Multi-hop Scheduling and Local Data Link Aggregation Dependant Qos in Modeling and Simulation of Power-aware Wireless Sensor Networks

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ABSTRACT

In this study of wireless sensor networks (WSN) protocols, the application Qos, system, and protocol performance metrics are measured for a large scalable wireless deployment using a typical wireless radio and an energy model. As there are many different types of WSN algorithms, we have categorized it into pro-active, re-active, and query driven information processing. A typical Qos is based on the useful lifetime of sensor nodes, after which reliability of the sensor data cannot be guaranteed and typically, a threshold such as a percentage of the sensor drains out of energy or a minimum through-put of real-time data from the sensor network is expected, which is used to compare the Qos of the routing algorithm. The results from lifetime based Qos, measured in simulation seconds, for the implemented protocols show that with varying sampled data sources for a BE Qos multi-hop deployment and varying percentage of cluster heads in a time- synchronized deployment, the lifetime is based on network size and protocol invariant. However, low sensing ranges result in dense networks, and therefore, it becomes necessary to achieve an efficient medium-access protocol subjected to power constraints. Scalability of sensor network applications are based on energy energy-harvesting techniques in which the various layers of the network interoperate and extend the system network lifetime, the battery residual power per node, and the application reliability in terms of cross-layer energy savings. In this study, we have extended the lifetime metrics from a constant metrics into a break down of how much percentage of time is spent for Tx, Rx, and Idle tasks, respectively. This helps one to highlight the cross-layer energy dissipation per node and how the performance of an algorithm differs in terms of duty-cycling. Furthermore, we have shown that the energy savings due owing to the distributed algorithms in a large sensor network will not be practical without a complimentary lower-layer MAC. We show have demonstrated that the Qos is very much related to the ambient conditions, namely, are the Rx and Idle modes. From these preliminary results, we have added a new category of WSN protocols which are based ion the renewable energy resources, namely, the Fusion Ambient Renewable Measuring Sensors (FARMS). The study of sensor FARMS -harvesting applications allows one to measure the impact on Idle, Sleep, and renewable energy cycles as well as their unique deployment (density) needs, as all the sensor are not active(Rx) at all times. We have also shown that the efficiency of cross-layer Qos performance of routing algorithms with MAC losses has a long tail which is similarly observed in Power Law. In this sensor network model we like to show the complexity of clustering, messaging and data rate in terms of $\bigcirc(\sqrt(N)\log N)$, $\bigcirc(N)$ and $\bigcirc(\log_2 N)$ where N is the number of nodes.

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Categories and Subject Descriptors

C.2.2 [**Computer-Communication Networks**]: Network Protocols; C.2.2 [**Computer-Communication Networks**]: Metrics—*complexity measures, performance measures*

General Terms

Design, Experimentation, Measurement, Performance

Keywords

Algorithm complexity, Qos for link quality, Power Aware Routing, MAC layer duty-cycling, Distributed algorithms, Wireless Sensor network, Renewable energy resources

1. INTRODUCTION

Tuning the cross-layer parameters is very essential when working with constrained wireless sensor network (WSN) protocols. As the unique nature of deployment includes the needs of harsh environments for sensor networks, the integration of data Qos and the network throughput Qos is an essential part of a well-designed sensor network. As data is sensed at the lower layers that are MAC-dependent, we need to analyze the reliability of the data gathering protocol as well as its functions in a dense deployment. The sensor network STACK will need to have a tight-link layer acknowledgement to achieve the desirable Qos. The lower-level protocol works in a very small tiny window that is typically defined as the time to live (TTL) of the underlying protocol, and hence, it is very efficient and requires enough correlated sensors to measure the parameters, such as light, temperature and humidity, and bestow a time-stamp to them. Once the data payload is defined with the updated information about time and value, it has to be efficiently routed. A design should be constructed in such a way that it allows to multi-hop the payloads using least energy, and at the same time, efficiently schedule the node for local housekeeping, clustering, and ambient activities. Hence, a software infrastructure needs to be developed, which can allow queuing of messages, selection of best routes, and guarantee delivery mechanism to the available sink node that uses average Qos based on the available active nodes and residual energy. Power-aware sensor hardware specifications have evolved and have specifically given deterministic metrics for sensing and routing tasks in terms of μA and mA, indicating that data transmission is very much more power draining than normal sensing tasks. For a constant battery model delivering $mA - h$ power for the underlying radio model specified by the manufacturer, the minimal transmission is observed to be the preferred mode of operation for prolonged lifetime of the sensor network. This typical lifetime model shows that to operate in such a mode, the burden on Rx and Idle tasks, which when combined, take equivalently enough power when compared with the data transmission, suggesting that the design is for normal wireless network and not for energy-aware WSN. In this paper, we will use practical models that employ duty-cycling at the lower layers and measure the impact of Tx, Rx, and Idle over a long period of time, and use an amortized power-drain cost to accurately predict the lifetime of the simulated sensor network.

