumption will be minimized. Each sensor doing this individually results in reduction of energy consumption of the whole network. In order to ensure equilibrium found in Equation 4, W must be dynamically changed as follows,

- If a QIU occurs,
  W is decreased with a probability of $min[2 \cdot \frac{E_{QIU}}{E_{VIU}}, 1]$:
  $$W' = W/(1 + \alpha)$$
  Since a QIU involves receiving a query message and transmitting a reading as the answer, in contrast to a VIU which only involves transmitting a reading, E_{QIU} is always higher than E_{VIU}. Therefore, with each QIU, W will be decreased with a probability of 1. Since $E_{QIU} \geq E_{VIU}$, $2.\frac{E_{QIU}}{E_{VIU}} \geq 2$. Therefore, the probability becomes $min[2, 1]$, which is always 1.
- If a VIU occurs,
  W is increased with a probability of $min[2 \cdot \frac{E_{VIU}}{E_{QIU}}, 1]$:
  $$W' = W(1 + \alpha)$$

Here, α is the adaptation parameter which should be greater than 0. In their work, Olston et al. (2001) obtained the same equilibrium relationship using Chebyshev's equation.

5 Prediction of Energy Harvested and Consumption

In addition to battery, a sensor node can have energy harvesting mechanisms such as solar, movement, wind, or chemical compositions. Generally, depending on the amount of energy left in a sensor node, we should determine how often the node should communicate with the sink node. To make an informed decision on how to operate sensor nodes, we have to predict the amount of harvested energy and the energy consumption. Since, the development of a prediction algorithm is not the main focus of our work, we use the technique presented in Ali et al. (2010). This can be always replaced with another if necessary.

We use the following formula from Ali et al. (2010) to predict the solar energy harvest for the $(n+1)^{th}$ T_H time slot. Here, T_H is the prediction interval.

$$e_H(n+1) = \alpha_H.e_H(n) + [(1-\alpha_H) \cdot \mu_H(D, n+1)] \cdot \Phi_{HK} \tag{5}$$

where $e_H(n)$ is the harvested energy for the n^{th} time slot, α_H is a weighting parameter with value $0 \leq \alpha_H \leq 1$, and $\mu_H(D, n+1)$ is the average of past D days' energy harvested for the $(n+1)^{th}$ time slot of the day. Φ_{HK} is a measure of how much active today in terms of harvesting compared to previous days.

To predict energy consumption, we used a similar technique. The predicted energy consumption for the $(n+1)^{th}$ T_C time slot (T_C is the prediction interval) is expressed in the following equation,

$$e_C(n+1) = \alpha_C \cdot e_C(n) + [(1-\alpha_C) \cdot \mu_C(D, n+1)] \cdot \Phi_{CK} \tag{6}$$

where, $e_C(n)$ is the energy consumption of n^{th} time slot, α_C is a weighting parameter with value $0 \leq \alpha \leq 1$, $\mu_C(D, n+1)$ is the average of past D days' energy consumption for the $(n+1)^{th}$ time slot of the day. Φ_{CK}, is used to indicate how busy today compared to other days.

6 Adaptive Sensor Operation

When an energy harvesting sensor node is considered, other than the energy stored in the battery, it can accumulate more energy by harvesting. However, the maximum amount of energy available is upper bounded by the capacity of the battery. When a sensor node is in operation, it will consume energy for sensing, to be alive and for communication. It will always incur the cost of sensing and being alive, but we will be able to reduce the energy consumption due to communication by manipulating when and how the sensor node communicates (It may be possible to adapt sensing frequency in response to environment, to save more energy. However, it is not the focus of this work). More precisely, energy consumption can be minimized by maintaining the optimal W value (As we have proved above, which can be achieved through maintaining the derived relationship between the probabilities of VIUs and QIUs).

A battery-powered sensor node always should minimize the energy consumption to achieve a longer lifetime. However, still it is finite. In contrast, an energy harvesting sensor node, as long as it maintains an equilibrium between energy harvested and consumption, can enjoy infinite life-time, given that the sensor components do not fail. Therefore, we propose different modes of operation for sensor nodes to control communication related energy consumption. This way, when energy is sufficiently available, nodes can afford to more communication and be more responsive to queries, so less delay is introduced and the sink node gets updated regularly. When the energy available drops to a certain threshold level, nodes transition to a new mode where less communication happens, but still updates the sink. Here, the nodes take decisions individually about the mode transitions. Furthermore, if the energy storage is almost depleted, we believe that it is important to reduce communication until more energy is harvested instead of letting the sensor nodes to shutdown. Therefore, we further reduce the communication.

