IAENG International Journal of Computer Science, 35:3, IJCS_35_3_01

A Unified Clustering and Communication Protocol for Wireless Sensor Networks

Nauman Aslam, William Phillips and William Robertson

***Abstract*— In this paper we present an energy-efficient cross layer protocol for providing application specific reservations in wireless senor networks called the "Unified Clustering and Communication Protocol" (UCCP). Our modular cross layered framework satisfies three wireless sensor network requirements, namely, the QoS requirement of heterogeneous applications, energy aware clustering and data forwarding by relay sensor nodes. Our unified design approach is motivated by providing an integrated and viable solution for self organization and end-to-end communication is wireless sensor networks. Dynamic QoS based reservation guarantees are provided using a reservation-based TDMA approach. Our novel energy-efficient clustering approach employs a multi-objective optimization technique based on OR (operations research) practices. We adopt a simple hierarchy in which relay nodes forward data messages from cluster head to the sink, thus eliminating the overheads needed to maintain a routing protocol. Simulation results demonstrate that UCCP provides an energy-efficient and scalable solution to meet the application specific QoS demands in resource constrained sensor nodes.**

***Index Terms* — wireless sensor networks, unified communication, optimization, clustering and quality of service.**

I. INTRODUCTION

Wireless Sensor Networks have generated a phenomenal interest in the research community in recent years due to the number of military, commercial and industrial applications that they will be used for in the near future. While a great deal of research has been done on architecture, topology control, energy conservation, and location-based algorithms of WSNs [1-4]; providing application specific QoS in WSNs remains one of the most challenging tasks faced by the research community. Some researchers have investigated and developed new models of quality of service (QoS) support for WSN. For example, in [5, 6] SPEED and RAP were proposed for real time communication in WSN. In SPEED, end-to-end soft real time communication is achieved by using a combination of feedback control mechanisms and geographic forwarding. RAP implements a velocity monotonic scheduling to account for both time and distance constraints on packet delivery. Considering the resource constrained nature of sensor nodes with respect to communication, computation and storage [1] an approach which minimizes energy consumption and control overhead while meeting the QoS objectives is highly desirable.

For emerging WSN applications, typically the sensors are part of a heterogeneous sensing environment consisting of several applications each with its own unique QoS demands. In such environments, it is very important to prioritize data based on their criticality to the system in order to ensure real-time response to emergency and disaster response situations [7]. Critical data must be given priority over other traffic requiring a QoS-aware sensor network system that ensures efficient use of the sensor's resources and real time access to the collected measurements [8]. Application performance can be ensured by providing priority-based resource reservation. Another solution for enhanced application performance in wireless networks is the cross layer design approach in which information is exchanged over two or more layers [9, 10]. In wireless networks, cross layer design (CLD) techniques can be divided into two categories; the first category creates new interfaces to facilitate direct interaction between the layers involved while the second merely merges adjacent layers [11]. The new interfaces approach can be subdivided based on the direction of interaction into upward, downward, back and forth. As application performance guarantees and prioritized access to medium for critical data transmission are our focus, we employ the downward information flow approach for QoS reservation. This approach was chosen as it renders a simple design while keeping the existing protocol stack intact. As shown in Fig. 1, following a cross layer design paradigm, the MAC layer interacts with the application to create dynamic resource reservations, granting channel access to applications based on their priority. The MAC layer employs a reservation-based protocol that allows flexible assignment of bandwidth to the sensor nodes based on application demands. The reservation is done by maintaining a priority index for each application level. While the transport layer stack is shown in Fig. 1 for completeness, our protocol does not make use of it.

Our approach presents a novel and elegant solution for addressing QoS, energy efficiency, and data forwarding issues all in a modular cross layer design approach in a unified fashion. The unified clustering and communication protocol (UCCP) design approach encompasses all the elements required in end-to-end communication in WSNs. At the core of the unified design strategy, a clustering topology was considered as it is a standard approach for achieving high energy efficiency and is highly scalable in WSNs [12].

Manuscript received June 4, 2008.

Nauman Aslam is with the Department of Engineering Mathematics and Internetworking, Dalhousie University, Halifax, Nova Scotia, Canada. (e-mail:nauman.aslam@dal.ca, phone: +1-902-494-2053)

William Phillips is with the Department of Engineering Mathematics and Internetworking, Dalhousie University, Halifax, NS, Canada, B3J-1L1

William Robertson is with the Department of Engineering Mathematics and Internetworking, Dalhousie University, Halifax, NS, Canada, B3J-1L1

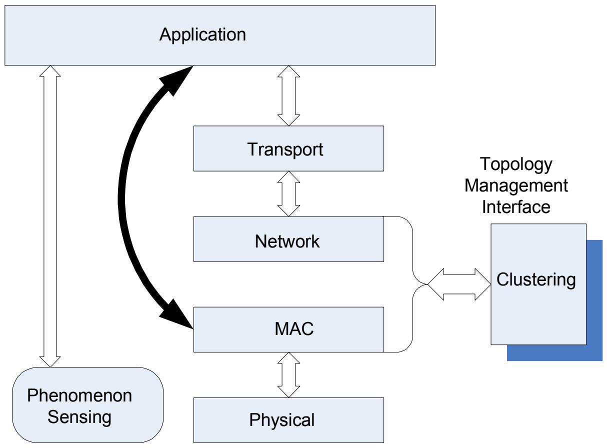


Figure 1: Cross layer design approach for unified clustering and communication protocol

Cluster formation is a process whereby, given multiple choices, sensor nodes decide with which cluster head they should associate. Typically cluster head selection involves a metric based on parameters including residual energy and distance to the cluster head [13-15]. The decision is critical as a poor choice can lead to increased energy consumption, thus compromising network life. The novelty of our proposed clustering technique consists of employing a multi-criterion optimization algorithm (MCOP) for satisfying the multiple criteria simultaneously. The MCOP employs preference function modeling techniques [16] that results in the formation of energy efficient clusters that extend the lifetime of the network. At the MAC level, the proposed protocol assumes a single time slotted channel and uses a TDMA frame like structure consisting of a reservation period, a scheduled access period and a forwarding period. Our protocol incorporates a traffic adaptive slot allocation algorithm which is used by the cluster head to create the transmission schedule for scheduled access in each TDMA frame. Nodes use the application priority index to request resources in the next scheduled access period, which is then used by the cluster head to generate the transmission schedule.