2. MOTIVATION

Qos for sensor network can be based on the reliability of data and the power consumption during its entire useful lifetime. Currently, most of the metrics are defined for individual layers, namely network and MAC layers, as this writing application needs to select the right routing algorithms and its corresponding hardware that provides sufficient bandwidth using the MAC, to provide custom solutions. This is a daunting task, and as most of the application developers do not know the details of the MAC, it makes it even harder to deploy and scale a large network. To simplify the many dependencies, we have used the Qos of the sensor service, which is independent of any specific algorithm, protocol, or battery model. This service-based measurable index is solely based on its dependence on the data link layer MAC. The lower-layer MAC provides adaptability for reliable data and saves power to sense the new data from the sensors, as well as offers constant tension to update new data and compute reliable paths to the sinks. The power savings calculated is solely based on the sleep states in motes, duty-cycling, harvesting periodicity, and reliable fusion of the sensor data, which makes it independent of the energy model. To simulate the cross-layer dependencies, the setup is broken down into three steps: the first step uses a non-network simulator that only implements the distributed algorithms that are dependent on the random ad hoc placement of nodes per meter square, resource allocation, cluster head rotation, and variable RF control. The second step uses network simulator that has loadable MAC modules and a corresponding battery model for Tx, Rx, and Idle states with their respective mA used by the radio. This allows accurate measurement of energy drain for Tx, Rx, and Idle for a real-time clock, for aggregating the sensor data. The third step combines the first and second steps, coding into real sensor node using the network simulator that can deploy large number of nodes for a given RF radio range. This allows accurate measurement of the data periodicity for a CBR source that routes the data payload over the sensor network. The simulated results calculated are prioritized for parameters that are not dependent on large constant energy resources but are based on Qos, which include data reliability, MAC latency, and energy-savings owing to sleep scheduling. These MAC-dependent parameters are adapted for ultra-low-duty cycles for renewable lifetime model of energy-harvesting application that rely on ambient energy (FARMS) [2]. This simulation approach allows the integration of specific needs for emulating a real mote, as well as the study of the adaptation of MAC to Qos, which is independent of the lifetime model.

2.1 RENEWABLE ENERGY MODEL AND ENERGY HARVESTING

For a multi-hop sensor network using a lifetime renewable energy model [2], an active node that is ready to transmit at a given instance will take a time period t to reach its neighbors, and the response time for receiving the message back will be $2 \times t$ or a preset TTL value. To efficiently multi-hop, we need to at least have one neighbor that can respond to the active node, but in a large WSN network, the traffic is directly proportional to the number of neighbors. The model has to take into consideration the example deployment that has sufficient number of receiving nodes to respond to the on-demand traffic generated by active nodes. If the receiving nodes do not have sufficient energy to aggregate the new data and re-transmit them, then it needs to have an active queuing by which it can avoid the complete loss of the new data it received, but relaying it when it has enough charge resulting in a latency $f(x) = \sqrt{n} = 1$, n number of nodes or best-effort Qos. To study the MAC characteristics for constrained devices, which are uniquely dependent on varying node densities as well as limited transmission ranges and power, the model needs to have a scheduling periodicity and must select new available active nodes in the multi-hop path between nodes to forward the data. The routing algorithm that is dependent on the density of the network also needs to find a leader node to multi-hop from the clusters to the sink nodes.

