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FARMS: Fusionable Ambient Renewable MACS

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***Abstract*—We address two critical issues in wireless sensor networks: (1) an extension of common Quality of Service (QoS) parameters to study the effects of ultra-low duty cycling applications, and (2) propose a new WSN passive clustering routing protocol using sleep cycles based on available renewable energy resources : Fusion Ambient Renewable MACS (FARMS). The results from lifetime based QoS in a time synchronized deployment show that for a best effort QoS multi-hop deployment with varying percentage of cluster heads, the lifetime is network size and protocol invariant. However, low sensing ranges result in dense networks and thus it becomes necessary to achieve an efficient medium-access protocol subject to power constraints. We present cross-layer energy dissipation per node and show the performance of the network by varying duty-cycles. The study of sensor FARMS harvesting applications allows to measure the impact on idle, sleep and renewable energy cycles and their unique deployment (in terms of density) needs as all the sensor are not active at all times. We show that efficiency of sensor deployment QoS can be provided in terms of distributed load balancing (20% static clustering) at each node, power-aware sleep scheduling (2X increase in lifetime), data aggregation efficiency(B-MAC performs 3X times better than CSMA) in multi-hop passive clustering implementations.**

I. Introduction

Tuning the cross-layer parameters is very essential in working with constrained WSN protocols. As the unique nature of deployment needs under harsh environments for sensor networks the integration of data QoS and the network throughput QoS is an integral part of a well designed sensor network. As data is sensed at the lower layers which are MAC dependant we need to analyze how reliable the data gathering protocol is and how well it coexists in a dense deployment. The lower level protocol have a small time to live (TTL) window to record parameters such as light, temperature and humidity and to log time-stamp. To efficiently route the updated data packet information, an architecture should be in place to multi-hop the payloads using least energy and at the same time efficiently schedule the node for local house keeping, and clustering and ambient activities. For this a software infrastructure needs to be developed which allows queuing of messages, selection of best routes and fault-tolerant routing mechanisms.

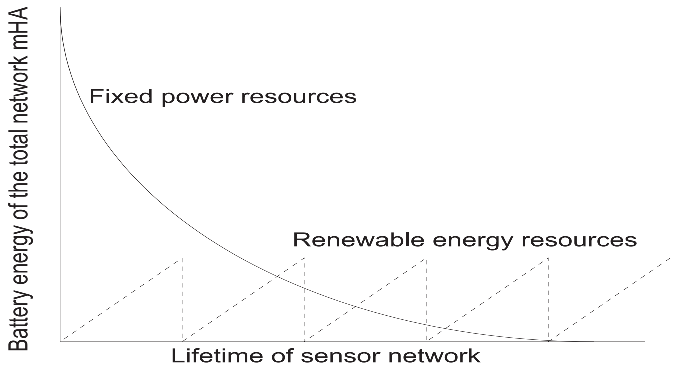
Power-aware sensor hardware specifications have evolved and have specifically provided operating power metrics for sensing and routing tasks which are in μA and milli-amps, which indicates that data transmission is very much more power draining than normal sensing tasks. For a non-replaceable AA battery delivering milli-amps-hrs power for the fixed lifetime [3] radio model specified by the manufacturer it shows that minimal transmission is the preferred mode of operation in order to prolong overall lifetime of the sensor network. This fixed lifetime model [3] shows that to operate in such a mode the burden on the radio Rx and Idle which when combined takes equivalently the same power compared to data transmission suggesting that the design is for normal wireless network but not for power-aware wireless sensor network applications such as FARMS with resource constraints. In this paper we will use cross-layer models which use duty-cycling at the lower layers and measure the QoS gains of distributed load balancing at each node, power-aware sleep scheduling, data aggregation efficiency in terms of scheduling the radio Tx, Rx and Idle over the lifetime of the sensor network. The simulator battery model uses an amortized radio power drain cost based on mAh(sensing power usage is in μA and sensor radios power usage is in milli-amps) to predict accurately the residual energy of the sensor node of the sensor network and lifetime in real-time clock for uniformity in comparison of WSN algorithms.