The rest of the paper is organized as follows. Section II presents related work in the areas of energy-efficient clustering mechanisms, QoS implementation and routing in wireless sensor network environments. Section III presents our system model and assumptions. Section IV presents the design and architectural overview of the proposed UCCP. In Section V we present the novel multi-criterion optimization based clustering scheme. Section VI presents the reservation-based TDMA MAC protocol. Simulation results and analysis are presented in Section VII and the main conclusions and directions for future research are presented in Section VIII.

II. RELATED WORK

Wireless sensor networks have been an extremely active area of research in the last few years and a significant amount of work has been done in areas of topology control, clustering, MAC and network layers. Since our technique provides a unified solution addressing MAC, network, topology control and QoS aspects in a modular cross layer design, we provide a summary of the related work which has similarities in both individual modules and the integrated approach.

LEACH [12] is a well known protocol which can be considered as both a clustering and an integrated approach for application specific WSN. In LEACH topology control in achieved by self organizing the sensor nodes using a clustering algorithm to form single hop clusters. Every sensor node periodically elects itself as cluster head with some probability and broadcasts its decision. The remaining sensor nodes receive the broadcast from one or more cluster heads and associate themselves with a cluster head based on minimum communication cost. Since a cluster head handles more data than non-cluster head nodes, its energy is dissipated at a higher rate than the non-cluster head nodes. To balance the over all energy consumption across the network the role of cluster head is rotated among all sensors. The LEACH protocol is energy-efficient; however, the expected number of clusters is predefined. Another disadvantage of LEACH is that it does not guarantee good cluster head distribution and assumes uniform energy consumption for cluster heads. An extension of LEACH as an integrated solution is proposed in [17], which uses a cross layer design approach. The technique jointly addresses routing, MAC, physical and energy aspects. Routing is performed based on a clustered self organized structure and employs the CSMA protocol at the MAC level. Authors in [18] have proposed a unified framework encompassing routing and a MAC layer protocol. Sensor nodes are organized in layered manner based on hop-count from the base station. For an arbitrary node x in layer i, its neighbours are classified as; INWARD if it located in layer i - 1, OUTWARD if located in layer i + 1 and PEER if located in layer i respectively. A sensor node selects one of it neighbours in the inner layer as its forwarding node. The selection of forwarding nodes can be done in either random or round robin fashion. TDMA is employed at the MAC level for collision free transmission.

For MAC layer protocols, the TDMA approach has emerged as a popular choice in WSN mainly because it provides an energy efficient and collision free channel access. TDMA based techniques are adopted both as integrated [12, 17, 19] and stand alone MAC protocols [20-24]. By using TDMA, nodes save energy by adapting to a low duty cycle when compared with the other contention based [25, 26] techniques. Power efficient and delay aware MAC (PDEMAC) [19] extends the single hop TDMA to a multi-hop sensor network using high powered access points. The protocol assumes that the access point is powerful enough to reach every single node in the network. The protocol consists of a topology learning phase, topology collection phase and scheduling phase, where most of the work is done by the access points. An access point is also responsible for schedule creation and synchronization among the sensor nodes. The authors have shown that this technique results in significant energy savings and enhanced delay performance. Providing delay guarantees for real time communication is considered in SPEED [5] and RAP [6]. SPEED achieves end-to-end soft real time communication by using a combination of feedback control mechanism and geographic forwarding, whereas RAP implements velocity monotonic scheduling to account for both time and distance constraints on packet delivery. It is worthwhile to note that aside from energy efficiency, consideration has been given to achieve a measure of application QoS. However, none of the above mentioned protocol considers a situation with more than one application and a mechanism of service differentiation among those applications.

Among the clustering protocols [12, 14, 27-30] are the most prominent and well referenced in the literature. The HEED [14] algorithm forms single hop clusters by randomly selecting cluster heads according to a hybrid metric based on residual energy and a secondary clustering parameter, such as node proximity to its neighbours or node degree. A careful selection of the secondary parameter helps load balancing among the cluster heads during the cluster formation process. Fast Local Clustering (FLOC) was proposed in [28] which produce non-overlapping and approximately equal size clusters. The clustering is such that all nodes within one hop from a cluster head belongs to its cluster, and no node m hops away from the cluster head may belong to its cluster. The authors in [30] proposed an algorithm which forms a rooted spanning tree of the network and then forms the desired sub clusters. In [29] a distributed weight based energy-efficient hierarchical clustering scheme is proposed where each node after discovering its neighbours calculates its weight based on residual energy and distance to its neighbours. The largest weight node becomes a cluster head. Our work is closely related to the Energy Efficient Clustering Scheme (EECS) presented in [27] Mao Ye et al. which takes into account the unbalanced energy dissipation. However, EECS uses a weighted cost based scheme, whereas, we attempt to tackle the problem from an optimization perspective.

III. NETWORK MODEL AND ASSUMPTIONS

We make following assumptions for our sensor network:

1. Nodes are dispersed randomly following a Uniform distribution in a 2-dimensional space.
2. The location of the Base Station (BS) is known to all sensors. BS is considered to be a powerful node having enhanced communication and computation capabilities with no energy constraints.
3. All nodes remain stationary after deployment.
4. All nodes are homogeneous in terms of energy, communication and processing capabilities.
5. Nodes are location unaware i.e. they are not equipped with any GPS device.
6. The nodes are capable of transmitting at variable power levels depending on the distance to the receiver as in [12]. For instance, the MICA Motes use MSP430 [31] series micro controller which can be programmed to 31 different power levels.
7. The nodes can estimate the approximate distance by the received signal strength, given the transmit power level is known, and the communication between nodes in not subject to multi-path fading.
8. We assume that the deployed sensors belong to different applications with three priority levels namely: high, medium and low.
9. We use the energy model presented in [12].

IV. UCCP DESIGN

To meet the demands of dynamic application specific QoS requirements in a heterogeneous sensing environment in an energy efficient manner we present a protocol called Unified Clustering and Communication Protocol (UCCP). We adopt a cross layer design strategy for interaction between the MAC and the application layer for prioritized access to the medium for applications having urgent delivery requirements. One of the major objectives of the protocol is to propose a viable and energy efficient solution for end-to-end communication taking into account the QoS constraints of the applications. For this reason we use a clustered topology that transmits data from the cluster head to the sink, thus restricting communication to two hops. As shown in Fig. 2, each UCCP round consists of two major phases namely, a self organization phase and a data transmission phase. In the self organization phase nodes communicate with each other to form a clustered topology. The data transmission phase is sub-divided into TDMA frame transmission from sensor node to cluster head and from cluster head to sink. In a multi-cluster network it is typical to have interference caused by neighbours, thus we assume that a unique CDMA code is used within each cluster to avoid this problem.

