

Robust Extreme Energy Efficient Sensor Networks

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Robust Extreme Energy Efficient Sensor Networks

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ABSTRACT

Despite much research on sensor networks in general and on event-response applications in particular, simultaneously achieving the desired timeliness of response, longevity, and wide-area coverage still remains a significant challenge. In this paper, we present a robust, flexible, and extremely energy efficient sensor networking system solution with the goal of enabling orders of magnitude improvements in sensor network lifetime for time-stringent event-response applications with wide area coverage requirement such as Maritime Domain Awareness and Environmental Monitoring. We first present a cross-layer hierarchical energy adaption framework, a main departure from traditional approach of single-component adaptation and efficiency paradigm. The proposed solution consists of the following components: duty-cycle optimized radio, low-power adaptive multi-modal MAC (LPA-MAC), and cross-layer adaptive reconfiguration (CARE). This paper focuses on the cross-layer design aspects of LPA-MAC and CARE. For LPA-MAC, we conduct a thorough investigation on the relationship among duty cycle, synchronization mode and traffic load. Contrary to common belief, we find that there exists a range of energy-optimal duty cycles for a given traffic load. The resulting relationship provides us with critical guidelines on how to adaptively select near optimal operational mode so that only the least possible energy is consumed for given traffic loads. For CARE, a concept of adaptively reconfiguring a backbone structure is introduced and evaluated. Preliminary simulation results indicate more than two orders of magnitude in energy saving over an “always-on” system with comparable timeliness.

1. Introduction

In this paper, we develop and validate, through extensive simulation, a system design with several innovative features tackling fundamental challenges for persistent sensing with unattended sensors such as environmental monitoring and security/intrusion detection. Unlike existing sensor networking systems which are heavily focused on local-area coverage only, persistent wide-area sensing have stringent and yet conflicting requirements:

- **Long Lifetime:** Since military or environmental sensors are likely to be located in hostile/remote areas, making physical access on a regular basis becomes impractical. This forces sensor nodes to be in sleep mode as much as possible.
- **Fast Detection Time:** Time-stringent event-response applications force the nodes to be in wakeup mode as much as possible.
- **Wide Adaptation Range:** In remote or restricted areas, it is not practical or possible to deploy a large number of nodes due to safety or cost concerns. Consequently, it is more desirable for sensor nodes to have adaptive data rates and large communication for wide-area sensing, forcing the use of high-power components.

Given these conflicting and challenging requirements, our objective is to enable orders of magnitude improvements in sensor network lifetime for wide-area time-stringent event-response applications by developing innovative cross-layer adaptive protocols optimized for ultra-low duty cycling while simultaneously achieving long lifetime, low latency, and good modalities for performance, energy, and system complexity tradeoff features. In order to satisfy these challenging goals, we begin by thoroughly examining the way sensor network employs duty cycling, a common approach to achieving low energy consumption. That is, nodes in the sensor network periodically cycle between a wake state and a sleep state. We observe that while putting nodes in the sleep mode saves energy, this is likely to increase the response time when an event is detected. Consequently, our first goal is to construct radio architecture design and duty cycling paradigm such that nodes wake up for listening as frequently as needed while spending as minimal energy as possible so that we can establish the foundation for simultaneously accomplishing the desired timeliness of response and longevity.

Built upon this rapid radio sleep/wakeup transition feature as one of the key enablers, we propose cross-layer hierarchical energy adaption system architecture which consist of three key components: duty-cycle optimized radio, Low-Power Adaptive multi-mode MAC (LPA-MAC) and Cross-layer Adaptive Reconfiguration (CARE).

The architecture leverages well-known techniques such as hierarchical structure, and encompasses across the entire stack (RF hardware, MAC, synchronization and routing/application), thus enabling a comprehensive “Energy-Based Topology Control with Extreme Adaptivity”. The proposed architecture has the following powerful adaptation capabilities: 1) Adaptively adjust the duty cycle based on mission requirements; 2) Adaptively adjust the duty cycle based on traffic demand and network conditions (enabled by LPA-MAC); 3) Adaptively reconfigure the network topology based on energy level at each node or the link quality using the parameters passed among different layers — cross-layer optimization — enabled by CARE.