II. Motivation

QoS for sensor network can be based on reliability of data and the power consumption during its useful lifetime. Currently most of the measured performance metrics are limited to network and MAC layer communications. To overcome the dependencies between layers, and to reduce the complexity which effect QoS as a result of these dependencies we propose QoS of a sensor protocol service which is independent of any specific distributed algorithm, communication protocol or manufacturer's battery model. This service based implementation allows scheduling of the MAC for ultra-low duty cycling[6]. The lower layer MAC provides adaptability for reliable data aggregation in a cluster and power savings by forwarding data using passive clustering using sleep schedules.

III. Renewable Energy Model and Energy Harvesting

Designing a multi-hop sensor network using a lifetime renewable energy model as shown in figure 1(a), an active node which is ready to transmit at a given instance will take a time period t to reach its neighbors and the response time of receiving the message back will be $2 \times t$ or a preset



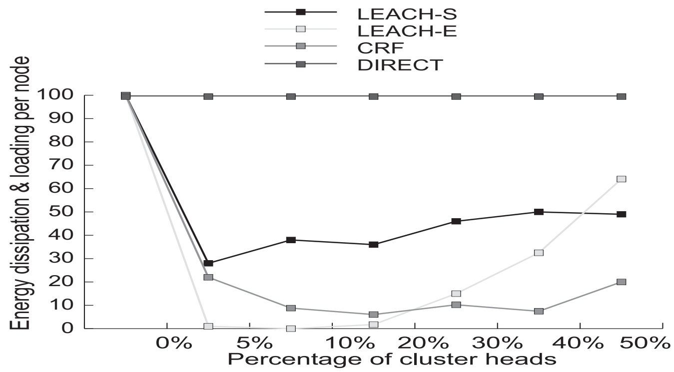


Fig. 1. (a) Lifetime models using static and passive clustering. (b) Energy dissipation impact per node using static clustering

TTL value(Time to live for the communication protocol). To efficiently multi-hop data to sink we need to at least have one neighbor which is awake to respond to the request of the transmitting node. In a large WSN network the traffic is latency($f(x) = \triangle$) or best effort QoS. To study the MAC characteristics for constrained devices which are uniquely dependant to varying node densities, limited transmission ranges and power the application model needs to have a scheduling periodicity and selecting new available multi-hop nodes in the path between data source and sink. The data routing algorithm which relies on the density of network and independant of network and upper layers using passive clustering which makes the multi-hop path between cluster to cluster possible when forwarding data across the multi-hop FARMS.

IV. Cross-layer Simulation Modeling

The architecture combines the upper network layers which solely deal with distributed cluster head selection with the frequent connectivity needs required by the lower layers to achieve balanced performance in terms of energy savings for sensing and routing activity.

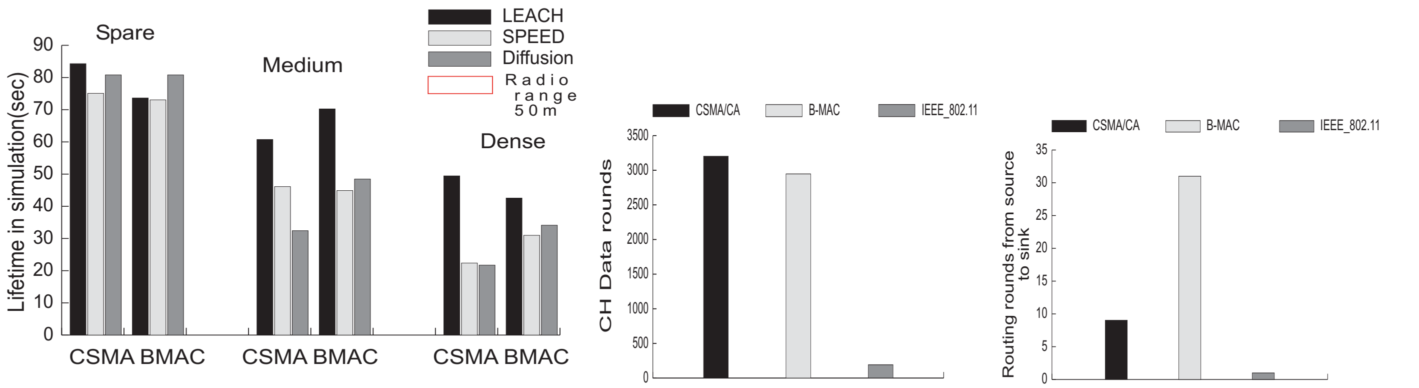
A. Protocol design tool - RF Dependency

The design tool incorporates flooding algorithm based on Control Radius Flooding discovery protocol (CRF) which divides the sensors into three multi-hop zones as described in the pseudo algorithm on the right. This allows to calculate the minimum RF distance needed for the nodes according to the network density thus minimizing energy wastage when routing. CRF-STACK [2] API's implements the network layer routing with optimal QoS and allows to integrate with MAC cross-layer QoS and manufacturer's specific radio models.