V. SELF ORGANIZATION PHASE

In this section we present details about the self organization phase in our framework. Essentially, this phase provides a topology management interface in our cross layer design rendering a clustered topology for forwarding the data to the sink. Clustering techniques provide effective means of achieving energy efficiency and scalable performance [12, 14]. Cluster formation is a process whereby sensor nodes decide with which cluster head they should associate among multiple choices. Typically, for a sensor node, cluster head selection decision involves a metric based on parameters including residual energy and distance to the cluster head. Such a selection can lead to poor energy dissipation because the nearest cluster head may be located at a greater distance from base station than the other cluster heads. Thus for that particular node this may not be the best choice. Hence, additional factors like residual energy and node degree may also be of importance when making a decision. The proposed clustering technique [32] employs an algorithm based on a multi-criterion optimization (MCOP), an engineering design technique used extensively in operations research. Typically MCOP deals with satisfying conflicting and possibly non-commensurable criteria in an optimal fashion. The motivation behind the MCOP-based cluster formation technique is to maximize network life time by selecting the best cluster head for a group of sensor nodes by considering multiple criteria such as distance of node to the cluster head, distance between cluster head and sink and residual energy.

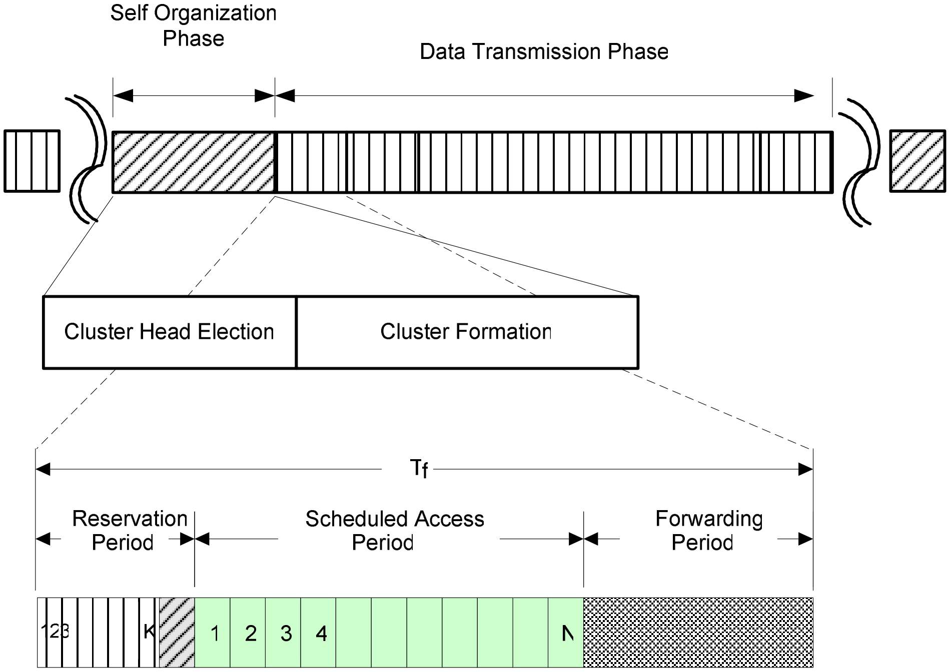


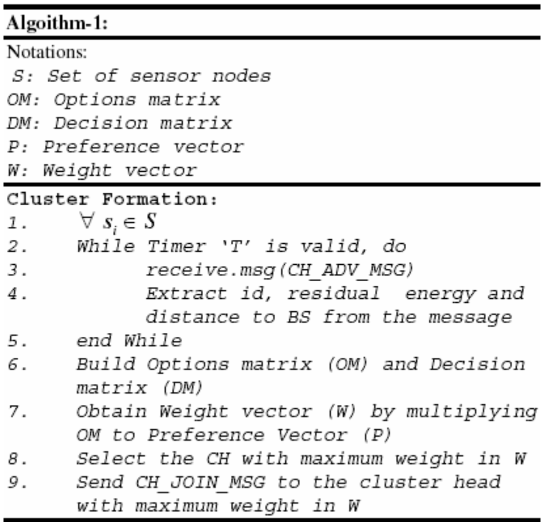
Figure 2: Organization of Unified Clustering and Communication Protocol

A. Multi-Objective Cluster Formation

The core of most clustering algorithms for WSNs employs techniques that attempt to maximize the energy efficiency. In our technique, the prime focus is optimizing the energy usage in cluster formation; i.e. the decision process used by an ordinary sensor node to associate itself with a cluster head is based on minimum overall communication cost. Many previously proposed clustering algorithms have attempted to exploit this in various ways. For example in [13] the sensor nodes select their cluster head based on the strongest signal strength. In [27] the authors have tackled the problem of unbalanced energy consumption by using a weighted cost function. The cost function takes into account the factors such as distance of a node to base station, distance of node to cluster head and distance of cluster head to base station to produce a composite cost metric that load balances the energy consumption. We argue that the same problem can also be tackled by applying the multi-criterion optimization technique.

Our technique is inspired by preference function modeling [16] which has been successfully used to find an optimal path based on multiple user constraints [33]. The basic idea is to use a preference function proposed in [16] which accepts a value from user criterion x and returns a value *s(x)* scaled between 1 and -1 (1 represents the best and -1 represents the worst value respectively). A decision matrix is built and used to find the optimal choice for a given criterion. The preference vector contains the scaled weighted values for each of the parameters involved in the decision process. The weight matrix is obtained by multiplying the decision matrix with the preference vector to find the weight for each of the available choices. The best choice is given by the maximum weight in the weight vector. Algorithm-1 describes the steps in cluster formation.

At the beginning of each clustering period all nodes set their state to 'PLAIN'. The timer *'T'* guarantees that the nodes cluster head contender nodes successfully receive the competition message. Each node computes the probability to become a cluster head contender. If the computed probability is less than the defined threshold value *'T'* (in simulations a *T* is set to 0.15), it promotes itself to the ‘CH_Conetnder’ state and broadcasts a competition message within $R_{COMPETE}$ radius. At the end of this phase there will be approximately *(p x n)* CH contenders in the network. After the timer *'T'* expires, each contender checks if any competition messages were received. If any message was received, it checks if there is a contender with higher residual energy. If a node with higher residual energy is found it drops out of the competition. The ties are broken in favour of the contender with higher id.