To build a strong foundation for designing LPA-MAC, we conducted a thorough investigation on the relationship among duty cycle, synchronization mode and traffic load. The resulting relationship provided us with guidelines on how to adaptively select near optimal operational mode so that the energy consumption is minimized for a given traffic load while maintaining end-to-end timeliness comparable to that of an always-on system.

The proposed cross-layer hierarchical energy adaption system architecture takes into account the heterogeneous nature of the sensor node capability based primarily on the availability of energy sources (electricity, solar, or battery-powered) and RF (short-range vs. long-range). Specifically, we designed a hierarchical network which consists of backbone nodes (BNs) and non-backbone nodes (NBNs). BNs are responsible for relaying messages while NBNs do not relay messages. In order to balance the energy level at each node and increase the network lifetime, BNs are periodically or adaptively selected so that no single node’s energy is completely drained before other nodes. Once the backbone network is formed, routing can take place over the backbone network only. This way, NBNs are not involved in routing information exchange and relaying messages. Therefore, significant amount of energy can be saved for NBNs. The network reconfiguration is conducted periodically with a large time scale or incrementally triggered by certain events, thus, the overhead associated with the reconfiguration is negligible.

As part of establishing CARE algorithms, we have identified key parameters to be passed across different layers so that the energy consumed at each layer can be minimized. Those parameters include duty cycle periods, reconfiguration period, energy level at each node, link quality, whether a node a backbone or not, and mission/QoS requirements. We have conducted an extensive simulation study to evaluate the performance of the proposed cross-layer system architecture. Simulation results show that the energy saving under the proposed

architecture is almost 100 times compared with that of an “always-on” system.

Fundamental to the cross-layered energy adaptation is our novel duty-cycle optimized radio architecture. It separates the wakeup signal processing (which must occur very frequently in order to meet time-stringent responsiveness, and thus must be extremely energy efficient), from data signal processing (which will occur rarely and thus can be energy intensive for long-range communication). With its rapid wakeup and shutdown features, this architecture has the potential to minimize the energy penalty that needs to be paid for fast event detection time which demands frequent wakeup of the receive chain. Due to space limitation, detailed description of the radio architecture [11] is omitted here.

The rest of the paper is organized as follows. In section 2, we describe our assumption and design principles. An algorithm for CARE and its simulation results on the performance are presented in Section 3. In section 4, we conduct a thorough investigation on the relationship among duty cycle, sync mode, traffic load and energy saving for an LPA-MAC protocol. Section 5 discusses our integration approach to further conserve energy and satisfy mission requirements. In Section 6, we conclude the paper.

2. Design Principles

Assumptions

In reality, not all sensor nodes are created equal from the perspective of their energy sources and roles. For this reason, we assume that there are 3 types of sensor nodes. Type 1 nodes have uninterrupted power sources (e.g., access to electricity infrastructure). Examples are data collection centers with Internet connections through satellite, fiber optics or wireless services. Type 2 nodes have either moderate level of power (such as large-capacity batteries) or energy-harvesting capabilities. They may be used primarily as relays, though they can certainly collect raw data through attached sensors. Type 3 nodes are powered with small-capacity batteries only, and often deployed on the edge of the coverage areas. In the current study, no mobility is assumed.

Design Principles

Given that the sensor network is heterogeneous, it is natural to have a hierarchical architecture which consists of BNs and NBNs. Higher power nodes (Type 1/2) will rotate to serve as BNs based on network conditions and energy level at each node. Network conditions are updated periodically through neighbor discovery or synchronization. Since the network is dense, in order to avoid draining energy from only a few fixed nodes, periodically or adaptively, we apply topology control techniques (or network reconfiguration) to select a set of