Sensor radio states are typically controlled by the MAC layer protocol. MAC protocol tries to ensure that the receiver antenna does not miss any incoming messages due to being in a wrong antenna state (for example, in sleeping mode). Since there is no guarantee on when a node will receive a message, the MAC protocol has to keep the receive antenna on even when no packets are received, and this scenario is known as idle listening. However, to reduce energy consumption caused by idle listening, researchers have developed MAC protocols like TMAC (Van Dam et al. (2003)) that are able to reduce idle listening, but not to fully eliminate.

MAC protocol must be given authority to control the antenna states in multi-hop node arrangements, where it is not possible to arbitrarily switch off and switch on the antennas according to decisions made by another layer. For example, the application layer. Because each node in a multi-hop network has its own responsibility in forwarding messages destined for others, and their states are not synchronized. We refer to this control mechanism as MAC-driven control. However, in a network where all the sensor nodes are only one hop away from the sink node (e.g., in a cluster based sensor node arrangement), by using a scheduling mechanism such as periodic listening we can completely switch off the receiving antenna when a sensor node is not supposed to receive any messages, thereby saving considerable amount of energy. Here, the application can be given the control of changing antennas states, and one node switching off its antenna does not break the communication links to other nodes. Therefore, using Application-driven control we are able to save more energy compared to a MAC-driven method, because we can change the radio state when needed.

We propose two mode transition strategies. They show considerable energy savings over current control methods used. A MAC-driven mode transition, which is suitable for multi-hop node arrangements and a Application-driven mode transition, which is suitable for one-hop node arrangements. Furthermore, in both methods, we use the equilibrium relationship given in equation 4 to achieve the best energy efficiency.

6.1 MAC-driven Mode Transition

There has been lots of work done aiming to improve energy efficiency using better routing or MAC layer protocols in wireless networks. Energy consumption by RX/TX antennas is one of the main contributors (most of the times the highest contributor) to the total energy consumption. Improvements to MAC protocols in the form of low-power listening and duty-cycling tries to switch off antennas when they are not used. However, due to energy consumed in idle listening in these methods, researchers have developed better solutions like adaptive low power listening (e.g., Jurdak et al. (2007)) and T-MAC protocol(Van Dam et al. (2003)) to further improve energy efficiency. Since T-MAC shows better energy savings (around 98% less compared to basic CSMA) than others, we use T-MAC as the MAC protocol in our work.

In the proposed MAC-driven mode transition, the antenna states are fully controlled by the MAC protocol (i.e., MAC-driven control). Depending on the application's traffic and communications happening in the contention domain, the MAC protocol controls the antenna states. Here, we define two modes that a node can operate according to the available energy as follows,

[Mode_FO] – *Full Operation***:** The sensor node answers all the QIUs and send VIUs as needed (i.e., as defined in 2) without any restriction.

[Mode_FB] – *Fallback***:** When a sensor node does not have enough energy to safely operate(i.e., without shutting down) in Mode_FO, it will switch to Mode_FB. Here, QIUs will not be answered and a fixed W will be maintained. Due to fixed W values maintained, number of VIUs will also be limited. Essentially the sensor node reduces all its communication with the sink node until enough energy is harvested.

It is evident that due to lack of communication, Mode_FB should result in lover energy consumption than Mode_FO.

6.2 Application-driven Mode Transition

We propose Application-driven Mode Transition and claim that, it can achieve considerably higher energy savings compared to other generally used control methods as well as the MAC-driven Mode Transition, when used in one-hop node arrangements (e.g., cluster based sensor node arrangement). Here, Application-driven control is used as oppose to MAC-driven control.