Algorithm-1:

Notations:

```
S: Set of sensor nodes
OM: Options matrix
DM: Decision matrix
P: Preference vector
W: Weight vector
```

```
Cluster Formation:
$\forall s_i \in S$
While Timer 'T' is valid, do
    receive.msg(CH_ADV_MSG)
    Extract id, residual  energy and
    distance to BS from the message
end While
Build Options matrix (OM) and Decision
matrix (DM)
Obtain Weight vector (W) by multiplying
OM to Preference Vector (P)
Select the CH with maximum weight in W
Send CH_JOIN_MSG to the cluster head
with maximum weight in W
```

In case the contender does not receive any competition message meaning that there is no other contender in its $R_{COMPETE}$ neighbourhood, it promotes itself to the 'Cluster_Head' state. After the cluster head election process, each elected cluster head broadcasts a 'CH_ADV_MSG' within R_{CHADV} radius. The advertisement message contains the value of residual energy and the cluster head's distance to the sink. Once each node has received the advertisement message from one or more cluster heads, it will start computing the MCOP cluster formation algorithm. The important steps in the whole decision process are building the Options, Decision matrices and the Weight vector. A detailed explanation for each of these steps is given below:

1. Build *OM (k x n)*, where *k* is equal to the number of cluster heads in node's radio range and n is equal to the number of parameters important to the decision criterion. Each element $x_{i,j}$ in the Options Matrix represents the j^{th} parameter for the i^{th} cluster head.

$$OM = \begin{bmatrix} x_{1,1} & x_{1,2} \,..\, x_{1,n} \\ x_{2,1} & x_{2,2} \,..\, x_{2,n} \\ . & . \,..\, . \\ x_{k,1}, & x_{k,2} \,..\, x_{k,n} \end{bmatrix} \tag{1}$$

2. The options matrix is converted into a decision matrix (DM) as follows;

$$DM = \begin{bmatrix} s_{1,1} & s_{1,2} \,..\, s_{1,n} \\ s_{2,1} & s_{2,2} \,..\, s_{2,n} \\ . & . \,..\, . \\ s_{k,1}, & s_{k,2} \,..\, s_{k,n} \end{bmatrix} \tag{2}$$

Each element in DM is found as follows;

$$s_{i,j} \leftarrow 2\frac{(x_{i,j}-b_j)}{(a_j-b_j)} - 1 \tag{3}$$

Where,

a_j = *Best value of* $x_{h,j}$ *for h=1,2,3...k*

b_j = *Worst value of* $x_{h,j}$ *for h=1,2,3...k*

The best and worst values used for calculation in (3) are unique to each parameter. For example, for an arbitrary sensor node the best value for residual energy represents the maximum value in the column of *OM*, which represents the residual energy values for cluster heads that are in the sensor node's range. In case of distance of sensor node to the cluster head, the best value will represent the minimum value in the corresponding column (distance of closest cluster head to the sensor node).

3. Obtain the weight vector W by multiplying the decision matrix DM with the preference vector.

$$\begin{bmatrix} w_1 \\ w_2 \\ . \\ w_k \end{bmatrix} = \begin{bmatrix} s_{1,1} & s_{1,2} \,..\, s_{1,n} \\ s_{2,1} & s_{2,2} \,..\, s_{2,n} \\ . & . \,..\, . \\ s_{k,1}, & s_{k,2} \,..\, s_{k,n} \end{bmatrix} \begin{bmatrix} p_1 \\ p_2 \\ . \\ p_n \end{bmatrix} \tag{4}$$

$$\begin{bmatrix} w_1 \\ w_2 \\ . \\ w_k \end{bmatrix} = \begin{bmatrix} \text{weight}_1 \\ \text{weight}_2 \\ . \\ \text{weight}_k \end{bmatrix} \tag{5}$$

The best choice is given maximum weight in the weight vector.

B. Message Types

The following types of messages are used in the cluster head election:

1. C_COMPETE_MSG: This message is broadcast by each cluster head contender within the compete radius $R_{COMPETE}$. It contains the sensor node ID and the residual energy.
2. CH_ADV_MSG: Each elected cluster head sends this message within RCHAD radius to let the plain sensor nodes know about their status. This message contains node ID, residual energy and its distance to the base station. Residual energy and distance to the base is used for cost calculation in cluster formation.
3. CH_JOIN_MSG: This message is sent by each node to the cluster head which it decides to join after cost calculation. The message contains node ID, residual energy and the ID of cluster head to join.

VI. TDMA-BASED DATA TRANSMISSION PHASE

The Data Transmission phase in our framework follows a TDMA structure. As shown in Fig. 2, each TDMA frame is further subdivided into three main parts namely reservation period, scheduled access period and forwarding period. Once the nodes are organized in a clustered hierarchy, this phase begins and continues to remain operational until there is a need for re-clustering. A TDMA technique is adopted for the following reasons. When using the downward cross layer design approach, TDMA provides a simpler solution for bandwidth/resource reservation as compared to contention based access mechanisms. TDMA has been a popular choice as a MAC layer protocol for WSN. A number of protocols [18, 20-24] were proposed using some flavour of TDMA primarily because of its distinct advantages in energy saving over traditional contention-based MAC protocols. By using TDMA, nodes can avoid packet collisions and save energy by switching their radio transceivers on only for short periods of time when they are either transmitting or receiving packets. Hence, sensor nodes are also able to eliminate the idle listening problem which adds a significant energy overhead in the case of contention based MAC protocols. We now describe the details about the different parts of the data transmission phase in the following subsections.

A. Reservation Phase

The dynamic resource reservation problem has been addressed earlier in the literature [24] in the context of wireless networks. Considering the unique nature of WSNs we introduce a distributed approach in which both sensor nodes and the cluster head participate in resource allocation. The reservation period consists of bi-directional communication between the sensor nodes and cluster head. This period is further divided into two parts. The first part consists of reservation mini slots. Sensor nodes use mini slots to convey the reservation request to the cluster head. The duration of mini slots is much smaller than the data transmission slot. Sensor nodes contend for the reservation mini slots using a slotted aloha protocol. Each reservation request contains the application priority index and number of slots required for the next scheduled access period. In the second part, the cluster head calculates the slot assignment schedule. This schedule is broadcast to all nodes. Sensor nodes in the cluster receive this schedule and update themselves accordingly.