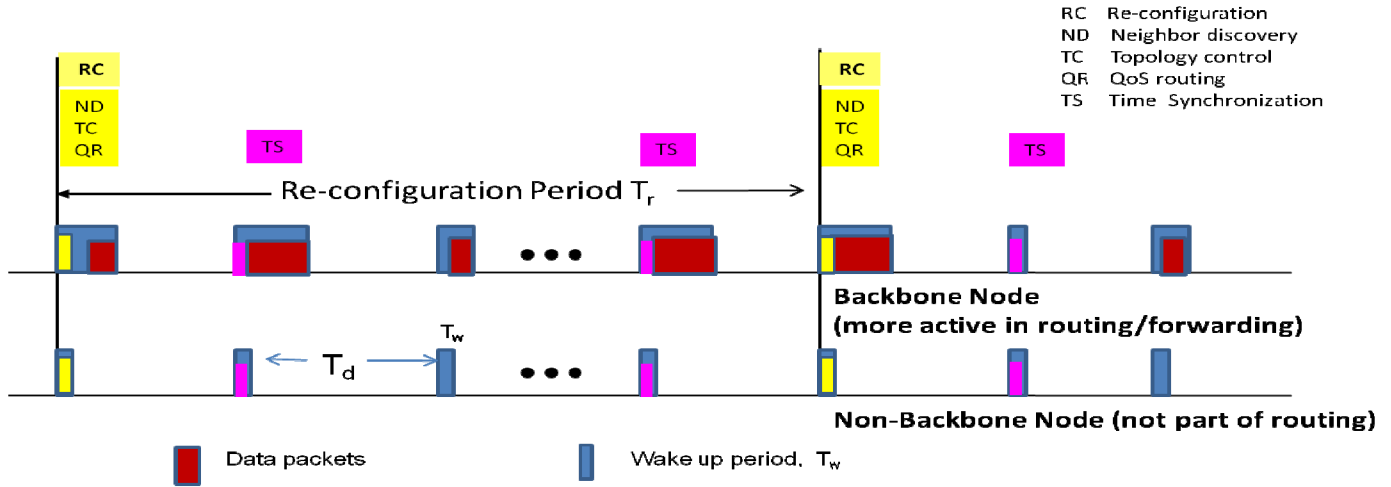


Figure 1 Illustration of relationship among reconfiguration, sync, and Mac (with hierarchical sleeping periods)

higher power nodes to serve as BNs based on the energy level at those nodes as well as their harvesting capabilities. The objective of topology control is to select a minimal set of BNs so that the network is connected. In doing so, NBNs will be sleeping except when synchronization is needed.

Once the backbone is selected, routing can be done by selecting paths only within the BNs. Once topology and routing paths are determined, data transmission can take place over the backbone network by selecting appropriate MAC modality and time synchronization algorithm. Here, we propose a two-level of sleeping schedule: backbone sleeping schedule and non-backbone sleeping schedule (see Figure 1). As shown in Figure 1, NBNs are not responsible for relaying data packets and only wake up during its wake up periods and during synchronization, while BNs stay awake much longer than NBNs as BNs are active in routing and forwarding. Note that the neighbor discovery, topology control and routing are conducted in a relatively long time scale, for example, in minutes or hours, while synchronization and MAC are done in a relatively short time scale. Synchronization and MAC is done in a relative short time scale.

3. Network Reconfiguration for CARE

In this section, we describe some of the key functions in network reconfiguration: neighbor discovery, topology control and routing.

Neighbor discovery

In order to balance energy utilization at all the nodes, nodes periodically exchange neighbor information such as node ID, node energy level, list of one hop neighbors, whether a node is a BN, and location information if available. To avoid extra overhead, such information can

be exchanged during synchronization. Once nodes receive the information, it updates its neighbor table. The BNs can also update the neighbor table by intercepting incoming packets during normal operations.

Topology Control/Backbone Network Formation

Based on the information obtained from neighbor discovery, each node is aware of the latest network state. A new backbone network can be formed/updated so that the network resources can be used more efficiently (for example, balancing the energy level at each node). The objective of backbone network formation/update is to select a set of BNs (as minimum as possible) which are connected and have relatively higher remaining energy level.

To form a backbone network, the first step is to select a connected dominating set (CDS) from all the nodes. A CDS has the feature that all nodes that are not in the CDS are adjacent to some nodes inside the CDS, while all nodes inside the CDS are connected. Taking the energy level at each node into account, nodes whose remaining energy level is above a given threshold are more favorable candidates for the CDS.

Once candidates are selected, a CDS will be generated using a distributed algorithm. In choosing a distributed algorithm, we favor those that have far less communication overhead than computational overhead. The algorithm proposed by Wu and Li [7] is a good option, and we will use a modified version, under which Type 1 nodes are always selected as BNs (Other CDS construction algorithms presented in the literature could be used as well as they are distributed and have minimum extra overhead).

Firstly, a marking process is executed. Initially all candidate nodes are not marked (type 1 nodes are marked). We mark a candidate node if it has two neighbors that are

not neighbors to each other. Finally, all marked candidate nodes are part of the CDS.