When considering a multi-hop network, even in Mode_FB of the MAC-driven mode transition, a sensor node can not completely switch off its RX/TX antennas. In a multi-hop network each node has to act its part to keep the connectivity by relaying messages destined for others. In contrast, in a single-hop network or in a cluster based network where all cluster members are only one hop away from the cluster head, we can arbitrarily switch off the RX/TX antennas of a sensor without affecting the communication links to others. To have this kind of control over the RX/TX antennas, the MAC protocol must be modified to control antenna states according to the commands given by the application layer (i.e., application's decisions according to the energy availability). Akkaya et al. (2005) provides an overview of some of these techniques. However, it is important to note that this type of control is only applicable to single-hop sensor arrangements or in the networks that are arranged as clusters, where all the sensor nodes are one hop away from the sink node or the cluster head.

One-hop node arrangements are quite common in real world sensor deployments. For example, having energy scavenging leaf nodes interact with a powered mesh is practical in applications such as energy efficient buildings Schmid et al. (2010). Leaf node to head node communication in an area as mentioned in Chen et al. (2002), and leaf node to branch node communication as mentioned in Yerva et al. (2012), also consider one-hop communication. While multi-hop communication is more flexible, it actually adds complexity to the system, and practical system deployments often end up deploying one-hop networks for the sake of simplicity and better performance. Therefore, application-driven mode transition has its practical usage.

For Application-driven mode transition, we define three modes of operation for sensor nodes to follow,

[Mode_PR] – *Periodic Reception*: In this mode, the sensor node switches on RX antenna periodically according to a period consistent with the sink node. And all the sensor nodes in the cluster uses the same period. QIUs can be submitted by the sink node during these reception periods and all the sensor nodes in the cluster will hear the same message (an example message will deliver commands like Äll the nodes with $W > 0.5$ should update the sink ̈). However, the sink node has to wait until the next reception period of a sensor node to send a query. It should be noted that, all the sensor nodes follow the same period. By selecting a small period, we can make this wait time negligible. However, that increases the energy consumption. The advantage here is that a sensor node can switch off its receiving antenna when it is not supposed to receive messages from the sink node. Still a packet transmission from the sensor node to the sink can occur due to a VIU or as an answer to a QIU at anytime.

[Mode_PT] – *Periodic Transmission*: In this mode, a sensor node periodically transmits the readings to the sink node and the RX antenna is kept switched off all the time. Therefore, no QIUs will be received or answered by sensor nodes in this mode. In our simulations we set one periodic transmission per second. However, this period can be changed according to the application's requirement. Since, receive antennas are switched off all the time, this mode shows higher energy savings. Furthermore, this mode does not use QIUs or VIUs and W is not dynamically updated.

[Mode_FB] – *VIU Fallback*: In this mode, a sensor node generates VIUs, but no QIUs will be answered. A fixed value for W is maintained. Furthermore, a packet transmission from the sink node to a sensor is only allowed to occur immediately after a VIU. Sink node uses this opportunity to communicate any control information. In our simulations we have used $W = 4$.

In packets from sensor nodes to the sink node, one data field is used to carry the W value without using a separate packet. Therefore, there is no additional communication required to communicate W. Furthermore, each mode of operation has different energy consumption rates because of their differences in communication level. It is possible to define more modes according to the requirements. However, according to the above mode definitions and the communication level of each mode it is evident that $E_{Mode\_PR} > E_{Mode\_PT} > E_{Mode\_FB}$. During the simulation section, we will evaluate the energy consumption comparison experimentally.

The sensor nodes in low capable modes including Mode_FB (in both in MAC-driven and Application-driven mode transition) and Mode_PT does not have the capability to answer QIUs. If a query needs a higher accuracy than of the data saved in the database at the sink node, still the sink node will query the network. However, the nodes which are in low capable modes will not answer the QIU, but the others will answer. Therefore, only a small fraction of the nodes will not satisfy the accuracy requirement. However, even the sensor nodes in low capable modes keep the sink node updated to some acceptable level. Therefore, the data from that nodes also provide some degree of accuracy and can be considered as valid. Furthermore, since the sink node does not wait extra for the non-answering nodes, any extra delay would not be added.

6.3 Mode Transition Strategy

We propose to switch the mode of operation of a sensor node according to the amount of remaining battery energy, predicted harvested energy, and predicted energy consumption (Figure 3). The predicted energy consumption depends on which mode the system will operate in the next time slots and the accuracy level maintained. Higher accuracy and more responsive operation mode results in higher predicted energy consumption. When a node harvests more energy, it can transition into a more capable mode. The decision on which mode to operate must be taken at the beginning of each time slot so that we are able to make decisions frequently enough. Further, by making decisions in discreet time intervals we are able to eliminate unnecessary thrashing between modes and keep the system stable in one mode for at least T_C time units.