B. Slot Allocation Algorithm

The purpose of the proposed heuristic-based slot allocation algorithm is to take the individual resource reservation requests from sensor nodes and create a global map of resource requirements in a cluster. This global map is compared to the available resources and the application priority index is used to determine which reservation/QoS demands can be met for the next scheduled access period. Flexibility in dynamic assignment is further optimized by setting up resource allocation limits for each priority. An initial allocation limit (IAL) is given to each priority type at start up. If demands for each traffic class do not exceed the IAL, the slot scheduling is performed by assigning the desired number of slots to the node. However, if more resources are required for the high priority traffic then the additional requirements are met by an overload allocation limit (OAL). For any traffic of a priority class i, the OAL refers to the number of its slots that can be used by any other traffic class of greater priority. Thus the minimum available resources (number of slots) that are always available to each traffic class are given by,

$$\text{Minimum available slots} = IAL - OAL \qquad (6)$$

A CH uses Algorithm-I shown below for slot allocation scheduling. As described in Algorithm-I, the CH starts collecting the reservation requests from its member nodes. Each reservation request contains the node id, amount of packets to be transmitted in the current TDMA frame, and the application priority index. Once the CH has received all requests, it begins resource allocation starting from the application with the highest priority level. Lines 2 to 15 describe the resource allocation for high priority application where the CH checks if the number of high priority requests fall below the predefined IAL. If true, the slot allocation is performed by placing the sender id in the schedule and the remaining difference of available slots is added to the medium priority pool. If the number of high priority requests exceeds the predefined IAL, then an attempt is made to perform allocation by taking the number of slots allocated to OAL for low priority applications. If the demands are still not satisfied, then the allocation for high priority is made by adding the slots belonging to OAL of medium priority to the high priority pool. Lines 16 to 24 describe the resource allocation performed for medium and low priority application following a similar procedure. The proposed heuristic-based algorithm attempts to satisfy the reservation demands of high priority applications in an optimal manner by manipulating the allocation limits while maintaining fairness by using hard bounds for medium and low priority applications. The latter ensures that a minimum bandwidth is always allocated to medium and low priority applications.

ALGORITHM-II

Input Parameters:

S_i^k = Number of slots requested by node *i* for application *k*

N = Total number of slots in TDMA frame

N^H, N^L and N^M as the values for IAL for high, medium and low priority applications respectively such that

$N = N^H + N^M + N^L$

$N^{\hat{L}}$, $N^{\hat{M}}$ are OAL for low and medium priority respectively

Output: Slot assignment schedule

```
1.  For CH_j ∈ CH, collect $S_i^k$ where, i=1, 2… m are the
    cluster members
2.  for k==H
3.      if $\sum S_i^k \le N^H$
4.          Allocate the slots to high priority requests
            by placing the id of sender in the schedule
5.          Update remaining slots to the medium
            priority pool $N^M$
6.      elseif $\sum S_i^k \le N^H + N^{\hat{L}}$
7.          Repeat Step 4
8.          update the remaining slots to the low
            priority pool $N^L$
9.      elseif $\sum S_i^k \le N^H + N^{\hat{L}} + N^{\hat{M}}$
10.         Repeat Step 4
11.         Update the remaining slots to the
            medium priority pool $N^M$
12.     else
13.         Allocate slots to high priority requests
            from $N^H + N^{\hat{L}} + N^{\hat{M}}$
14.     end
15. end
16. for k==M
17.     if $\sum S_i^k \le N^M$
18.         Allocate the slots to medium priority requests by
            placing the id of sender in the schedule
            update remaining slots to the low
            priority pool
19.     else
20.         Allocate slots to high priority requests
            from $N^M + N^{\hat{L}}$
21.         Update $N^L$
22.     end
23. end
24. for k==L
25. Allocate the slots to the low priority requests from
    $N^L$ and any remaining slots from high or medium
    priority
26. end
```

C. *Scheduled Access Period*

The Scheduled Access Period contains collision free data transmission slots. Sensor nodes use these slots to transmit data to the cluster head using the assignment schedule as mentioned earlier. We assume that the number of slots is fixed in this period and each slot can contain one data packet.

D. *Forwarding Period*

In this period, data from cluster heads is transmitted to the sink. Simultaneous transmission to the sink from more than one cluster head can cause interference. We assume that each cluster head uses a unique CDMA code to avoid this problem.

VII. SIMULATION RESULTS

This section presents simulation results to demonstrate the performance of UCCP. We present the results in two parts. The first part investigates clustering and measures the increase in network life time obtained by using the cluster formation scheme used in UCCP. Here, the main focus is on energy conservation. In the second part, we evaluate the integrated performance of the scheme with respect to meeting the QoS requirements of the applications. We analyze our proposed technique for a number of performance metrics related to application performance including end-to-end delay and application delivery ratio. The network simulation model is built using MATLAB. All simulation results are means of 25 runs.

A. *Clustering Results*

Simulations for all protocols were performed in MATLAB. A similar model as defined in [13, 14, 27] is used to measure the network life time in rounds, where each round consists of a clustering period and data period. In each round a set of new cluster heads is elected and remaining nodes become cluster members. In the data period, each node sends five data packets of 100 bytes each to the cluster head. The cluster head sends an aggregated message of 500 bytes to the sink. Percentage of active nodes is the commonly used criterion for measuring the network life. The lifetime on an individual sensor node is measured in number of rounds before its energy is depleted. The life time of a network can be defined in either the number of rounds till the first node dies or a certain percentage of nodes die. Although the network life time measured to the death of the first node is used extensively in the literature including [13, 14, 27], we argue that this definition is a bit strong for large scale networks, since some of the sensor nodes continue to be operational thus maintaining a certain degree of connectivity required for data gathering. Therefore, in addition to the first node death, we also measure the network life when 25% and 50% of the nodes are dead. For UCCP clustering simulations, we consider three parameters, important to cluster formation namely; distance of node to the cluster head, distance of cluster head to the sink and residual energy of the cluster head. The first two parameters are used to calculate the communication cost and the last parameter is for selecting a cluster head based on higher residual energy. Table I summarizes the important simulation parameters used.

Table I: Simulation Parameters

Sensor Deployment Area	100 x 100 m
Base Station Location	(50,175) m
Number of Nodes	100 – 500
Data Packet Size	100 bytes
Control Packet Size	25 bytes
Initial Energy	0.5 J
$E_{Elect.}$	50 nJ/bit
ε_{fs}	10 pJ/bit/m^2
ε_{mp}	.0013 pJ/bit/m^4

Network lifetime is the most important performance metric for WSNs. Using this metric the UCCP clustering is evaluated under different topology configurations and network sizes. For a fair comparison with EECS, we use $R_{COMPETE}$ (competition radius for cluster head candidates) equal to 26 *m* and value of *T* (probability of a node to become cluster head candidate) equal to 0.15. These values are reported as optimal in [27]. The parameters for LEACH and HEED were based on the model provided in [13, 14]. In order to evaluate the scalability of the proposed scheme, two different network sizes are used. Fig. 3 and 4 show the network life time in data collection rounds. The results indicate that the first node death occurs after 920 rounds and 980 rounds for network size of 200 and 500 nodes respectively. Under the first node death criterion, UCCP extends the network lifetime approximately 16 % compared to EECS, 25% compared to LEACH and 120% compared to HEED. These results clearly demonstrate that UCCP clustering enhances network life significantly as compared to other protocols because sensor nodes are able to optimize different communication costs involved in data transmission to the BS. Moreover, the cluster formation process ensures that sensor nodes dissipate their energies at a balanced rate by considering multiple factors that influence energy consumption.

