ELSEVIER

Available at
www.ComputerScienceWeb.com
POWERED BY SCIENCE @ DIRECT®

Computer Networks 41 (2003) 331–346

COMPUTER
NETWORKS

www.elsevier.com/locate/comnet

Power-aware virtual base stations for wireless mobile ad hoc communications

Ahmed Safwat [a,*], Hossam Hassanein [a], Hussein Mouftah [b]

[a] *Telecommunications Research Laboratory, School of Computing, Queen's University, Kingston, ON, Canada K7L 3N6*
[b] *School of Information Technology and Engineering, University of Ottawa, Ottawa, ON, Canada K1N 6N5*

Abstract

In this paper, we propose a novel infrastructure formation scheme for wireless mobile ad hoc networks. The proposed architecture, namely, power-aware virtual base stations (PA-VBS), mimics and maintains the operation of the conventional fixed infrastructure in cellular networks. In the PA-VBS protocol, a mobile node is elected from a set of nominees to act as a temporary base station within its zone based on its residual battery capacity. We study the characteristics and performance of PA-VBS by means of simulation. It is shown that PA-VBS scales well to large networks of mobile stations, and that it outperforms other infrastructure-formation protocols in terms of load balancing. The PA-VBS architecture facilitates the development of a comprehensive and promising framework for quality of service (QoS) management in wireless mobile ad hoc networks once the proper integration of the MAC protocol with the routing and call admission control mechanisms is established. Moreover, it lays the groundwork for assigning bandwidth, and/or implementing priorities, and hence for QoS-based routing by conveying the quality of a path prior to call setup. To the authors' best knowledge, this is the first time that energy is used as a basis for developing a wireless mobile infrastructure, and achieving load balancing.

Keywords: Wireless mobile ad hoc communications; Wireless mobile infrastructure; Energy conservation; Routing; Medium access control; Quality of service

1. Introduction

Ad hoc wireless networks eradicate the costs of infrastructure deployment, setup, and administration. Ad hoc wireless networks allow anywhere, anytime network connectivity with complete lack of control, ownership, and regulatory influence. The interest in wireless ad hoc networks stems from their suitability for different types of application scenarios ranging from home and road to office and school. Since there is no fixed infrastructure, a wireless mobile ad hoc network can be deployed quickly. Thus, such networks can be used in situations where either there is no other wireless communication infrastructure present or where such an infrastructure cannot be used because of military tactics, an emergency (as a result of a natural disaster or an enemy attack), cost reasons, etc. The limited energy capacity of the mobile devices making up the network draws our attention to the importance of power awareness in

---

[*] Corresponding author.

E-mail addresses: safwat@cs.queensu.ca (A. Safwat), hossam@cs.queensu.ca (H. Hassanein), mouftah@site.uottawa.ca (H. Mouftah).

1389-1286/03/$ - see front matter © 2002 Published by Elsevier Science B.V.
PII: S1389-1286(02)00419-X

ad hoc network/protocol design. In a multi-hop ad hoc network, or in a wireless LAN operating in independent basic service set (IBSS) mode, wireless stations must always be ready and willing to receive traffic from their neighbors. Due to the non-existence of a fixed infrastructure, the wireless stations must always be awake. On the contrary, in a wide area or local area cellular environment, a wireless node may be scheduled to sleep to conserve energy whenever it is not involved in the transmission or reception of data or voice [1]. Base stations and wireless access points are in charge of buffering all incoming packets to sleeping nodes. Thus, in a wireless ad hoc network, the energy consumption of the network interface card (NIC) may be significant.

Wireless ad hoc networks composed of wireless nodes with an unlimited supply of power were studied in [2]. Refs. [3–7], addressed minimum-energy routing. The approach was to minimize the total energy expenditure to reach the destinations. Consequently, some nodes are overused and their batteries are thus depleted. In [8], bounds on the system lifetime were derived for static sensor networks. Hence, these derivations may not be used for mobile wireless ad hoc networks.