3. LIFETIME MODELING-SYSTEM PERFORMANCE USING MAC DEPENDENCE

3.1 Multi-hop MAC's

Limited research has been carried out on integrating different network layers into one layer or to investigate the benefit of cross-layer interactions between routing and MAC layers for sensor networks. Most of the existing protocols can use RTS/CTS extensions to achieve collision-free broadcast. Hence, to have an effective cross-layer scheduling, one of the suggested design is the combination of MAC/physical-layer integration and Routing/MAC/physical-layer integration. A variable length TDMA scheme has been proposed, in which the slot length is assigned according to some criteria for optimum-energy consumption in the network. Among these criteria, the most crucial ones are the information about the traffic generated by each node and the distance between each node pair. Based on these values, a linear programming (LP) problem has been formulated, in which the decision variables are normalized time-slot lengths between the nodes. The LP program is solved using an LP solver that returns the optimum number of time slots for each node pair as well as the related routing decisions for the system. The proposed solution could be beneficial in situations where the required data must be prepared. However, it is generally difficult to obtain the node-distance information and the traffic generated by the nodes. Besides, the LP solver can only run on a powerful node. The dynamic behavior of sensor networks will require online decisions that are very costly to calculate and hard to adapt to an existing system. Multi-hop Infrastructure Network Architecture (MINA) is another method for integrating MAC and routing protocols. This proposed design uses a layered multi-hop network architecture, in which the network nodes with the same hop count to the base station are grouped into the same layer. Channel access is a TDMA-based MAC protocol combined with CDMA or FDMA. The super-frame is composed of a control packet, a beacon frame, and a data transmission frame. The beacons and data frames are time-slotted. In the clustered network architecture, all the members of a cluster submit their transmission requests in beacons slots. Accordingly, the cluster head announces the schedule of the data frame. The routing protocol is a simple multi-hop protocol where each node has a forwarder node at one nearer layer to the base station. The forwarding node is chosen from the candidates based on the residual energies. Moreover, the transmission range of the sensor nodes is a decision variable, as it affects the layering of the network (the hop-counts change). The simulations were run to determine a good range of values for a specific scenario.

3.2 Performance Analysis of WSN data aggregation algorithms

Our performance evaluation of data aggregation algorithms uses a single-hop neighbor discovery and a distributed method to select a cluster head. After the completion of the protocol process, the metrics measured are the control protocol overhead, the data payload received without errors at the cluster head, and the running average of the performance of the data aggregation algorithms, i.e., if all the neighbors respond successfully, then it is considered as 100% aggregation, otherwise a loss of data aggregation is reported owing to insufficient data. In this study, we assumed a population of M sensor nodes, sharing the same noiseless radio channel, without any hidden or exposed terminals. In addition, we also considered a single-hop fully connected cluster of nodes, i.e., all the sensors can hear transmission from any sensor in the cluster [2]. Furthermore, no central control existed and each sensor node had an equal probability of generating a packet for transmission to any of the rest of the $M-1$ nodes in the cluster. Every packet consisted of a header and a payload part. The header was used for synchronization of the receiver and carried control information, such as the address of the receiver node and the total length of the packet. The payload was the useful sensor information transmitted between the nodes. Owing to the high density deployment of the sensor network, the MAC protocol must be designed with features, such as collision avoidance when multiple sensors access the same channel, filtration of sensed payload data from interference noise, and decreased battery consumption owing to idle listening when the protocol is idle, which consumes as much energy as it does when receiving, as in the case of IEEE 802.11. The simulation of the variation of MAC with node density is shown in Figure 1.

3.3 Link Protocols

Data link protocols can be categorized into two main IEEE wireless standards.

3.3.1 *Sampled*

Communication is unsynchronized, data transfer wakes up the receiver. Some examples are B-MAC, Aloha with Preamble Sampling, Mica1 LPL, CC2500, Reactive Radio.

3.3.2 *Slotted*

Communication is synchronized, data transfers occur in slots. Some examples are S-MAC, T-MAC, TRAMA, 802.15.4.

In sensor networks, multicast is an important type of communication pattern. In protocols that include clustering, cluster heads communicate with their members and thus, all the intended receivers may not be the neighbors of the cluster head, but may just be a subset of the neighbors. We used this type of data aggregation at the cluster heads using clustering for various link protocols. We used GlomoSIM, with 100 nodes deployed in a 140 Œ 140 m with a radio range of 50 m. As this is a close deployment of a dense network, we expected a lot of collision and data loss.

3.4 Carrier Sense Multiple Access - CSMA-CA

Carrier Sense Multiple Access (CSMA) and its variants appear in several major MAC protocols designed for WSNs [6], such as S-MAC, T-MAC, Shift, and IEEE 802.15.4. The CSMA-based protocols have the benefits of low complexity, scalability, and ability to adjust to population changes. On the other hand, they suffer from energy-wasting problems, such as packet collisions, overhearing, and idle listening. Assumptions: constant length packets, No errors, except those caused by collisions. No capture effect, each host can sense the transmissions of all the other hosts. The propagation delay is small when compared with the transmission time, once a node receives a packet that needs to be sent, it broadcasts a jam signal onto the network to make sure that the channel is clear, as well as to inform the other devices not to broadcast. CSMA-CA acts to prevent transmission collisions before they occur, unlike CSMA-CD (Detect). To evaluate CSMA with the GlomoSIM, we used two categories of WSN algorithm: one using clustering, which has lots of time-synchronization overheads, and the other using multi-hop, which is highly distributed owing to its independent synchronization. As the definition of CSMA is collision avoidance, it performs well in a dense network, outperforming B-MAC and 802.11 in total successful data aggregation at the cluster heads. The simulation results are shown in Figure 1, 2.