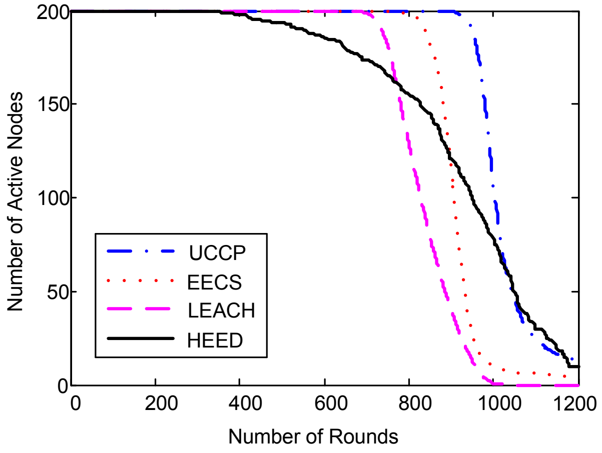


Figure 3: Network Life in Number of Rounds

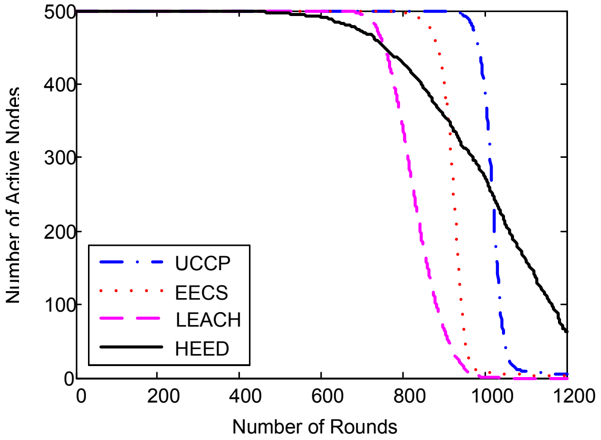


Figure 4: Network Life in Number of Rounds

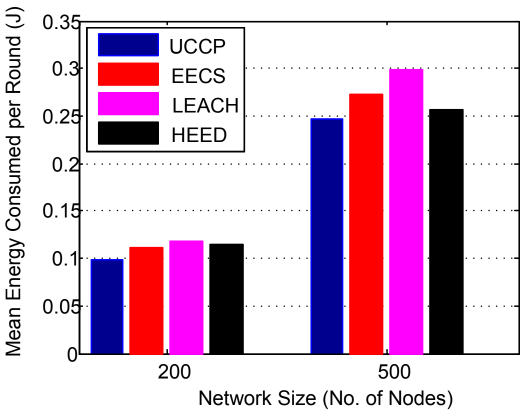


Figure 5: Energy Consumed per Round

Tables II summarize the results in terms of percentage of network lifetime improvement by UCCP clustering for different network sizes.

Table II: Improvement in network life achieved by UCCP

	Network Size = 200			Network Size = 500		
UCCP Improvement over	**Ist Node Dead**	**25% Dead**	**50% Dead**	**Ist Node Dead**	**25% Dead**	**50% Dead**
EECS	16.92	11.22	10.57	20.03	11.41	10.77
HEED	154.7	18.48	5.46	121.5	30.42	1.81
LEACH	31.22	25.61	21.11	35.85	30.08	27.78

The average energy consumed per round is also analyzed. Fig. 5 depicts the results for average energy consumed per round for two different network sizes. These statistics are collected using 1000 independent rounds with no dead nodes in the network. It can be observed that UCCP outperforms all other protocols because it renders the least amount of consumed energy for the cases considered here. In addition to the balanced energy dissipation behaviour, other factors such as low protocol overheads, and optimizing on the protocol implementation factors such as help UCCP achieve minimum energy consumption as compared to all other protocols. LEACH on the other hand performs worst because it delivers a topology where CH distribution is not well controlled and cluster formation does not take into account any parameter that optimizes the energy consumption between sensor node, CH and the BS. Hence, more energy is expended as compared to HEED, EECS and UCCP.

B. TMDA Results

Now we present the results specific to application performance including average end-to-end delay and application delivery ratio. To simulate a realistic heterogeneous sensing environment, we use three different application types with a different priority (high, medium and low) to investigate the performance metrics stated above.

Our simulation model assumes a single time slotted channel within a cluster. We use a total of 32 data transmission slots per scheduled access period. Each data transmission slot occupies 3.2 ms, which is calculated based on 250 Kbps channel rate and data packet size of 100 bytes. As outlined in the Section 6.2 for IAL, we use 16, 10, and 6 slots for high, medium and low priority applications respectively. Similarly, values of OAL for medium and low priority are taken as 6 and 3 slots respectively. In each TDMA frame each node generates the traffic following a Poisson distribution with intensity equal to the packet arrival rate. In the first experiment we measure the end-to-end delay for each priority application with increasing packet arrival rate. From Fig. 6 it is seen that when the traffic arrival rate is low, each application incurs consistent low delay mainly because there are enough resources available to satisfy the slot allocation demands for each application in the TDMA frame. However, with increasing traffic load, HP application performs much better than the MP and LP application. As the traffic for each application grows, the burden on cluster heads to satisfy slot request demands for each application also rises. The slot allocation algorithm used by a cluster head results in HP application being favoured in slot resource assignment. Thus, we see even with the increased traffic load HP application maintains a consistent delay. Whereas, the MP and LP packet do not get immediate access to the resources and have to be queued for transmission in the following TDMA frames resulting in much higher queuing delays. Fig. 6 also shows the results from scenario where no reservation is used for priority applications. In this case all priority applications are treated equally and get equal amount of resources for all traffic arrival rates.

Satisfying QoS demands for HP application by adaptive reservation is further exemplified in Fig. 7 which shows the delivery ratio vs. traffic load. The results in this figure also corroborate the analysis of Fig. 6 that under high loads, the HP application is able to maintain a higher delivery ratio as compared to MP and LP applications because of prioritized resource allocation. Again, for the case where no reservations are used we see consistent delivery ration values for all applications.