Developing an infrastructure for the infrastructure-less wireless mobile ad hoc networks is of utmost importance. Such an infrastructure reduces the problem of wireless mobile ad hoc communications, from a multi-hop problem, to a single-hop one, as in conventional cellular communications. The previous apprehension originates from the intuitive realization of the problems of medium access and routing in wireless mobile ad hoc networks and their effects on QoS-guaranteed communications. Infrastructure-based communications enable the use of simple variations of the widely used cellular protocols in ad hoc networks. Such a dynamic infrastructure will form the basis for developing MAC protocols, and routing algorithms, which can utilize it to conform to the different QoS requirements. Infrastructure-based wireless mobile ad hoc communications will help circumvent routing and medium access control issues. Therefore, in this paper, an energy-conserving wireless mobile infrastructure is developed for ad hoc networks. We propose a novel infrastructure-creation scheme for wireless mobile ad hoc networks, namely, power-aware virtual base stations (PA-VBS). Nevertheless, the developed infrastructure is, essentially, a mobile one. The wireless mobile infrastructure acts as the executive regulatory authority that carries out mobility tracking, and, hence, routing in wireless mobile ad hoc networks. The proposed infrastructure-formation scheme demonstrates quick response to topological changes in the ad hoc network. Additionally, the protocol is scalable to networks with large populations of mobile stations. It outperforms current infrastructure-creation schemes in stability and load balancing among the mobile stations forming the infrastructure.

This paper is organized as follows. The next section discusses existing infrastructure-creation protocols in wireless mobile ad hoc networks. In Section 3, the PA-VBS protocol is described in detail. This is followed in Section 4 by a thorough performance evaluation study of PA-VBS. Finally, Section 5 presents the conclusions drawn from the paper.

2. Previous work

In [9], the node with the highest connectivity is chosen to be the centre of the cluster. This, in fact, introduces a major drawback to the stability of the various clusters since under high mobility, cluster re-formations frequently take place. According to the scheme proposed in [10], a wireless node may only become a clusterhead if it is not associated with one. In our virtual base stations (VBS) protocol [11–13], MTs are elected as clusterheads based on their ID numbers. However, the VBS protocol puts more emphasis on a node becoming a clusterhead, or a VBS, rather than being supervised by one. Hence, if a node receives a merge request, it responds by sending an accept–merge message, even if it was being supervised by a VBS. Moreover, it is noteworthy that this neither degrades intra-cluster nor inter-cluster communications by any means. If the node that became a VBS was originally acting as a gateway for its previous VBS, it will remain a gateway, besides being a VBS. This becomes of great significance if the criterion upon which VBSs were elected was one that relies on the assets possessed by the MTs of the ad hoc network. Processing speed, main and secondary storage, and MAC contention experienced in the neighborhood of the MT can be among such assets. Consequently, if an MT chooses not to become a clusterhead, only because it is under the supervision of another MT, even though it possesses the required assets to become one, the node requesting to merge might experience degraded communications to other nodes in the ad hoc network because it does not have the proper resources, nor is it able to be associated with one that does.

Fig. 1 shows two illustrations of the VBS scheme. In Fig. 1(A), all the MTs are within radio range of one another, except 1 and 4. Due to the asynchronous transmission of the hello messages, MT 2 may broadcast its hello message before MT 1. Therefore, MTs 3, and 4, receive MT 2's hello message first. They send *merge–request* messages to MT 2 [a] and it sends *accept–merge* messages back to each one of them [b]. The scenario in Fig. 1(B) starts with MT 1 sending its hello message. MT 3, realizing that it heard from an MT whose ID number is smaller than that of their VBS, sends a merge–request message to MT 1 [a]. MT 1 sends back a merge–accept message [b]. After receiving the merge–accept messages, 3 sends a *dis-join* message to 2 [c], which removes them from its list of supervised MTs. 2 is still the VBS of 4, which did not send a dis-join message to MT 2 since it is not in the transmission range of MT 1.

3. The power-aware virtual base stations scheme

We herein adopt a new approach to achieve energy conservation by developing a novel infrastructure formation scheme for wireless mobile ad hoc networks based on the residual battery capacity of the wireless nodes. An overview of the proposed PA-VBS scheme is presented in Section 3.1. Moreover, a detailed description of the protocol, including the pseudocode of the algorithms that are of special importance to the operation of PA-VBS, is provided in Section 3.2. This is also in addition to the finite state machine describing the protocol, and its accompanying state transition table.