3.4.1 Design for collision avoidance

CSMA = Message Transmission = 2× Propagation

Clear Channel Assessment and Packet Backoff for channel arbitration. Link-Layer Acknowledgment for reliability, especially when picking leader nodes owing to path selection. Low Power Listening for low power communication, only a link protocol (a small core of media access functionality). Contains a set of interfaces that allow services to tune its operation. To eliminate idle listening, it is absolutely crucial for the MAC protocol to support the duty-cycling mechanism. To evaluate B-MAC with the GlomoSIM, we used two categories of WSN algorithm as described earlier. As the design of B-MAC is receiver-centric, it is always capable of receiving packets to the next hop with much less drop rate in multi-hop routing, when compared with CSMA and 802.11. The simulation results are shown in Figures 1, 2.

3.4.2 Design for collision avoidance

B-MAC = Preamble Length = Sleep Schedule = 100 ms

4. NETWORK MODEL

It is important to design and test the behavior of MAC protocols based on the kind of power used in scheduling states of the MAC. We identity two main techniques for dense wireless Sensor MAC protocols.

4.1 Local Power dissipation due to RF Interference

When MAC losses are considered as in figure 1,2, using power-aware MAC like CSMA and BMAC, the test bed provides many unique characteristics of cross-layer STACK analysis. If one takes into account the pathloss model which is the additional parameter of interest, it can be show that the interference due to high density MAC transmission during data forwarding, clustering and normal channel management has a long depleting tail and also follows Power Law [5] dissipation $\left\|\frac{1}{(1+r^2)}\right\|$, where r is the Transmitter range in meters. Figure 1, 2 shows the lifetime plot for various routing algorithms with MAC in varying densities (75,140, and 440 meter squares). BMAC performance better when compared to CSMA and delivers reliability on events at $P \geq 4.0$ and at the same time some of the event and query based algorithms have losses close to theoretical lower [5] bounds of $P = 3.0$.

4.2 Data Link Probability for Sensor Data Aggregation

The problem of Data Link probability for sensor data aggregation can be addressed in two different models which are adaptive to traditional sensor network protocols and the more flexible low-level MAC protocols services.

4.2.1 Random Sampled Data Events

When two variables are statistically dependent, knowing the value of one of them let us get a better estimate of the value of the other one. Consider a simple illustration of a two-variable MAC state where both states x and y are either charged(=1) or charging(=0). Suppose that a large number n of pairs of xy nodes are randomly produced. We assume the number of neighbors can be represented in terms of $\sqrt{(N)}$, where N is the number of neighbors.

THEOREM 1. *Let $n_{i,j}$ be the number of pairs in which we find $x = i$ and $y = j$, that is, we see the (0,0) pair n_{00} times, the (0,1) pair n_{01} times, and so on, where $n_{00} + n_{01} + n_{10} + n_{11} = n$. Suppose we schedule the node pairs where $y = 1$ —that is, the nodes which are available to receive and have sufficient energy $(0,1)$ and the $(1,1)$ pairs. Clearly , the fraction of those cases in which x is also charged 1 is*

$$\frac{n_1 1}{n_{01} + n_{11}} = \frac{n_{11}/n}{(n_{01} + n_{11})/n}$$

Intuitively, for a large sensor network deployment to know the probability of a successful transmission pairs $P(x|y)$ when a forwarding neighbor is available, when $y = 1$ and n is large. And indeed, this is what we get, because $\frac{n_{11}}{n}$ is approximately $P(y)$ for large n.

4.2.2 Distributed Data Events slotted at scheduled intervals

If an even such as node clustering C occurs in m different ways $C_1, C_2, C_3 ... C_m$ and if these m cluster head subevents are mutually exclusive —that is, cannot occur at the same time —then the probability of distributed clustering occurring is the sum of the probabilities of the subevents Ci. In particular the random variable y which can be random or node's remaining residual power can assume the value y in m different ways —with $x = v_1, x = v_2, .., x = v_m,$. Because these subevents are mutually exclusive, from the Law of Total probability that $P(y)$ is the sum of the joint probability $P(x, y)$ over all possible values for x. We assume the number of neighbors can be represented in terms of $\sqrt{(N)}$, where N is the number of neighbors. In this clustering case it is $\sqrt{(N)}$. Formally we have