At the beginning of each $(n+1)^{th}$ T_C time slot, a decision will be taken on which mode to operate based on predicted energy harvest and consumption. Basically, we select the most capable mode from the available modes while ensuring that there is a B_L amount of energy left in the sensor node until the end of a T_B time period even if no energy was harvested during that time. B_L and T_B is selected according to the application and to ensure uninterrupted operation of the sensor nodes.

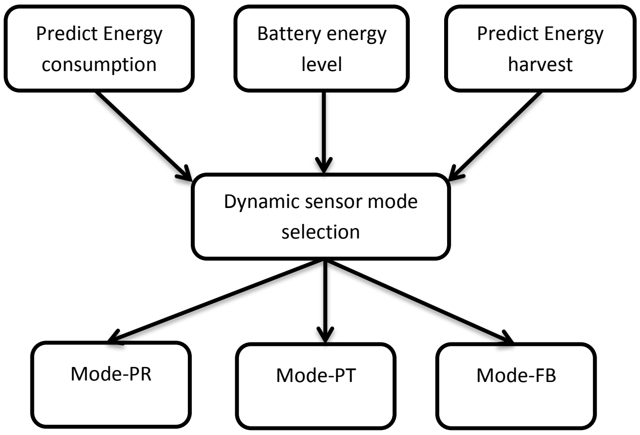


Figure 3: Application-driven mode transition (MAC-driven variant has only two modes)

The algorithm we developed for energy management and mode transition is shown in algorithm 1 (operation of the sink node), algorithm 2 (operation of a sensor node with Application-driven mode transition), and algorithm 3 (operation of a sensor node with MAC-driven mode transition). All the query analysis and decisions to query the network (i.e., issue QIUs) is done at the sink node. Decisions on whether to send VIUs (i.e., if the sensor reading varies beyond the last updated reading by W) and whether to answer a query (Due to wireless nature of the channel all sensor nodes will receive the queries) is made individually by each sensor according to its own parameters. With this independence (no unnecessary coordination among sensor nodes) and distributed decision making, our algorithm only adds negligible overhead to the data collection process, while ensuring longer network lifetime.

Algorithm 1 Sink node operation

```
for Each event trigger do
  if event = Application query then
    if any sensor with less accuracy then
      if MAC-driven Mode Transition AND Mode of
      at least one SN = Mode_FO then
        Initiate a QIU
      else if Application-driven Mode Transition AND
      Mode of atleast one SN = Mode_PR then
        Initiate a QIU
      end if
      for Each new answer received for QIU do
        Update the database entry for that sensor;
      end for
    end if
    Answer the application from database;
  end if
  if event = New VIU received then
    Update the database entry for that sensor;
  end if
end for
```

Algorithm 2 Sensor node operation (Application-driven mode transition)

```
Using Application-driven mode transition
for Each event trigger do
  if Event = Beginning of T_C time slot then
    Make a decision of Mode to operate
    if Mode ≠ Mode_PR then
      Switch off RX antenna
    end if
  else if Event = New sensor reading then
    Store the reading
    if Mode ≠ Mode_PT AND VIU needed then
      Send the Reading to the Sink
      if Mode = Mode_FB then
        Listen to incoming message from Sink
      else
        Update W
      end if
    end if
  else if Mode = Mode_PR AND Event = QIU received
  then
    if W > W_req then
      Update W
      Answer the QIU
    end if
  else if Mode = Mode_PT AND Event = Periodic TX
  then
    Send current sensor value to Sink
  end if
end for
```

Algorithm 3 Sensor node operation (MAC-driven mode transition)

```
for Each event trigger do
  if Event = Beginning of T_C time slot then
    Make a decision of Mode to operate
    if Mode = Mode_FB then
      Switch off RX antenna
    end if
  else if Event = New sensor reading then
    Store the reading
    if VIU needed then
      Send the Reading to the Sink
      if Mode = Mode_FB then
        Listen to incoming message from Sink
      else
        Update W
      end if
    end if
  else if Mode = Mode_FO AND Event = QIU received
  then
    Forward the QIU to other nodes
    if W > W_req then
      Update W
      Answer the QIU
    end if
  end if
end for
```

7 Performance Evaluation

7.1 Simulation Environment

We used the Castalia simulator release 3.2 (Castalia Wireless Sensor Network Simulator (National ICT Australia) (http://castalia.research.nicta.com.au/index.php/en)) for the performance evaluation of our algorithm. It's a simulator based on the OMNeT++ simulation platform (omnet (http://mirc.rsna.org)) and we modeled our algorithms as an application in Castalia.