3.1. Overview of the scheme

In our scheme, some of the MTs, based on their current residual battery capacity, become in charge of all the MTs in their neighborhood, or a subset of them. This can be achieved by electing one to be a PA-VBS. If a VBS moves or stops acknowledging its presence via its periodic beacons, also called *hello* messages, for a period of time, a new one is elected. Electing a single VBS from a set of nominees is done in an efficient way. Every MT has a *sequence number* that reflects the changes that occur to that MT. Sequence numbers are not only used for the sake of taking proper routing decisions, as in the case of the VBS protocol, but are also used to save battery energy whenever possible. In addition to the sequence number, a myVBS variable is used to store the ID number of the VBS in charge of that MT. If an MT has a VBS, its myVBS variable will be set to the ID number of that VBS, else if the MT is itself a VBS, then the myVBS variable will be set to 0, otherwise it will be set to −1.

MaxPower$_i$ (*MP$_i$*) is defined as the battery capacity whose value is in one-to-one correspondence with the amount of time in seconds that MT$_i$ when used by a class-1 user, would last, starting

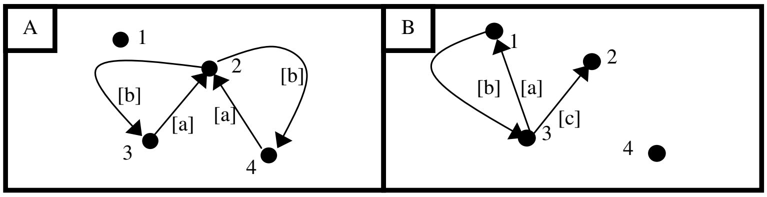


Fig. 1. Finding the VBSs.

from the time it had a fully charged battery, without having to be re-charged, provided that (1)–(3), below are true:

(1) It remains a class-1 user during the whole MP_i period.
(2) It does not become a VBS during the whole MP_i period.
(3) It has inactive neighbors during the whole MP_i period.

Likewise, *MAX_POWER* is a constant defined as the minimum required battery capacity for a class-1 user's MT to last, starting from the time it had a fully charged battery, for exactly one day without having to be re-charged, provided that the following are true:

(1) It remains a class-1 user during the whole one-day period.
(2) It does not become a VBS during the whole one-day period.
(3) It has inactive neighbors during the whole one-day period.

Besides, $\textit{NormalizedMaxPower}_i$ (NMP_i) is equal to $\text{MP}_i/\text{MAX\_POWER}$. Hence, NMP_i can be equal to 1 only when MP_i is equal to MAX_POWER. The current *NormalizedPowerValue* for MT_i, NPV_i, is equal to the instantaneous battery capacity of MT_i, divided by MAX_POWER.

As will be explained in Section 4, PA-VBS facilitates load balancing between the wireless nodes. This is largely due to the fact that PA-VBS takes the nodal activity of the MTs a VBS is in charge of into account when calculating the amount of consumed power.

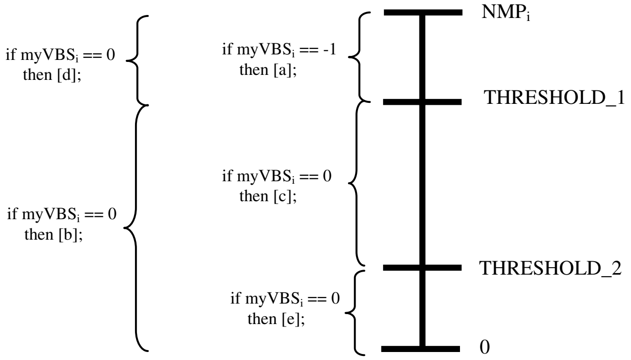
An MT is chosen by one or more MTs, to act as their VBS based on some power thresholds. MTs announce their NPVs in their periodic hello messages. An MT sends a *merge–request* message to another MT if the latter has an NPV greater than or equal to the former's, and a predetermined energy threshold. The receiver of the merge–request responds with an *accept–merge* message only if its NPV is above the first threshold, namely THRESHOLD_1, at the time it receives the merge request message, in which case it increments its sequence number by 1 to reflect the change, and sets its myVBS variable to 0. When the MT receives the accept–merge, it increments its sequence number by 1 and sets its myVBS variable to the ID number of its new VBS. If an MT hears from another MT whose NPV is larger than that of its VBS, it does not send a merge–request message to it as long as its VBS's NPV is above THRESHOLD_1 (also called the *association threshold*). A *dis-join* message is sent by an MT to its VBS only if the transmissions of the VBS have not been heard by the MT for some timeout period. If the VBS receives the dis-join message, it removes the sender from its list of MTs, which it is in charge of, and it increments its sequence number by one. Fig. 2 summarizes PA-VBS decision-making based on the energy thresholds.