This algorithm is conceptually very simple. However, the resultant CDS is not quite optimized, that is, there are potentially more nodes in CDS than necessary. In order to further optimize the algorithm, two reduction rules can be used (except for type 1 nodes).

Rule 1: For two marked nodes u and v , if the closed neighbor set (a node's neighbor list plus the node itself) of u is contained in that of v and $ID(u) < ID(v)$, unmark node u , where $ID(x)$ is the ID of node x .

Rule 2: For two marked nodes u and v , and another node w , if the closed neighbor set of node u is contained in the union of that of node v and node w , and $ID(u)$ is the smallest among the three, unmark node u .

All the nodes within the selected CDS will serve as BNs. If a node not in the CDS is one hop away from a BN, it will associate with that BN (if the node has multiple BNs as one hop neighbors, it will associate with a BN based on link quality, distance or energy level). If a node does not have a BN as one-hop neighbor (denote the set of such nodes as SN), it will call a rescue protocol.

Rescue protocol:

Initially all nodes in SN have a hop-count to CDS of $HC = \infty$ and next-hop $NH =$ its node Id, id . Each node in SN broadcasts a rescue request Q and waits for reply P . If a NBN receives a Q , it broadcasts a response P including its node Id and the hop count to the CDS. Once a node receives a $P<nid, hc>$, it checks whether $hc < HC$. If yes, it updates its NH and HC to CDS to nid and $hc+1$, respectively. Then it broadcasts $P'<id, HC>$. A node times out after certain time.

The network topology will be configured periodically to prevent the event that energy at a few particular nodes is drained too fast, as BNs consume more energy than NBNs. The period of reconfiguration is a configurable parameter at network start time. If the energy level of a particular BN is below a certain threshold or the quality of a link (with one end point being a BN) is poor before the planned reconfiguration time, that BN should inform other nodes about its status and triggers the *incremental reconfiguration* protocol described below.

Incremental configuration protocol:

A BN, with ID of id , who needs to be released as a BN, broadcasts a stop-request $SQ<id>$. Each NBN receiving $SQ<id>$ checks to see whether it is associated with this BN. If so, it checks to see if there is another BN neighbor; and if yes, it will associate with the new BN. If no other BN neighbors, the *rescue protocol* presented

before is used. If a NBN is not associated with this BN, it does nothing.

Routing over the backbone network

Once the backbone network is formed, routing can take place only over the backbone network. That is, an existing routing protocol developed for an ad hoc network can be used. Only BNs will participate routing information exchange and routes establishment. NBNs can safely go to sleep to conserve energy. Recall we assume that sinks are type 1 nodes, which are always BNs. Routing requests from NBNs are handled by their associated backbone neighbors. Once the message from a NBN is received at a BN or a packet collected from a BN, the BN will forward the message to one of the sinks using the routing protocol over the backbone network.

Simulation results

To evaluate the energy saving by applying the network reconfiguration, we conduct simulations in QualNet without considering the impact of low power MAC (to be discussed in next section). We assume the following simulation setting. The path loss model is assumed to be a two-ray model. The data rate is 1Mbps. We let the terrain size vary from 500mx500m to 1kmx1km. We assume that initially nodes are uniformly placed within the given terrain. We use CSMA as the MAC protocol and OLSR as our routing over the backbone network. For each set of the simulations, the run time is set at 3,600 seconds. In figure 2, we compare the energy consumption by allowing only BNs participating routing and relaying messages with that under a flat network in which all nodes are involved in routing and relaying data. We observe that the energy consumed is only 20% of that under a flat network. Note that as mentioned before, the energy consumed due to reconfiguration overhead is negligible and is not considered. The benefit of the reconfiguration and routing over the backbone network is apparent.