CTP (Collection Tree Protocol) Omprakash et al. (2009) is used as the routing protocol to route data packets from the sensor nodes to the sink node, and a flooding mechanism is used to send queries from the sink node to every sensor in the network. T-MAC is used for the MAC layer. However, we modified it to send MAC level acknowledgments to the routing layer to support CTP. Radio parameters of CC2420 radio module is used to model radio parameters (CC2420 is the radio module used in TelosB and Micaz motes).

Sampling rate for sensor readings is set to 10 samples/second. In each sampling period, the sensing value increases 0.1 with probability p and decreases 0.1 with probability q, and we set p and q to 0.55 and 0.45 respectively. Furthermore, we switch the values of p and q every hour to simulate a change in the trend. We model the queries using a uniform distribution with a query frequency of 1 query/second and each query demands an accuracy randomly from the range between [0,8], which is a very high accuracy demand comparing to Dang et al. (2011); Kansal et al. (2006)). We dynamically change W according to QIUs and VIUs following equation 4 to achieve best energy efficiency, and the allowable range for W is set to [0,8].

Solar irradiation (mW/m^2) data from the National Renewable Energy Laboratories website Solar Resource Data (National Renewable Energy Laboratories USA) (http://www.nrel.gov/rredc/solar_data.html) was used for energy harvesting stats. We divide each day into 24 equal time slots. Initially, 3 days of data related to consumption and harvesting are loaded into the system. In our simulations, $T_B = 12$hours, $T_H = 3600$seconds, $T_C = 3600$seconds, and $B_L = 500$J.

Furthermore, we tested with three basic sensor node arrangements,

- Arrangement-1: One sink node and one sensor node
- Arrangement-2: One sink node and four sensor nodes that are one hop away from the sink node
- Arrangement-3: One sink node and 100 sensor nodes that form a multi-hop network

In Arrangement-2, although the sensor nodes are one hop away from the sink node, when one sensor node communicates with the sink node the other sensor nodes in the contention domain can hear the communication and it triggers the receiving antennas of other nodes causing energy consumption. In contrast, in arrangement-1 the sensor node triggers its receiving antennas only for the communications intended for itself. Although arrangement-1 may not be used in practice, it is the ideal situation where application control of sensor a nodes' modes performs the best, and we use it as an reference.

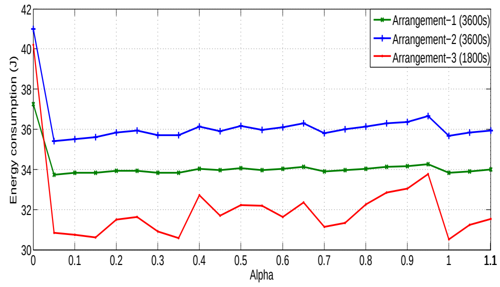


Figure 4: Energy consumption while changing α in Mode_FO

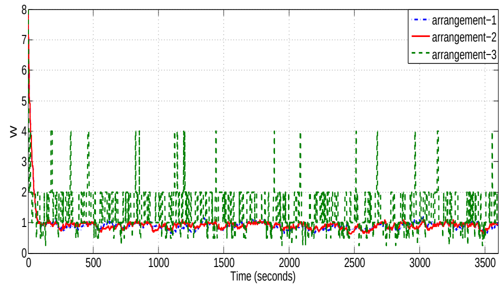


Figure 5: Dynamically changing W with QIU and VIU

7.2 Impact of α

The adaptivity parameter α controls the degree of changes in W when we dynamically adjust it according to the frequency of QIUs and VIUs. Therefore, the total energy consumption of the system depends on α. We have simulated the sensor nodes' power consumption for 3600 seconds in Mode_FO for different network arrangements to find the best α when our dynamic precision setting is used. Figure 4 shows that $\alpha = 0.05$ gives the lowest energy consumption in Arrangement-1 and Arrangement-2, and $\alpha = 1$ in the multi-hop network arrangement. For further performance studies we used the best α value obtained here.