3.2. Detailed description of the protocol

This section contains the pseudocode for the algorithms that are of special importance to the operation of PA-VBS. MTs broadcast their current NPVs as part of their hello messages. Hello messages contain other useful pieces of information, such as the sequence number and the *iAmNoLongerYourVBS* flag. The iAmNoLongerYourVBS flag is used by a node acting as a VBS (see Fig. 3) to convey to the MTs it is currently in charge of whether it can support them for another hello period or not. When this flag is set to false, the MTs receiving the hello message know that they will still be served by their VBS for another hello period, and therefore do not need to look for a new one for at least one more hello period. However, if that flag was set by the VBS to true, then the MTs will return to their initial state (see Fig. 4). This actually takes place when the NPV of the VBS drops below the second energy threshold, namely THRESHOLD_2.

Upon receiving a hello message, the MT sends a merge request message to the sender, if and only if one of the following two cases is satisfied:

(1) The MT is neither a VBS nor being supported by one, and the following hold:
    (a) Its NPV is less than the NPV of the sender of the hello message.



[a]: send a merge request message to an MT with NPV greater than mine.
[b]: merge request messages can be sent by the MTs supported by this VBS, provided that the receiver's NPV is greater than THRESHOLD_1.
[c]: discard any merge request.
[d]: no merge request messages will be sent by the MTs supported by this VBS.
[e]: set the iAmNoLongerYourVBS flag to true.

Fig. 2. PA-VBS decision-making based on the energy thresholds.

```
if (myVBS == 0)
    if (iAmBelowThreshold_2())
        N = 0;
        cancelAllMyMTsTimers();
        iAmNoLongerYourVBS = true;
        mySequenceNumber++;
        myVBS = -1;
    else
        iAmNoLongerYourVBSFlag = false;
```

Fig. 3. Using the iAmNoLongerYourVBS flag by a VBS for service denial.

```
if ( (myVBS > 0 ) && (theSenderOfTheHelloIsMyVBS()) )
    if (iAmNoLongerYourVBS == true)
        cancelMyVBSTimer();
        mySequenceNumber++;
        myVBS = -1;
    else
        restartMyVBSTimer();
        lastPowerValueReportedByMyVBS =
        myVBS.normalizedPowerValue;
```

Fig. 4. Using the iAmNoLongerYourVBS flag by an MT to detect service denial.

   (b) The NPV of the sender is above THRESHOLD_1.
(2) The MT is currently supported by a VBS, and the following hold:
   (a) The last reported NPV by the current VBS is below THRESHOLD_1.
   (b) The NPV of the MT is less than the NPV of the sender of the hello message.
   (c) The NPV of the sender is above THRESHOLD_1.

The pseudocode of the algorithm executed by the MT to determine whether to send a merge request to its neighbor, upon receiving a hello message from it, is shown in Fig. 5. The pseudocode shows that the MT does not send a dis-join to its current VBS. This can be explained as follows. Even though the MT sent the merge request based on the conditions listed above, this does not necessarily mean that the node receiving the merge request will accept the merge at the time the request is actually received. If the merge request was sent at time t_0 when the VBS was capable of supporting the MT, it might have been received at time t_1 when its NPV was below THRESHOLD_1.