Input: N Sensors motes
Output: Hiercheal CRF-Tree of the deployed sensors partitioned according to RF distance
MIN-PWR-LEVEL = Set min. energy allowed by radio
MAXZONE = 3
STD-PACKET-LEN = 16
Begin Initialize
CRFRange = 0
NewNeighbors = 0
TreeHopList[3] = 0
ControlledNeighborList = 0
ParentZoneMotes=0
SibblingZoneMotes=0
ChildZoneMotes=0
MULTI-HOP-TX = 0
do
foreach *Zone LT MAXZONE* **do**
    NewNeighbors = Flood(ControlledNeighborList, $\nabla CRFRange$)
    $If(NewNeighbors > 0)$
    Begin
    TreeHopList[ii].MoteNo $\leftarrow NewNeighbor$
    TreeHopList[ii].Parent $\leftarrow ControlledNeighborList$
    ControlledNeighborList $\leftarrow TreeHopList[ii]$ End
    $\nabla CRFRange \leftarrow \nabla CRFRange + MIN - PWR - LEVEL$
end
Until all motes are classified into zones
$MULTI - HOP - TX = \nabla CRFRange$
$ParentZoneMotes = TreeHopList[0]$
$SibblingZoneMotes = TreeHopList[1]$
$ChildZoneMotes = TreeHopList[2]$
Return CRF-Tree

B. Simulating Power-ware Cluster Head Selection for WSN

The protocol design tool [2] allows modeling cluster head selection parameters based on a distributed probability by abstracting MAC losses from previous work [1,2,3] which are typically not available in a scalable network simulators. The true nature of ad-hoc placements of nodes, the random density of placements which effect clustering algorithms, gradual increase(typically few hardcoded distances are available in hardware) of the RF power during neighborhood discovery and the number of nodes which can vary from 100-1,000 in a single simulation. It allows picking the percentage of cluster heads during clustering as this is a design variable when using a fixed number of simulated nodes. The battery consumption takes into account the power consumed according to the specification of the node distribution and the minimum adjustable radio power calculated by CRF.



(a) MAC performance for sparse, medium and high density deployment with constant radio range

(b) Local data aggregation protocols performance at the cluster head

(c) Multi-hop protocols performance from source to sink

Fig. 2. MAC performance comparison for data aggregation and multi-hop algorithms using SPEED, Directed Diffusion and LEACH

C. Performance of Distributed Algorithms - Static Clustering

The simulation is repeated by changing percentage of cluster heads and calculating the number of routing rounds during its lifetime. Figure 1(b) illustrates that the drain on node energy follows the Power law which states that if the transmit cost is proportional to the square of the distance then load balancing uses the $80 - 20$ rule [3] for routing. Various clustering algorithms are implemented using the protocol design which are LEACH-S(standard), LEACH-E(energy efficient) and CRF(uses variable RF control). From the simulation results the optimal power-aware QoS is achieved for LEACH-S and CRF when the percentage of cluster heads are at 20%. Suggesting that what ever the WSN size it needs to follow the 80-20 rule for maximum lifetime. The energy aware version LEACH-E uses a more optimal way of selecting the cluster heads, it uses a more specific threshold which is based on the energy residual value and random placement of nodes as in the case of LEACH-S. This further brings down the likelihood of being a cluster head from, 0.20% to $0.20\% + threshold$ value making it narrower to a few available motes. This cluster head selection allows to evenly deplete the rest of the motes by using less than 10% cluster heads leading to a reusable resource phenomena called caching. Caching typically defines as a selective resource which is highly reused to make the re-selection process faster and efficient. It attains optimal performance before other clustering algorithms such as LEACH-S or CRF. In the energy aware version of CRF we use the above caching technique and partition the sensor network into a hierarchal tree with up to three levels. The forward routing tree consist of parents, sibling and children, always the sibling are designated as reusable caching cluster heads. The implementation uses traditional caching algorithm which maintains a most recently used objects, the implemented cluster heads also use a similar use count. The use count is decremented each time it acts as a cluster head and does not leave the cache till it is almost depleted but not dead (can receive and forward to neighbor). The results show that depletion rate is evenly distributed over the lifetime of the network when using the cache making the cluster selection process independent of data aggregation algorithm such as sampled or polled time slots. The optimal cluster head percentage for all the cluster based algorithms converge before 20% while maximizing the lifetime.