Operation of our proposed algorithm decreases W when QIUs occur and increases W when VIUs occurs, while ensuring the equilibrium defined in Equation 4. As an example to show how this happens, we present one-second sampled values of W for a sensor node using MAC-driven mode transition with arrangement-3 in Figure 5.

7.3 MAC-driven Mode Transition

We first compare the adaptive precision setting method that we use in Mode_FO against three other generally used fixed precision setting data collection methods. Namely, QIU only (i.e., the sink generates a QIU for each query submitted by the application and does not use VIUs), fixed precision of 4 (i.e., $W = 4$, here both QIUs and VIUs occur. Furthermore, 4 is used because it is exactly half of the maximum allowable imprecision of 8.), and fixed precision of 0.5 (i.e., $W = 0.5$, this maintains highly accurate data in the sink and almost only VIUs occur). Figures 6a, 6b and 6c show the one-hour energy consumption of the above methods in different node arrangements. It is evident that the dynamic precision setting method we use yields the lowest energy consumption.

Furthermore, table 1 shows the per hour energy savings achieved by the dynamic precision setting method we use over the other generally used data collection methods and it is evident that the dynamic precision setting method saves considerable amount of energy.

Table 1 Per hour energy savings (J/hour)

Node arrangement	QIU only	w = 4	w = 0.5
1	3.468	1.44	2.44
2	5.586	2.002	2.866
3	21.113	4.167	1.651

Next, we compare the energy consumption in MODE_FO and Mode_FB. In Mode_FB, a sensor node does not reply to QIUs. However, it generates VIUs using a fixed W of 4. Therefore, Mode_FB has far less communication compared to Mode_FO. Figures 7a, 7b and 7c show the comparison of one-hour energy consumption in different node arrangements. Note that the energy stats here are for a specific sensor node and not of the entire network.

It is interesting to note that Figures 7a, 7b and 7c show that although Mode_FB significantly reduces the amount of communication needed by a node, it does not save a significant amount of energy for that node. There are two main reasons for that. First, since we use a standard MAC protocol it is not possible to arbitrarily switch off the receiving antenna even when not needed. In Mode_FB, although a sensor node does not respond to QIUs, it still receives all of them and then ignores them. Furthermore, when the received antenna is switched on, it hears all the communication happening in its contention domain. All of these cause unnecessary energy drain which could have been avoided by switching off the reception antenna when the sensor node moves to Mode_FB. Therefore, to get the full benefits of different modes of operation, MAC protocol should be modified to control the reception antennas directly according to application decisions. Second, in a multi-hop network, although a specific node does not respond to any QIUs, it still has to forward the messages destined for the other nodes. Therefore, comparatively less energy saving is achieved over Mode_FO.

7.4 Application-driven Mode Transition

In Application-driven mode transition, the application has control over switching off and on of antennas. Due to the prior negotiated periodic reception intervals, application is able to make these decisions without loosing any incoming packets. Here, the receive antennas are only kept on, during the reception intervals. Therefore, we are able to save significant amount of energy. However, as described previously in Section 6 this is only suitable for one-hop networks or cluster based network arrangements. Figure 8 demonstrate the energy savings that can be achieved using Application-driven control over the MAC-driven control mechanism when arrangement-1 is considered. Here, most capable modes (i.e., Mode_PR for Application-driven control and Mode_FO for the MAC-driven control) without any mode transitions are considered. It is clearly noticeable from the figure that, Application-driven control mechanism saves considerable amount of energy even over the MAC-driven control which already performs better than other generally used control mechanisms as we have shown in the previous section.