The pseudocode of the routine executed by an MT when it receives a merge request from one of its neighbors is shown in Fig. 6. As stated in line 1, if and only if the receiving MT's NPV is currently above THRESHOLD_1 will it then proceed to accept the merge request. If the condition in line 1 is satisfied, the receiver increments the number of MTs it is in charge of by 1, sets its myVBS variable to 0 to reflect that it is currently a VBS, and increments its own sequence number by 1 (see lines 2–4). In line 5, the VBS starts a timer to trigger the initiation of a timeout period. The timer is reset every time the VBS receives a hello message from the MT. If the timer expires, the VBS will no longer be in charge of the MT. This can happen if the VBS, or, equivalently, the MT, moves out of the wireless transmission range of the MT. If it happens that they come within the wireless transmission range of each other after the expiration of the timer, then the MT must send a new merge request to the VBS. The VBS may then accept or reject the merge request based on its NPV at the time of the reception of the merge request. If the receiver of the merge request was being supported by another node acting as its VBS, then it cancels the timer corresponding to its VBS, and sends a dis-join message to it (lines 7–9). In the case where a node is incapable of serving a neighbor, PA-VBS supports two means of notifying an MT of a rejected merge request. The first is an *implicit merge reject* method where the MT assumes that its merge request was rejected if it does not receive anything back from the VBS. The other method relies on sending a *merge reject* message back to the MT informing it that its request cannot be supported (line 11). The implicit merge reject method can be utilized in highly congested zones, while merge reject messages can be used otherwise.

When an MT receives an accept–merge message it performs the algorithm in Fig. 7. The receiver sends a disjoin message back to the issuer of the accept–merge message, as in line 2, if it is either a VBS or an MT supported by one. Otherwise, the

```
if
    ((received NPV>=THRESHOLD_1) && (received NPV> my NPV))
    &&
    ( (myVBS == -1)
    ||
    ((myVBS > 0) && (lastEnergyValueReportedByMyVBS < THRESHOLD_1)))
        sendMergeRequestMessageTo(senderOfHello);
```

Fig. 5. The merge decision process.

```
1.  if (MTisAboveThreshold_1())
2.      N++;
3.      myVBS = 0;
4.      mySequenceNumber++;
5.      startTimerForTheMT();
6.      sendAcceptMergeMessageTo(senderOfMergeRequest);
7.      if (myVBS > 0)
8.          cancelTimerOfMyOldVBS();
9.          sendDisjoinMessageToMyOldVBS();
10. else
11.     do nothing; or sendMergeRejectMessageTo(senderOfMergeRequest);
```

Fig. 6. The mergeRequestReceipt( ) algorithm.

```
1.  if (myVBS >= 0)
2.      sendDisjoinMessageTo(senderOfAcceptMerge);
3.  else if (myVBS == -1)
4.      myVBS = ID of the sender of the accept-merge;
5.      storeLastEnergyValueReportedByMyVBS();
6.      startTimerForMyVBS();
```

Fig. 7. The acceptMergeReceipt( ) algorithm.

receiver of the accept–merge message executes lines 3–6. It first sets its myVBS variable to the ID number of the node from which it received the accept–merge message (line 4). It also stores the NPV sent by its VBS, for future merge-related decisions, and starts a timer corresponding to its VBS. If the timer expires, the MT will no longer be associated with its VBS. The MT can then be associated with another VBS, regardless of the last NPV reported by its previous VBS. Hence, even if the last reported power value was above THRESHOLD_1, the MT can still issue new merge request messages.

The pseudocode shown in Fig. 8 is used by an MT whenever a dis-join message is received. If the MT is a VBS, it increments its sequence number by one, decrements the number of nodes it is in charge of by one, and cancels the timer corresponding to the sender of the dis-join message, since it is no longer responsible for it (lines 2–4). Otherwise, the received dis-join message is discarded because the receiver is not a VBS (see lines 7–8).

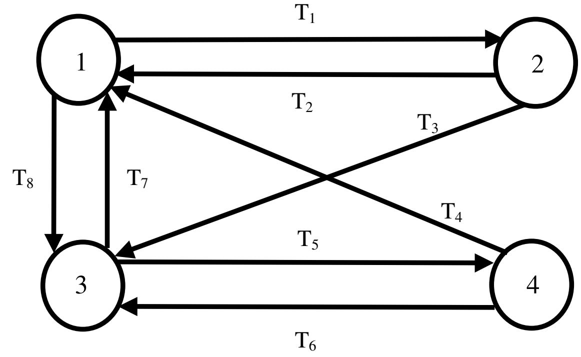


Fig. 9. The finite state machine at node *i*, FSM$_i$, running the PA-VBS architecture.