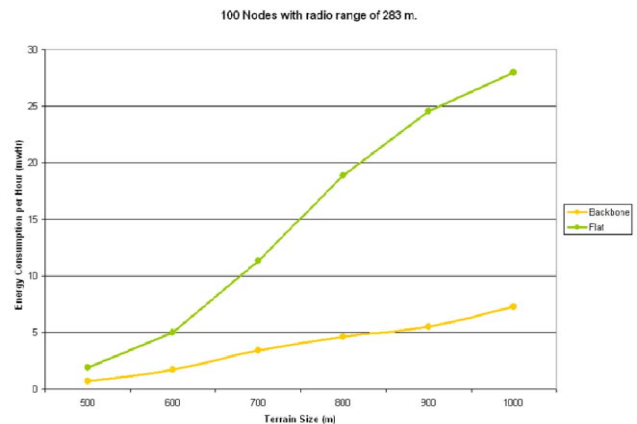


Figure 2 Energy saving of CARE compared with a flat network

4. Time Synchronization and LPA-MAC

Time synchronization

In a generic sensor network, one node's clock is different from its neighbors' due to time offset, frequency offset, and randomness. Time synchronization among neighboring nodes is necessary for two reasons. For environmental monitoring or intrusion detection, it is important to know when the event exactly occurs. Sensor should record/report each event with an accurate time stamp. When duty cycling is used, for synchronous MAC protocols, time synchronization is necessary for the nodes to rendezvous at the right time instants for successful transmission and receiving. To rendezvous, each node exchanges information with its neighbors about when it will wake up, and each node's schedule is according to its own clock.

There are two types of time synchronization protocols: instant synchronization and predictive synchronization. In instant time synchronization protocols, a node corrects its clock reading by adopting its neighbor's. Predictive synchronization protocols include flooding time synchronization protocol (FTSP) [8] and rate adaptive time synchronization (RATS) [3]. In our implementation, we modify the RATS algorithm, which is suitable only for pair-wise local time synchronization, and add a global time synchronization mechanism with negligible communication overhead. We implement a modified version of the global synchronization mechanism, Flooding Time Synchronization Protocol (FTSP) [8], due to its high performance in terms of synchronization precision. In [12], we analyze the impact of two parameters on the precision of linear regression based time synchronization protocols: (1) the frequency at which the time stamp data are collected; (2) the window size, i.e., the number of time stamps used for linear regression. Based on rigorous theoretical analysis and extensive experimental and simulation results, we show that counter to intuition, given the prediction interval, a more frequent synchronization may result in worse time synchronization performance. This discovery suggests that a linear regression based time synchronization protocol can achieve both high precision and good energy efficiency by operating at a low synchronization frequency.

Low-Power Adaptive MAC

To save energy, the radios stay in the sleep mode most of the time and wake

Lp Mode	Idle On Interval	Sleep Interval	Idle Duty Cycle(%)
0	always	NA	100
1	50 μ s	50 μ s	50
2	50 μ s	450 μ s	10
3	50 μ s	950 μ s	5
4	50 μ s	1450 μ s	3.33
5	50 μ s	4950 μ s	1
6	50 μ s	9950 μ s	0.5
7	50 μ s	24950 μ s	0.2
8	50 μ s	99950 μ s	0.05
9	50 μ s	499950 μ s	0.01

up periodically to check if they should stay awake and prepare to receive data. That is, the radios are duty cycled. An example of 10 duty cycles is given the table.

The benefit of duty cycling does not come free of cost. To enable duty cycling, it is necessary for the radios to know when to wake up and when to transmit since communication is possible only if the transmitter and the receiver can rendezvous at the same time. There are three main approaches based on whether synchronization information is available or not: synchronized, asynchronous and hybrid approaches. On synchronized protocols, such as S-MAC [1] and T-MAC [2], nodes exchange a schedule that specifies when nodes are awake and asleep. Knowing when nodes will be awake in order to communicate reduces the time and energy wasted in idle listening. However, it introduces extra traffic due to synchronization. Asynchronous protocols such as B-MAC [4], WISEMAC [5], and X-MAC [6] use preamble sampling to link together a sender with data to a receiver. Idle listening is reduced in asynchronous protocols at the expense of the sender. For example, when a sender has data, in B-MAC, the sender transmits a preamble that is at least as long as the sleep period of the receiver. The receiver will wake up, detect the preamble, and stay awake to receive the data. This allows low power communication without the need of explicit synchronization between the nodes. However, there is an overhearing problem in B-MAC where receivers who are not the target of the sender also stay awake during the long preamble. X-MAC addresses the overhearing overhead associated with long preambles by using a strobed sequence of short packets including the target ID allowing for fast shutdown and response. In a hybrid approach, such as UBMAC [3], nodes maintain their own asynchronous schedules yet exchange the schedule with other nodes for communication.