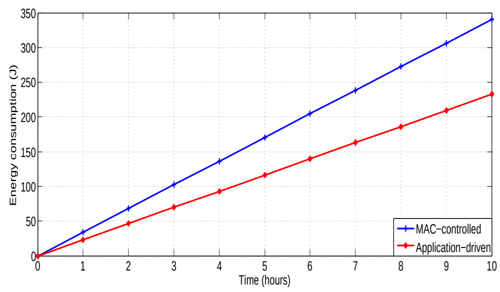
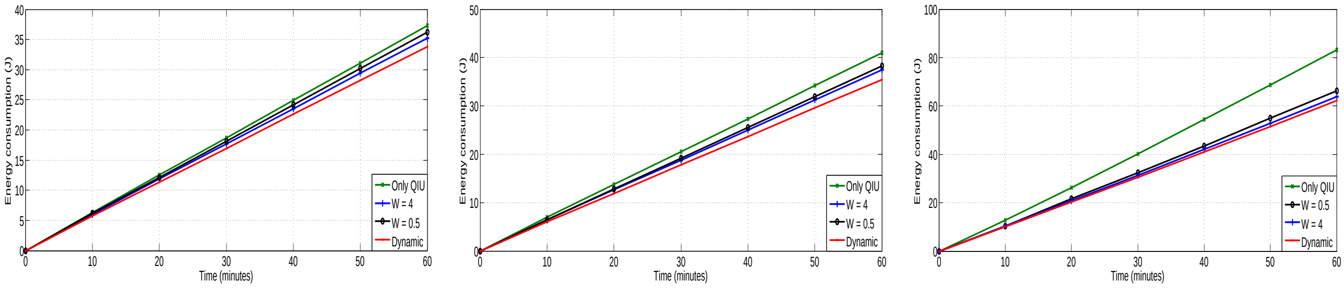


Figure 8: Energy consumption comparison between Application-driven and MAC-driven antenna state transition methods in arrangement-1

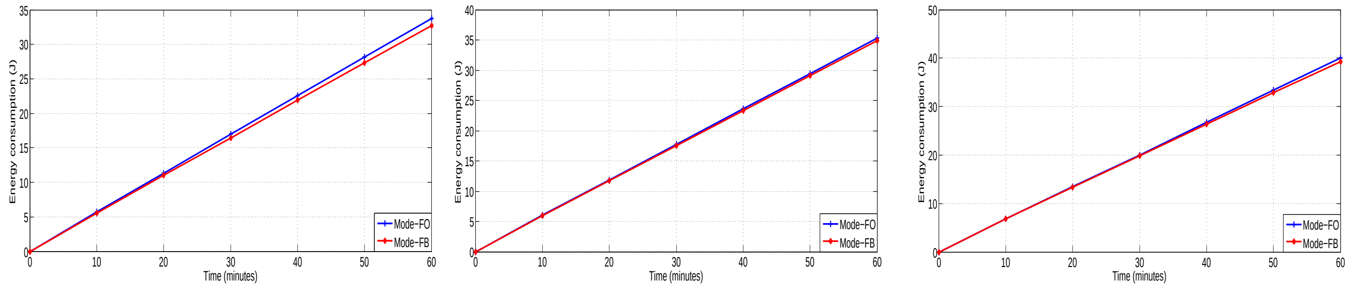
8 Mode transitions for uninterrupted service

To demonstrate how the mode changes can be used to extend the life-time of a sensor node and how an energy harvesting sensor node can move into a less communicating mode of operation until enough energy is accumulated to move back in to a more capable mode, we developed a discrete event simulator where Application-driven control mechanism is used to control switching off and on of the reception antenna. As we have shown in the section 7.3, although MAC-driven control has high energy savings than other generally used methods, it does not show a considerable difference of energy consumption between different modes of operation. However, the Application-driven control shows perfectly identifiable energy savings even between different modes of operation. Therefore, Application-driven mode transition is the natural candidate for the



(a) arrangement-1 (b) arrangement-2 (c) arrangement-3

Figure 6: Energy consumption in MODE_FO



(a) arrangement-1 (b) arrangement-2 (c) arrangement-3

Figure 7: Comparison of energy consumption in Mode_FO and Mode_FB

mode transition strategy for achieving uninterrupted operation of energy harvesting wireless sensor networks. However, it should be noted that we only make this claim for one hop networks or the cluster based network arrangements. For multi-hop networks there is no choice other than using the MAC-driven control mechanism to achieve both higher energy savings and less complex node operation (i.e., not using highly complex scheduling mechanism).

In order to show dramatic mode changes we used 500 J initial battery level and a 20 Joules per hour energy harvesting rate for the sensors (Mode changes occur rarely if actual values are used for these parameters. The sensors do not encounter energy limitations within a short period of time, because of the energy efficient equilibrium between VIUs and QIUs that we follow). Other energy parameters such as antenna TX/RX energy consumption, idle energy consumption and adaptivity parameter α are the same as those used previously. The simulation is conducted for 100 hours assuming a single-hop network. In order to clearly show that the mode transitions occur differently with energy harvesting, we simulated the mode changes with and without energy harvesting considered.