Fig. 9 shows the finite state machine at node *i*, FSM$_i$, running the PA-VBS scheme. The state transition table is shown in Table 1. FSM$_i$ shows that any node *i* in the wireless ad hoc network, can be in one of four states. A node is in state 1 if and only if it is a VBS, and its NPV is greater than THRESHOLD_1. State 2 is reached when a node is a VBS, but its NPV lies between the two energy thresholds. If a node is neither a VBS, nor being supported by one, then it reaches state 3. Finally, a node in state 4 is one being supported by a VBS. An MT can be in state 1 and reach state 2 in one step if it consumes an amount of normalized energy equal to the difference between its NPV and THRESHOLD_2. Transitions from state 2 to state 1 become feasible as a result of battery recharging. If a VBS in state 1 is supporting a single MT, and receives a disjoin message form it, or, equivalently, if the timer for that MT expires due to its, or the VBS's, motion, then the VBS will no longer be in charge of any other MT, and hence transits to

```
1.  if (myVBS == 0)
2.      mySequenceNumber++;
3.      N--;
4.      cancelMTTimer(senderOFDisjoinMessage);
5.      if (N == 0)
6.          myVBS = -1;
7.  else
8.      discard the received dis-join message;
```

Fig. 8. The disjoinReceipt( ) algorithm.

Table 1
The state transition table for FSM_i (TH1: THRESHOLD_1; TH2: THRESHOLD_2)

Transition	Event	Condition	Action
T_1	Power consumption	$TH2 <= NPV_i <= TH1$	No more accept–merge messages
T_2	Charging	–	Send accept–merge messages to received merge request messages, N++, myVBS = 0, and mySequenceNumber++
T_3	The VBS's timer for its only MT expires, or a dis-join message is sent by the MT	The MT becomes associated with another VBS, or the MT is out of range	myVBS = −1, mySequenceNumber++, and $N = 0$
T_4	Merge request received from a neighbor	$NPV_i >= TH1$	Accept merge sent to neighbor, dis-join sent to my VBS, myVBS = 0, mySequenceNumber++, $N = 1$, and start timer
T_5	Accept merge received from a VBS	$NPV_{VBS} > NPV_i$, and $NPV_{VBS} > TH1$	myVBS = ID_{VBS}, mySequenceNumber++, start timer,and store the reported NPV
T_6	The iAmNoLongerYourVBS flag is set to true, or the MT's timer for its VBS expires	–	myVBS = −1, and mySequenceNumber++
T_7	Merge request received from neighbor	$NPV_i > NPV_{neighbor}$, and $NPV_i > TH1$	Accept merge sent to neighbor, myVBS = 0, mySequenceNumber++, and start timer
T_8	The timer, for the only MT, expires, or a dis-join message is sent by the MT	The MT becomes associated with another VBS, or is out of the wireless range	MyVBS = −1, mySequenceNumber++, and $N = 0$

state 3. Transitions in the opposite direction are also possible since an MT, that is not currently serving any other node, can receive a merge request message and move to state 1 on the condition that its NPV is above THRESHOLD_1. FSM_i clearly shows that transitions are not possible between states 2 and 4. Moreoever, transitions from states 1 to 4, and states 3 to 2, are infeasible. An MT in state 2 must first reach state 3 before reaching state 4. This is because a direct transition from state 2 to state 4 is infeasible. In addition, an MT in state 4 can only reach state 2 via state 1. This is due to the fact that a node that is not acting as a VBS can become one provided that its NPV is above THRESHOLD_1. Once it is a VBS, its normalized battery capacity can drop below THRESHOLD_1, but still remain above THRESHOLD_2. In this case, it remains a VBS (and transits to state 2) provided that its NPV does not drop below THRESHOLD_2. Likewise, an MT in state 1 can only reach state 4 via state 3. In PA-VBS, a node cannot ask for another MT's support if it is acting as a VBS. Therefore, a VBS cannot be supported by another MT in one step. Besides, a node in state 3 ought to first become a VBS with an NPV greater than THRESHOLD_1 (which implies transiting to state 1) before reaching state 2.

4. Power-aware virtual base stations performance evaluation

In this section, the performance of the PA-VBS infrastructure-creation scheme is studied. Section 4.1 describes our power consumption model. This is followed in Section 4.2 by a description of the simulation model. In addition, a description of the performance metrics that were taken into consideration in evaluating the performance of PA-VBS is given in the same section. The results of the conducted simulation experiments are presented in Section 4.3. The simulation results show that PA-VBS surpasses VBS in its overall performance.