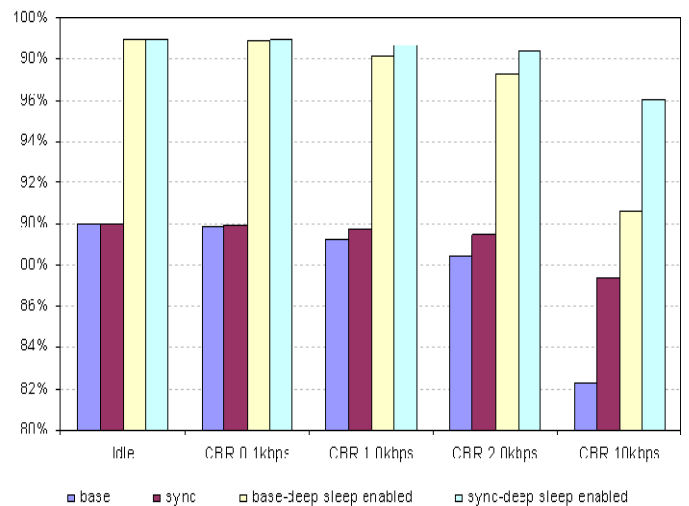


Figure 3 Energy consumed for a given duty cycle (1%) for different sync schemes and traffic load.

Which duty cycle and sync scheme should be used so that the energy consumed is near minimum for a given traffic load? Even though there are many MAC protocols proposed in the literature, there is no study on answering this question. In this paper, we conduct thorough investigation on the relationship among duty cycle, sync scheme, traffic load and energy saving, through simulation. Simulation results show that it is not necessarily true that the less the duty cycle, the less the energy consumed.

Simulation results

In the simulation, we assume the following parameters based on our SensorBone™ implementation [10]. The power consumed by a node is 868 mW when transmitting and is 486.26mW when receiving. The power consumed is also 486.26mW when a node is awake but idle. When a node is sleeping, it consumes 44.2mW (the PXA processor is on, but the transceiver is off). It consumes 0.16mW when a node is in a deep sleep mode (both the PXA processor and the transceiver are off). The data rate at the physical link is assumed to be 1Mbps (here, we chose 1 Mbps as the peak rate could be up to 1 Mbps, and conclusion holds for other data rate as well). In order to better understand the relationship among duty cycle, sync scheme, traffic load and energy saving, we only consider two nodes (without considering the effect of networking protocols). A constant bit rate (CBR) flow between the two nodes is assumed. The packet length is 1 kbits, with various packet intervals, resulting in traffic load from 0 to 2 Mbps (to simulate congestion situations).

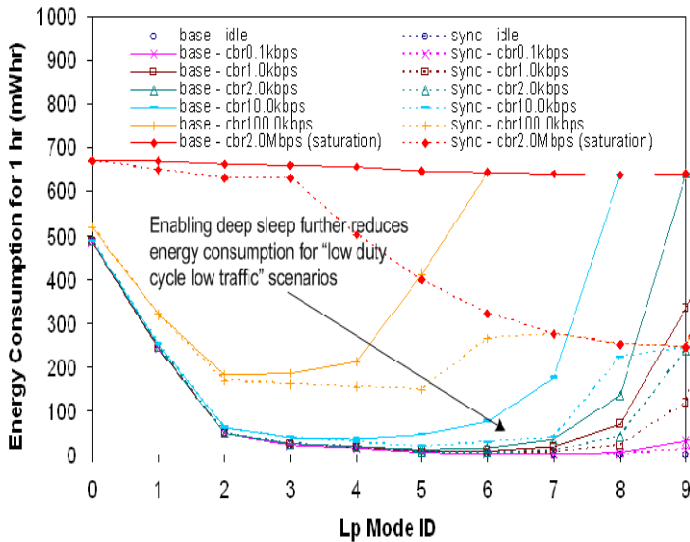


Figure 4 Relationship among duty cycle (Lp mode ID), sync scheme (base—asynchronous, and sync—synchronous), traffic load (idle, .1kbps, 1 kbps, 2 kbps, 10kbps, 100 kbps, and 2Mbps) and energy saving.

From figure 3, we noticed that, for higher traffic load, the energy saving under a sync approach is much better than the asynchronous approach and, for lower traffic load, the energy saving could be up to 99% over an “always on” system.