Figure 9 shows the mode transitions of a sensor node when energy harvesting is not available. Although it consumes less energy than other fixed precision setting methods by maintaining the relationship between QIUs and VIUs according to Equation 4, the sensor node still uses energy for operations and the battery level drops continuously. Therefore, when a critical battery level is reached, the node moves in to a less energy consuming mode, but it can not move back in to a higher capable mode because there is no way to gain more energy. In contrast, when energy is harvested, there is a source of energy to recharge batteries. Therefore, the sensor node is able to move back to a more capable mode when enough energy is harvested(Figure 10).

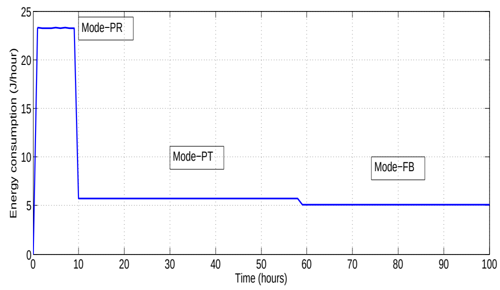


Figure 9: Mode transitions without energy harvesting

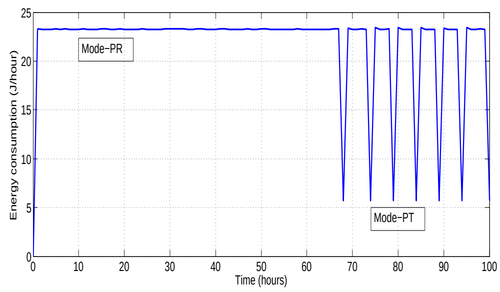


Figure 10: Mode transitions with energy harvesting

9 Conclusions

Both theoretical analysis and simulation results given in this paper show that quality-aware data collection with dynamic precision setting mechanism allows greater energy savings than fixed precision setting methods. Therefore, proper quality-aware data collection results in longer network lifetime. More importantly, for energy harvesting sensor nodes, proper energy management combined with the quality-aware data collection yields uninterrupted services. However, in emergency situations where it not possible to harvest energy and the battery level is critical, the nodes have to transition in to states where further energy savings is possible in order to avoid shutdown. The different modes of operation we defined with different energy consumption levels helps to do this. The proposed algorithm keeps a sensor node in a more capable mode when enough energy in battery is present and in less capable modes when battery level is critical. We showed that intelligent transition between these modes achieves uninterrupted service. It is rare that a node get to critical battery levels when energy harvesting sensor nodes and quality-aware data collection are used together.

When a sensor node's antenna state transition is controlled by the MAC protocol, there is no considerable difference in energy consumption between different modes of operation. In contrast, when application-driven mode transition is used, greater energy consumption differences are observed between different modes of operation. However, it has to be noted that the application-driven mode control is only suitable for networks where the sink node is one hop away from the sensors and in cluster based node arrangements. In either case, quality-aware data collection consumes less energy, but with MAC-driven mode transition, the energy savings between modes is marginal. However, when quality-aware data collection is used in conjunction with Application-driven control, far greater energy savings are achieved and clearly identifiable energy consumption differences are observed between modes. Therefore, it is evident that tight cooperation between the MAC layer and the application layer unlock the full potential of quality-aware data collection in energy harvesting sensor networks.

Furthermore, our algorithm successfully uses the knowledge of energy consumption predictions, energy harvest predictions, different modes of operation, quality-aware data collection and dynamic precision setting to keep the sensor nodes alive while satisfying the application queries. The algorithm moves the sensor nodes between different modes of operation to balance the energy consumption and the available energy to realize uninterrupted service. However, tight cooperation between the MAC layer and the application layer should be used (Application-driven control) to get considerable differences of energy consumption between different modes of operation, hence the full potential of the optimization methods introduced in this work.

As future work, we are looking in to more tighter methods to build coordination between Application layer and MAC layer to control sensor antenna states as well as into methods to dynamically control sensing frequency according to the environment to get better energy efficiency.

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