V. Life-time Modeling-System Performance using MAC Dependance

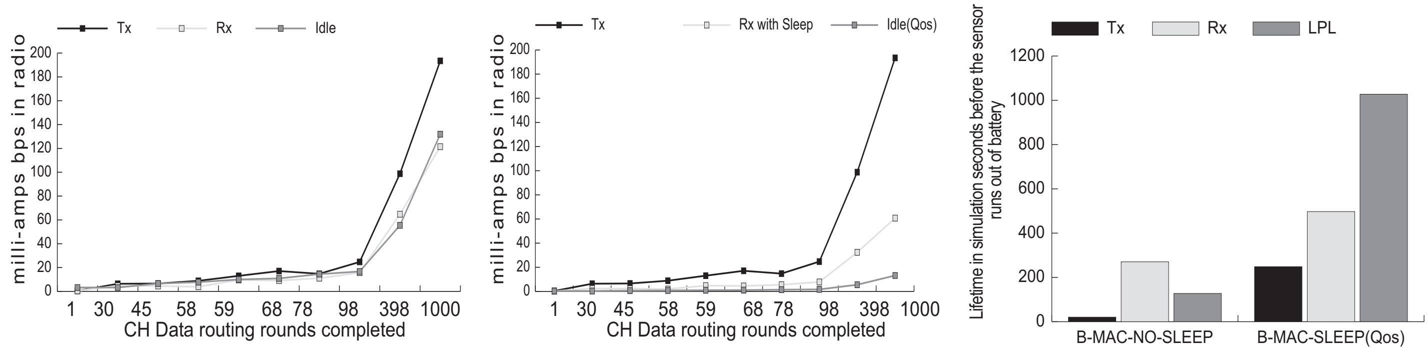
Limited research has been carried out on integrating different network layers into one layer or to benefit from cross-layer interactions between routing and MAC layers for sensor networks. Most of the existing protocols can use RTS/CTS extensions to achieve collision free broadcast. In this testbed we use LEACH(proactive), SPEED(Stateless Geographic Non-Deterministic forwarding) and Directed diffusion(Information dissemination).

A. Multi-hop MACS- Passive Clustering

So to effectively have cross layer scheduling one of the suggested design of integrating MAC/physical layer integration and Routing/MAC/physical layer integration. This uses passive clustering which uses sleep schedulign between nodes and is independant of the network and upper layers.

B. Performance of WSN Data Aggregation Algorithms

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 was chosen from candidates based on the residual energies. Moreover, the transmission range of the sensor nodes is a decision variable, since it affects the layering of the network (the hop-counts change). Simulations were run to find a good range of values for a specific scenario which allow to measure the power consumed in mAh and at the same time to better have application control the time spent in Tx, Rx and Idle tasks. The simulation of the of WSN protocols with 802.11/CSMA/B-MAC with varying node density is shown in figure 2(a), which shows that for a fixed range radio a spare deployment is ideal and B-MAC does optimal with medium density and when the collision is maximum in high density deployment CSMA does better. The sensor network service QoS comparative metrics for optimal performance is categorized in Figure 5, table. In section IV(B) the simulation results were based on network layer



(a) MAC performance with data forwarding (b) MAC performance with 20% nodes as cluster heads with application control (c) Lifetime comparison with sleep schedules

Fig. 3. Radio characterization for normal and renewable lifetimes

performance in this section we study the MAC communication losses and the data sensing reliability [4] in sensor networks. Our performance evaluation of data aggregation algorithms uses a single-hop neighbor discovery and a distributed method to select a cluster head. Once the cluster head selection process is complete the metrics measured are the control protocol overhead, the data payload received without errors at the cluster head and the running average of how efficient the data aggregation algorithms does, if all the neighbors respond successfully then it does 100% aggregation otherwise a loss of data aggregation is reported due to insufficient data.