$$P(y) = \sum_{x \epsilon \chi} P(x, y)$$

But from the definition of Theorem 1 $P(y|x)$ we have

$$P(x|y) = \frac{P(y|x)P(x)}{\sum_{x \epsilon \chi} P(y|x)P(x)}$$

THEOREM 2. *The above Equation is called the Bayes rule. Note that the denominator, which is just P(y), is obtained by summing the numerator over all x values. By writing the denominator in this form we emphasize the fact that everything on the right-hand side of the equation is conditioned on x. This is the other way of saying that the data-link quality is conditioned for a particular power-aware Qos chosen by the clustering algorithm. Hence the provability of error at the data-link layer is superior than the previous case, Theorem 1 is conditionally dependant and has the probability of error greater than the Bayes rule.*

LEMMA 1. *Sequence of length n from the source. In sensor each element in the sequence is independent and identically distributed (i.i.d.), then we can represent entropy in bit length.*

$$H(S) = -\sum P(X_1) \log P(X_1)$$

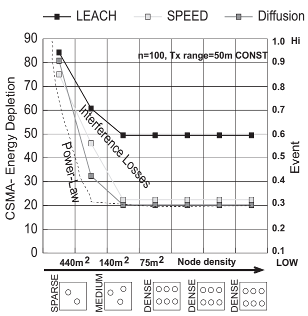

Figure 1: CSMA MAC performance with constant radio range

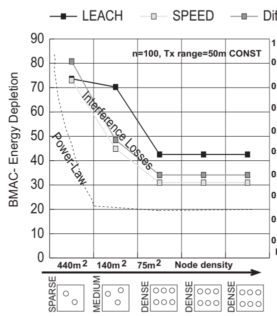

Figure 2: B-MAC performance with constant radio range

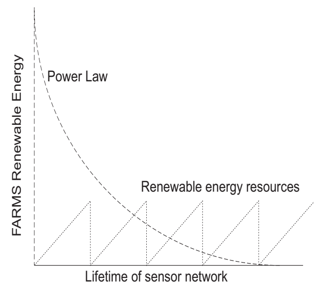

Figure 3: FARMS performance with constant radio range

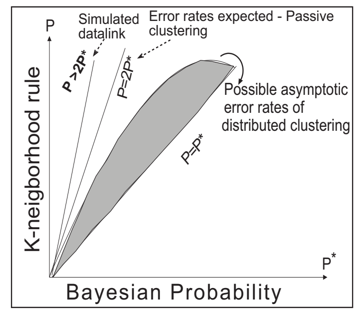

Figure 4: Bayesian reliability bounds for Theorem 1, 2

4.2.3 Comparison to Bayes Probability

The theorems allows to predict the asymptotic bounds of the data-link interference and allows modeling of the sensor network in terms of complexity defined for clustering $\bigcirc(\sqrt(N)\log N)$ for the two cases. The error bounds are shown in figure 4 in terms of Baysian probability. The data capacity as defined in Lemma 1 and is dealt in detail in a related work in [3],[4],[1].

4.3 MAC performance using ultra-low duty cycle

From the traditional energy model, a dynamic renewable model was adapted, as shown in Figure 3, which makes optimization at the lower layer, an essential part of the energy harvesting model. Sensor network harvesting provides mechanisms for network protocols to operate efficiently, and the three key elements of the renewable energy protocol design are, data reception, data transmission and neighbor Management. This phase of the enhancement of the simulator allows the improvement on the scheduling of the nodes that participate during routing using application control, as described in Theorem 1, more detailed of the protocol implementations are provided in the FARMS paper [2].

5. CONCLUSIONS

This work used the existing simulation models that are network-based, and specified the Qos framework for data reliability needed for sensor networks. The fusion of energy harvesting applications with power-aware MAC was studied in terms of deployment of low-level protocols for 802.11, CSMA, and B-MAC. Furthermore, if the data is routed using multi-hop algorithms and is MAC-centric, then the distributed sleep scheduling [2] is observed to reduce the percentage of energy lost during overhearing and collision. The performance of routing algorithms with MAC losses has a long tail which is similarly observed in Power Law. Simulation results show that the probability of data-link reliability is greater for clustering algorithms due to conditioning at the cluster head in CSMA which helps sensor network protocols and improves energy efficiency when using B-MAC. FARMS which uses a ultra low-duty cycling MAC due to varying charging times performs well in a dense sensor network configuration and has significant application role.

6. FUTURE WORK

Energy-aware enhancements and behavior of TDMA-MAC with more than 100 nodes with virtual clustering will be added to the current performance analysis of power-aware MAC's.

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