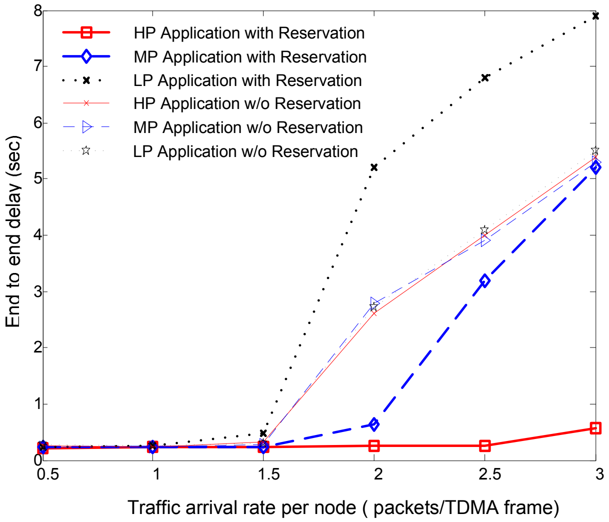


Figure 6: End-to-end delay with 32 data slots

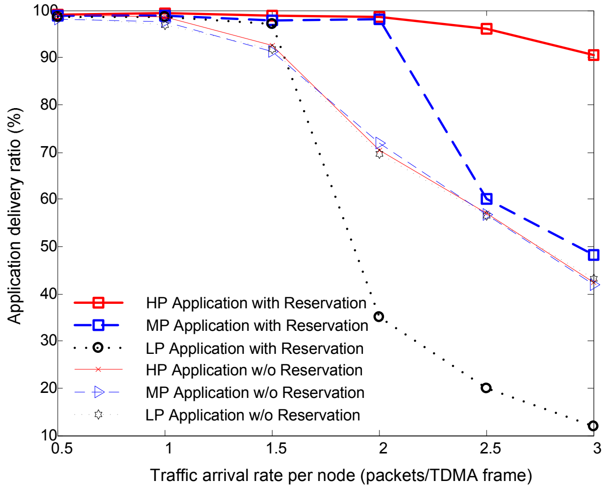


Figure 7: Application delivery ratio using 32 data slots

VIII. CONCLUSIONS

In this paper we have presented a unified approach for end-to-end communication in WSN. We have adopted a cross layer design approach to address the problem of satisfying QoS demands for priority applications in heterogeneous sensing environment. The topology management interface aides in achieving the self organization by a novel MCOP-based cluster formation technique. With this technique it is possible to consider multiple metrics for cluster formation which is critical for well balanced energy dissipation of the system. Although in the current paper we have only used three metrics, additional input metrics can be used without any significant cost of complexity. The technique incurs low control over heads because each node makes its decision to join the cluster head based on local information. Simulations' results show that favourable results are achieved when comparing with other well known protocols. At the MAC level the TDMA based protocol provides an adaptive reservation mechanism for satisfying dynamic application demands. Another benefit of using reservation based TDMA is that nodes are provided with contention free transmission slots; hence considerable amount of energy is saved by eliminating the idle listening. By adapting to a unified design, it is possible to eliminate the overheads and maintain QoS guarantees for priority applications. Simulation results show that by adaptive reservations the QoS demands for high priority application are met in an efficient manner. Therefore we conclude that such a unified approach provides a QoS aware, energy-efficient and scalable solution to variety of sensing application. Future enhancements to the protocol will incorporate accurate radio interference models and means for estimating link reliability. Such modifications will allow modelling a realistic communication environment.

REFERENCES

[1] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, " A Survey on Sensor Networks," *IEEE Communications Magazine*, vol. 40, pp. 102-114, 2002.

[2] N. Bulusu and S. Jha, *Wireless Sensor Networks: A Systems Prespective*: Arctech House Inc. , 2005

[3] C. S. Raghavendra, K. M. Sivalingam, and T. F. Znati, *Wireless Sensor Networks*: Kluwer Academic Publishers, 2004.

[4] I. Demirkol, C. Ersoy, and F. Alagoz, "MAC protocols for wireless sensor networks: a survey," *Communications Magazine, IEEE*, vol. 44, pp. 115-121, 2006.

[5] T. He, J. A. Stankovic, C. Lu, and T. Abdelzaher, "SPEED: a stateless protocol for real-time communication in sensor networks," in *Proc. 23rd International Conference on Distributed Computing Systems*, 2003, pp. 46-55.

[6] C. B. Lu, B. M. Abdelzaher, T. F. Stankovic, J. A. He, T., "RAP: a real-time communication architecture for large-scale wireless sensor networks," in *Proc. Eighth IEEE Real-Time and Embedded Technology and Applications Symposium*, 2002, pp. 55-66.

[7] K. Lorincz, D. J. Malan, T. R. F. Fulford-Jones, A. Nawoj, A. Clavel, V. Shnayder, G. Mainland, M. Welsh, and S. Moulton, "Sensor networks for emergency response: challenges and opportunities," *Pervasive Computing, IEEE*, vol. 3, pp. 16-23, 2004.

[8] C. Intanagonwiwat, R. Govindan, and D. Estrin, "Directed diffusion: A scalable and robust communication paradigm for sensor networks," *Proceedings of the ACM/IEEE International Conference on Mobile Computing and Networking*, pp. 56-67, 2000.

[9] W. Su and T. L. Lim, "Cross-Layer Design and Optimization forWireless Sensor Networks," *Proceedings of the Seventh ACIS International Conference on Software Engineering, Artificial Intelligence, Networking, and Parallel/Distributed Computing (SNPD'06)-Volume 00*, pp. 278-284, 2006.

[10] V. T. Raisinghani and S. Iyer, "Cross-layer design optimizations in wireless protocol stacks," *Computer Communications*, vol. 27, pp. 720-724, 2004.

[11] V. Srivastava and M. Motani, "Cross-layer design: a survey and the road ahead," *Communications Magazine, IEEE*, vol. 43, pp. 112-119, 2005.

[12] W. Heinzelman, A. Chandrakasan, and H. Balakrishnan, "An Application-Specific Protocol Architecture for," *IEEE Transactions on Wireless Communications*, vol. 1, 2002.

[13] W. Heinzelman, A. Chandrakasan, and H. Balakrishnan, " An Application-Specific Protocol Architecture for Wireless Microsensor Networks," *IEEE Transactions on Wireless Communications*, vol. 1, pp. 660-670, 2002.