C. Link Protocols

Link protocols can be categorized into sampled and slotted as shown in figure 4(a). In sampled the communication is unsynchronized and the data transfer wakes up the receiver. Some implemented examples used in this testbed are B-MAC, Mica1 LPL and CC2500. In the case of slotted the inter node communications is synchronized and it is the responsibility of the nodes to transfer data according to their pre-allocated slots. Some of the implemented examples of this link protocols are S-MAC, T-MAC, 802.15.4 and ZigBee. In sensor networks multi-cast is an important type of communication pattern, in protocols that include clustering. Cluster heads communicate with their members and thus the intended receivers may not be all the neighbors of the cluster head, but may just be a subset of the neighbors. We use this type of data aggregation at the cluster heads using clustering for various link protocols. Carrier Sense Multiple Access (CSMA) and its variants appear in several major MAC protocols designed for WSNs [5], such as S-MAC, T-MAC, Shift, and IEEE 802.15.4. CSMA-based protocols benefit from low complexity, scalability, and the ability to adjust to population changes. On the other hand, they suffer from energy wasting problems, such as packet collisions, overhearing, and idle listening [5].
CSMA = Message Transmission = $2 \times propagation$
It is absolutely crucial that the MAC protocol support duty cycling mechanism to eliminate idle listening. To evaluate B-MAC with the GlomoSIM [1] we use two categories of WSN algorithm as before. As the design of B-MAC is receiver centric it is always able to receive packets to the nexthop keeping drop rate to a minimum in multi-hop routing compared to CSMA and 802.11. Design for collision avoidance
B-MAC = Preamble Length = Sleep Schedule = 100ms
We use GlomoSIM from table 1 with 100 nodes deployed in a 140×140 meters with radio range of 50 meters. As this is a dense network deployment one would expect a lot of collision and data retries. To evaluate CSMA and BMAC design with the GlomoSIM we use two categories of WSN algorithm one using clustering which has lots of time synchronization overheads and other uses multi-hop which is highly distributed due to it being synchronization independent.
The MAC performance results for CSMA and B-MAC are shown in figure 2(b) and 2(c). CSMA and B-MAC perform equally well in local data aggregation where time synchronization is not a criteria and at the same time 802.11 performs very poorly due to collision and retries. In the case of receiver synchronization and shorter preambles used by multi-hop protocols B-MAC does 3X times better than CSMA in extending its lifetime and there is no change in performance in the case of 802.11. The sensor network QoS comparative metrics for optimal performance is categorized in figure 5, table(a). The performance of B-MAC is highlighted by its robustness to noise variance and adaptability to low-duty cycling modes which are characteristics of sensor networks.

D. Radio Characterization Consumption in milli-Amps(bps)

$$Cost\,(bps) = \frac{C_{batt} \times V \times 60 \times 60}{Energy_{load}} \times routing\,rounds \quad (5.0)$$

Radio characterization allows to calculate the minimum power in milli-amps for each bit it transmits and receives for the radio to handle its communication and adapt to application needs. By using a default battery model as shown in equation (1) we get the scheduling break down for a simulated routing algorithm as follows Tx=10.0 mA, Idle=744.3mA and Rx=175.35mA, as it is seen that overhearing wastes a lot of energy compared to transmitting as shown in figure 3(a). We modify the routing protocol which shares schedules between nodes so that a percentage of nodes are put to sleep. This mechanism reduces the receiver's overhead for a given region

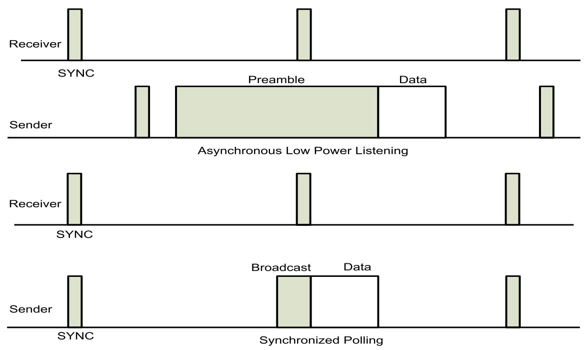
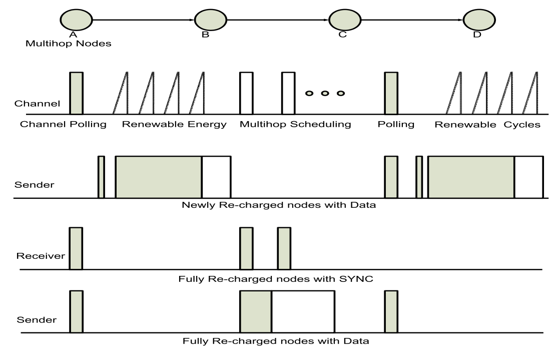