From Figure 4, we notice that there is no single duty cycle which yields the best energy conservation for all the traffic load considered. It is not necessarily true that the lower the duty cycle, the less the energy consumed. For example, for a traffic load of 100kbps, when the duty cycle is lower than 1%, the energy consumed is even more than the “always on” system. The “optimal” duty cycle for the traffic load of 100kbps is 10%. While for a traffic load of 1kbps, the “optimal” duty cycle is 0.5%. There are several reasons for this. Here, we assume the power consumed for transmission is twice of that for reception or idle. When the duty cycle is low, for asynchronous schemes, extreme long preambles are needed to be transmitted; and for synchronous schemes, sync packets consume energy. This calls for adaptive MAC which can dynamically switch from duty cycle to another so that the overall energy consumed is “minimized”.

To this end, we develop an adaptive multi-mode MAC, using a look up table (LUT) based on extensive simulations. In the table, the first column is a given traffic load, or an interval of traffic load, and the second column is the corresponding “optimal” duty cycle period. The low power multi-mode MAC will adaptively switch from one duty cycle to another based on the traffic load determined by the LUT. For easy implementation, the multi-mode MAC is being developed based on X-MAX [6].

5. Integration of Time Synchronization, MAC and Routing

In order to achieve more energy saving, we are developing adaptive cross-layer architecture, as shown in Figure 5,

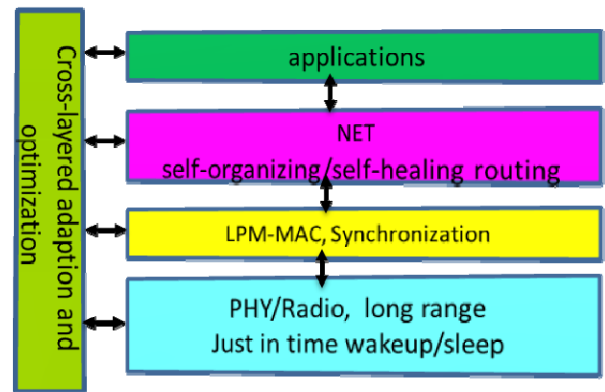


Figure 5 cross-layer optimization

which integrates the duty-cycle optimized radio, LPA-MAC, time synchronization and network

reconfiguration/routing. Key parameters passed across different layers include duty cycle period, T_d , reconfiguration period, T_r , (see Figure 1), energy level at each node, link quality, whether a node a backbone or not and mission/Qos requirement. Energy level at the physical layer will be used in the network reconfiguration. Application level requirements information such as delay and packet loss will be used in the MAC to select a near optimal duty cycle and will be used in the network reconfiguration. Information about the reconfiguration is passed to the PHY and MAC layers. The duty cycle optimized radio architecture has an extreme energy saving capability, that is, the radio is able to process only a short preamble which consists of the receiver's address. If the receiver's address inside the preamble is not the same as the receiver, the radio will ignore the rest of the packet and goes back to sleep immediately. Using the information from the network layer, an NBN can fully utilize this extreme energy saving capability and stays in sleeping mode in most of the time as an NBN is not responsible for routing and relaying packets. The traffic demand from the application will be used at the MAC layer for dynamically switching from one mode to another.

For many wireless applications, such as environmental monitoring, a fixed duty cycle provides good enough performance. However, in some other applications, such as intrusion detection, the timing requirement is much more stringent, and the use of a fixed duty cycle may not be sufficient. To address the problem associated with lack of responsiveness of the current duty cycled wireless data networks, we propose to use a dual-mode network operation scheme. Normally, the wireless nodes operate in the Normal Mode, which is characterized by a fixed and long wakeup cycle. If an emergency is detected, the portion of the backbone network involved (that is, only BNs on the path from source to destination) in delivering the emergency information transitions to the Emergency Mode, which is characterized by a much shorter wake up cycle or the lack of duty cycling at all.

6. Conclusions

In this paper, we present a comprehensive system solution for robust, energy efficient wireless sensor networks. The proposed solution consists of periodical or adaptive reconfiguration, time synchronization and low-power adaptive MAC. Preliminary simulation results show that up to 100 times in energy saving (without considering routing) can be achieved under LPA-MAC alone compared with an 'always on' system, and the energy saving from network reconfiguration and routing alone (without LPA-MAC) could be 80% of an 'always-on' system.

Our next step is to integrate the LPA-MAC with CARE as discussed in section 5 and to evaluate the performance of the integrated architecture in terms of energy saving, end-to-end timeliness of response, and coverage areas more extensively.

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