[14] O. Younis and S. Fahmy, " HEED: A Hybrid, Energy-Efficient, Distributed Clustering Approach for Ad Hoc Sensor Networks," *Transactions on Mobile Computing*, vol. 3, pp. 660-669, 2004.

[15] S. Soro and W. Heinzelman, "Prolonging Life Time of Wireless Sensor Networks via Unequal Clustering," in Proc. *In Proc.* of the 19th IEEE International Parallel and Distributed Processing Symposium (IPDPS'05), 2005.

[16] J. Barzilai, "Measurement foundations for preference function modelling," *Systems, Man, and Cybernetics, 1998. 1998 IEEE International Conference on*, vol. 4, 1998.

[17] C. Buratti, A. Giorgetti, and R. Verdone, "Cross-Layer Design of an Energy-Efficient Cluster Formation Algorithm with Carrier-Sensing Multiple Access for Wireless Sensor Networks," *EURASIP Journal on Wireless Communications and Networking*, vol. 5, pp. 672-685, 2005.

[18] J. Ding, K. Sivalingam, R. Kashyapa, and L. J. Chuan, "A multi-layered architecture and protocols for large-scale wireless sensor networks," *Vehicular Technology Conference, 2003. VTC 2003-Fall. 2003 IEEE 58th*, vol. 3, 2003.

[19] S. C. Ergen, "PEDAMACS: Power efficient and delay aware medium access protocol for sensor networks," *IEEE Transactions on Mobile Computing*, 2005.

[20] Z. Chen and A. Khokhar, "Self organization and energy efficient TDMA MAC protocol by wake up for wireless sensor networks," *Sensor and Ad Hoc Communications and Networks, 2004. IEEE SECON 2004. 2004 First Annual IEEE Communications Society Conference on*, pp. 335-341, 2004.

[21] N. Aslam, W. Robertson, S. C. Sivakumar, and W. Phillips, "Modeling Reservation based Medium Access Control Protocol in Clustered TDMA Sensor Networks using Network Calculus," in Proc. International Conference on Advances in the Internet, Processing Systems, and Interdisciplinary Research - VIPSI, Itlay, 2006.

[22] L. F. W. van Hoesel, T. Nieberg, H. J. Kip, and P. J. M. Havinga, "Advantages of a TDMA based, energy-efficient, self-organizing MAC protocol for WSNs," *Vehicular Technology Conference, 2004. VTC 2004-Spring. 2004 IEEE 59th*, vol. 3, 2004.

[23] S. S. Kulkarni, "TDMA service for sensor networks," *Distributed Computing Systems Workshops, 2004. Proceedings. 24th International Conference on*, pp. 604-609, 2004.

[24] P. Havinga and G. Smit, "Energy-efficient TDMA medium access control protocol scheduling," *Asian International Mobile Computing Conference (AMOC 2000)*, pp. 1–9, 2000.

[25] K. Jamieson, H. Balakrishnan, and Y. C. Tay, "Sift: A MAC Protocol for Event-Driven Wireless Sensor Networks," *Proceedings of the Third European Workshop on Wireless Sensor Networks, Feb*, 2006.

[26] W. Ye, J. Heidemann, and D. Estrin, "Medium access control with coordinated adaptive sleeping for wireless sensor networks," *IEEE/ACM Transactions on Networking (TON)*, vol. 12, pp. 493-506, 2004.

[27] M. Ye, C. F. Li, G. H. Chen, and J. Wu, "EECS: An Energy Efficient Clustering Scheme in Wireless Sensor Networks," *IEEE Int'l Performance Computing and Communications Conference (IPCCC)*, pp. 535-540, 2005.

[28] M. Demirbas, A. Arora, and V. Mittal, "FLOC: A fast local clustering service for wireless sensor networks," *Workshop on Dependability Issues in Wireless Ad Hoc Networks and Sensor Networks (DIWANS/DSN 2004)*, 2004.

[29] P. Ding, J. Holliday, and A. Celik, "Distributed energy-efficient hierarchical clustering for wireless sensor networks," *Lecture notes in computer science*, pp. 322-339, 2005.

[30] S. Banerjee and S. Khuller, "A clustering scheme for hierarchical control in multi-hop wirelessnetworks," *INFOCOM 2001. Twentieth Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings. IEEE*, vol. 2, 2001.

[31] I. Texas Instruments, "MSP430x13x, MSP430x14x Mixed Signal Microcontroller. Datasheet, " 2001.

[32] N. Aslam, W. Robertson, S. C. Sivakumar, and W. Phillips, "Energy Efficient Cluster Formation Using Multi-Criterion Optimization for Wireless Sensor Networks," in Proc. 4th IEEE Consumer Communications and Networking Conference (CCNC), 2007.

[33] W. Goodridge, W. Robertson, W. J. Phillips, and S. Sivakumar, "Heuristic Constraint-Path Routing Decision System," *Proceedings of the 3rd Annual Communication Networks and Services Research Conference (CNSR'05)-Volume 00*, pp. 3-8, 2005.

Nauman Aslam received the B.Sc. (Eng.) degree from the University of Engineering and Technology, Lahore, Pakistan, in 1994 and the Master's of Engineering degree in Internetworking (2003) and Ph.D. degree from the Dalhousie University, Halifax, Nova Scotia, Canada, in 2008. He is currently an Assistant Professor at the Engineering Mathematics and Internetworking Department at Dalhousie University. His research interests include cluster-based wireless sensor networks, wireless ad hoc networks, IP communications, and Quality of Service.

William J. Phillips received the B.Sc. degree in Engineering Mathematics and the M.Sc. degree in Mathematics from Queen's University at Kingston and the Ph.D in Mathematics from the University of British Columbia. Dr. Phillips held visiting positions at the University of Guelph, Queen's University, Dalhousie University, and Saint Mary's University before joing the Department of Applied Mathematics at Technical University of Nova Scotia. He is currently Professor and Head of the Department of Engineering Mathematics at Dalhousie University (merged with the Technical University of Nova Scotia in 1997).

William Robertson received the B.Sc. (Eng. Hons.) degree and the M.Sc. (Eng.) degree from Aberdeen University, Scotland, U.K., in 1967, and 1969 respectively, and the Ph.D. degree from the Technical University of Nova Scotia [(TUNS), now Dalhousie University], Halifax, NS, Canada, in 1986. Since 1983, he has held various positions at TUNS and Dalhousie University and is currently the Director of the Internetworking Program—a program leading to the Master's of Engineering in Internetworking. His research interests include signal processing and networking—QoS, routing, and wireless applications. Dr. Robertson is a member of the Association of Professional Engineers of Nova Scotia.