Fig. 4. (a) Time synchronization fixed lifetime model



(b) Time synchronization with renewable cycles

Node Distances	802.11	CSMA	B-MAC
Single-hop	Worst	Best	Good
Multi-hop	Worst	Poor	Good
QoS			$\underset{\longrightarrow}{SensingReliability}$

Fig. 5. (a) QoS multi-hop criteria for Fixed lifetime model

Power-aware MAC	Nodes Active	With select % of nodes to sleep
CSMA	Same	Lifetime increases by 2X
B-MAC	Same	Lifetime increases by 2X
QoS		$\underset{\longrightarrow}{ApplicationEfficient}$

(b) QoS criteria for power-aware MAC

avoiding energy wastage. With the modified sleep schedule the lifetime significantly increases as shown in figure 3(b,c) by 2X. The sensor network QoS comparative metrics for optimal performance is categorized in figure 5, table (b) for different MACS.

VI. Ultra-low Duty Cycling Application Scheduling in Real-time Clock

Section IV(B) and V(B) addresses communication and data aggregation cost for a proactive WSN algorithm. In this section we focus on scheduling using application specific needs in a form a protocol service. The ultra-low duty-cycling is typically $\leq 0.01\%$, due to this the necessity of the nodes to be active for a fraction of the time needing radio to be faster. Time synchronization schedules for all routing nodes share schedules with their multi-hop neighbors making it adaptive to the application low polling rates. In LPL, nodes wake up very briefly to check channel activity without actually receiving data. We call this action channel polling [6]. FARMS applications need to further schedule its harvesting renewable energy cycles and optimizes on finding nodes which can receive its updated data during the harvesting cycle.

A. Design of FARMS

FARMS is designed with two main goals: first, to functions in a duty cycle that is practical to renewable energy model, and second, to schedule to variable number of fully recharged nodes at a given time to multi-hop the sensor network traffic. As the renewable energy model has asynchronism due to its reliance in ambient energy resources one way of scheduling is to have a predetermined period which can be longer than re-charge cycles. As this may effect latency of the sensor network we adapt data driven approach. If the sensor has data and is fully charged then it can transmit. Transmission is possible but it does not guarantee of any available multi-hop nodes due to lack of synchronization and finite energy per node between recharges. We adopt several approaches to meet these goals. We combine asynchronous pooling with the use of expensive preamble which allows to synchronize with other receiving nodes and at the same time if the current node has already been synced up with receivers then it does a regular broadcast during the periodic poll to relay its data to the next hop. This combined channel polling and preamble based broadcast reduces the overall sensor network latency in a multi-hop configuration.

B. Synchronized Channel Polling

Figure 4(a) shows how the sender and receiver time synchronize in a single-hop configuration. If the sender and receiver are unsynchronized then a preamble is used which is as long as the channel poll. The penalty of synchronization is cost of maintaining the synchronization schedules. The schedules are distributed to the neighbors every SYNC packet as in S-MAC[5].

C. Synchronizing Multi-hop Nodes

We have an advantage of using mixed mode operation to exchange schedules to single-hop neighbors. To transmit the new data in a multi-hop fashion using MAC we need to adapt to varying and on-demand needs of the application. If there are M recharged nodes with new data the possibility to acquire the channel for collision free transmission is

$$A = M\left(1-p\right)^{M-1} \tag{6.0}$$

$$A_{max} = 1 - \left(\frac{1}{M}\right)^{M-1} \quad at\, p = \frac{1}{M} \tag{6.1}$$

Due to cluster to cluster multi-hop message hopping the number of receiving nodes able to receive the packets is very unreliable. This is due to be not being synchronized as in single-hop mode of operation. The sufficient condition is to receive the packets in the nexthop successfully is to have enough number of receiving nodes. The multi-hop nodes are depend on down stream traffic so it needs to adapt. Figure 4(b)