4.1. Power consumption model

For the sake of simplifying our analysis, both MP_i, for all i, and MAX_POWER, were assigned the corresponding unique duration in seconds. In addition, NPV_i was made equal to the unique value in seconds, corresponding to the current battery capacity of MT_i, divided by MAX_POWER. Depending on the user's activity, every user can be in 1 of 10 classes at any time. A user who frequently toggles between the ON and OFF modes of operation can be possibly classified as a class-1 user. On the contrary, a user who uses his/her MT for palm-computing, playing games, or listening to music, will be of a class other than 1, depending on the level of processing involved. The larger the number assigned to a user's class, the more processing done to accommodate the needs of the user, and, hence, the more power consumed.

The consumed energy during a period of time Δt is directly proportional to Δt. Therefore, and for the sake of finding out the amount of consumed energy, the operation period, called UpPeriod_i (UP_i), from the last time the consumed energy by MT_i was calculated until the present, is considered in the energy consumption calculations. The average nodal activity, α, is a measure that reflects the percentage of time a cluster's medium is used to carry packets originating from the node, or packets delivered to the node by its VBS. $\alpha_1/\text{CONSTANT}_1$ is defined as the amount of normalized energy drained from the battery of any MT in one day as a result of being a neighbor to exactly one node whose average nodal activity during the one-day period is α_1. In addition, $\alpha_2/\text{CONSTANT}_2$ is, by definition, the amount of normalized energy drained from the battery of any VBS in one day due to serving only one MT, provided an *average nodal activity* or, equivalently, *carried routing load factor* equal to α_2. This is regardless of the user class of the VBS and its MP. α_2 can be any value between 1 and 10 depending on how active the mobile node is. An α_2 value of 1 means that the MT does not lie on any routing path, and that it only broadcasts its periodic hello messages to its neighbors. In other words, a value of 1 will account for the minimum possible consumed/dissipated energy by a VBS; the consumed energy due to supporting a single mobile unit. Even though an MT can be inactive in terms of routing, there is still some minimum processing required by the VBS to support the wireless node. The clusterhead not only processes the periodic hellos of its nodes to be able to provide routing support for them, but also regulates medium access in its cluster, and carries out packet scheduling.

The energy of an MT is drained due to two factors. The first factor is user-driven. On the contrary, the other factor is neighbor-driven. User-driven power consumption was explained earlier. However, neighbor-driven power consumption exists if and only if the MT has one or more neighbors. If not, then the contribution of the neighbor-driven power consumption function to the total consumed power by the MT is 0. The user-driven consumed energy for MT_i is equal to: $\text{UserClass}_i * (\text{UP}_i/\text{MAX\_POWER})$. Further, the neighbor-driven share of the consumed energy is equal to: $[\alpha_1 * (n_i/\text{CONSTANT}_1) + \alpha_2 * (N_i/\text{CONSTANT}_2)] * (\text{UP}_i/\text{MAX\_POWER})$, where N_i is the number of MTs the VBS is currently supporting. In the case of a non-VBS node, MT_i, n_i translates to the number of wireless units which are neighbors to MT_i, whereas it is interpreted as the number of neighboring wireless nodes of MT_i which are not being supported by MT_i, otherwise. In addition, an MT can limit the number of mobile units it can support by setting its N_MAX_i variable to a value greater than or equal to N_MAX. Consequently, and to guarantee fair clustering, and achieve load balancing, an MT must be willing to support at least N_MAX mobile units. However, in our simulations, all the MTs had an N_MAX_i equal to N_MAX, and N_MAX was set to ∞. N_MAX_i can be used whenever the user experiences some unacceptable performance, in relation to the stand-alone applications running on the wireless unit, while it is a VBS.

It is noteworthy that the exact value of MAX_POWER for class-1 applications can be found using field-testing. Whenever a value is obtained, it can be substituted for the value in the formulas above. However, this should not affect the performance of PA-VBS. In addition, different MT units can have different MAX_POWER values. This also does not affect the correctness of our formulas. The only difference is that MAX_ POWER_i will now be used instead of MAX_ POWER. The same can be also done for CONSTANT_1 and CONSTANT_2. Experimental values can be obtained and substituted for CONSTANT_1 and

$CONSTANT_2$ in our power consumption formulas. Again, different MT units can have different values.