Power-aware MAC	Tx	Rx	Idle	QoS
CSMA	1%	80%	19%	Implemented by non-sensor network simulators
B-MAC	2%	65%	33%	TinyOS Framework(without realtime clock)
Application control static clustering	6%	45%	49%	Our study and first adaptation of power-ware QoS
Sleep scheduling FARMS with passive clustering	72%	5%	23%	$\xrightarrow{tunable\ close\ to\ design\ constraint}$

Fig. 6. Related work and QoS centric cross-layer enhancements for Fixed and Renewable lifetime models

shows how multi-hop scheduling increases its polling period between B and C within regular polls of A and C to forward the data. For a M neighbor cluster configuration assuming that only one can transmit at a time to successfully receive the message at the nexthop it needs to have few nodes awake. To adapt to increase in traffic and receive without packet drops is the multi-hop nodes need to increase its polling period given by

$$Polling_{adaptive} \geq 2M\ slots \tag{6.3}$$

In summary, adaptive polling slots are dynamically added and extended as driven by traffic. Regular polling slots are always reserved for new nodes to enter after they are recharged and have data to transmit, reducing channel capturing by any single node. Multi-hop streaming reduces latency by keeping fully charged nodes synchronized as well as buffer requirement at each node by quickly moving data over multiple hops.

D. Lower Bound on Energy consumption

Input: M Sensors motes
Output: Set Led on SYNC Pulse
foreach *Multi-hop Traffic* **do**
  If (Adaptive-Poll)
    Receive-Data(A$\rightarrow B$)
  If (Regular-Poll)
  Begin
    SynNewNodes() /* after recharge */
    OutputLed()
  End
end
Return SYNC-Schedule

To accomplish network wide synchronization we write an application which turns on the motes leds at regular intervals. This interval is time synchronized across clusters so when leds are flashing it will be visually synchronized even with minimal clock drift. The above program shown flashes the leds if enough active motes are available in a cluster, which is the design constrain of the multi-hop routing algorithm.

The energy model defines these four stable states, P_{tx},P_{rx},P_{listen},P_{sleep} and the radio during transition state during polling is P_{poll} (average). Expected energy is the sum of energy in each state

$$Energy = P_{listen}t_{cs} + P_{tx}t_{tx} + P_{rx}t_{rx} + P_{poll}t_{poll} + P_{sleep}t_{sleep} \tag{6.4}$$

The simulation are re-run using the new ultra-low power consumption model, manufacturer specified ultra-low duty cycle as shown in table, figure 6 using ($\leq 1\mu A$) during idle with B-MAC. Lifetime was initially calculated per node and using a well designed power-aware time scheduled multi-hop MAC. Our study and simulation results show that the scheduling is more distributed and the multi-hop scheduling can adapt to data traffic needs and tunable to the desired efficiency which are normally achieved by using network and upper layer scheduling. Simulation runs using 100 nodes with B-MAC and running minimal application control with 20% synchronized forwarding nodes use 72% for Tx, 23% Rx and 5% Idle as shown in figure 6, which converges with the initial design assumption for a large sensor network deployment, as the maximum lifetime criteria in section IV.

VII. CONCLUSION

The fundamental contribution of the paper is in providing an extensible sensor network protocol service which are ambient in nature running renewable energy sensor network applications and study the dependable protocol parameters effecting WSN algorithms using fixed lifetime model. These runtime tunable parameters are adaptable after deployment of the sensor network which are optimal based on static clustering, the density, overhearing losses, floor noise level and renewable energy resources. A reprogrammable structure in developing energy-aware renewable applications using FARMS to provide basic QoS for low data rates and data reliability with passive clustering independent to the cross-layers and application developers in a form of a sensor protocol service with emphasis on multi-hop MAC scheduling. Computational/networking characteristics of 'INSPIRE' [7] allows radio utilization which is optimized for passive clustering achieves similar reliability as static clustering using fixed lifetime model.

TABLE I
GLOMOSIM SIMULATOR

Network Configuration	100 nodes, Uniform distribution	420mX420m
WSN Algorithm implemented	LEACH	20% CHs
MAC Layer Configuration	B-MAC,CSMA,802.11	Using sleep cycles
Radio Propagation	Propagation pathloss Model	FREE-SPACE
Radio Frequency	Frequency 900 Mhz, Power 50m	BW $2X10^6$ bits(bps)
Data Collection	Sampled, Energy Harvesting	Slotted ZigBee, 802.15.4
Simulation Platform	Windows VISTA	Modules VC++

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