4.2. Simulation model and performance metrics

A packet-level discrete-event simulator was developed in order to monitor, observe and measure the performance of the PA-VBS protocol. Initially, each mobile station was assigned a unique node ID, a random position in the *x–y* plane, and a random battery capacity between the nodes' maximum power value and THRESHOLD_2. The conducted simulation experiments were set up for wireless mobile ad hoc networks covering a 200×200 unit grid. The wireless transmission range of the MTs was set to 20 units. Hello messages were broadcast every 1 s. The velocity of the mobile nodes was uniformly distributed between 0 and 10 units/s, and they were allowed to move randomly in any direction. Each simulation was run for 8 simulated hours (except for the simulations performed for the fourth experiment, which were run for 24 simulated hours), and the ad hoc network was sampled every 1 s. α_1 was neglected and set to 0. α_2 was randomly chosen between 1 and 10, and $CONSTANT_2$ was set to 10. The second and sixth experiments were conducted for variable values of THRESHOLD_1. THRESHOLD_1 was otherwise set to 0.75, whereas THRESHOLD_2 was set to 0.25. The first three simulation experiments were conducted for ad hoc networks with 25, 50, 75, and 100 mobile nodes. However, in the rest of the simulation experiments, the wireless ad hoc network consisted of 25 MTs, and the total energy consumed by each and every MT throughout the simulation experiment was obtained.

An explanation of the four noteworthy statistical performance metrics, measured by the simulators, follows:

1. *Average number of VBSs*—The smaller this number, the more the number of mobile nodes that have to be served by each VBS, and vice versa.
2. *Average VBS duration*—The average time duration (in seconds) for which a mobile node remains a VBS. This is a very important performance measure since it is a measure of system stability: the larger the duration, the more stable the scheme. Therefore, the ideal value for this measure is actually infinity, as in conventional cellular networks where a base station serves as a base station during its lifetime, or the whole lifetime of the cellular network.
3. *Total number of mobile nodes elected as VBS*—The total number of mobile nodes elected as VBSs during the whole simulation run-time. A small value of this statistic reflects the system's tendency to elect the same set of VBSs. This implies that a small fraction of the mobile nodes is elected as VBSs in the case of small values.
4. *Total energy consumed by every MT*—The total energy consumed by each and every MT throughout the simulation experiment. The closer these values are to one another, the more evenly distributed the load is amongst the nodes of the wireless mobile ad hoc network.

The results of the corresponding experiments were compared to the VBS infrastructure-formation scheme that was shown in [11–13], to overcome the drawbacks of the previously proposed infrastructure-creation protocols.

4.3. Simulation results

Observing the simulation results of Fig. 10, shows that PA-VBS produces a larger number of clusterheads than VBS. This is because PA-VBS distributes the work load amongst a number of nodes that satisfy the power requirements, unlike VBS which tends to elect the same set of nodes with the smallest IDs again and again. The growth in the number of clusterheads is linear with the number of MTs in the case of PA-VBS. On the other hand, the number of clusterheads in the case of VBS remains almost constant. In networks with much larger populations, especially those that have CBR-traffic sources, this will cause considerable MAC delays due to the large number of MTs that are simultaneously contending for medium access at a constant rate.

The average VBS duration, as explained before, is an important measure of the stability of any

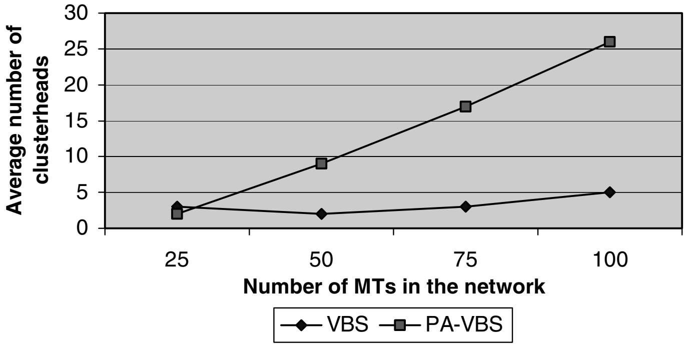


Fig. 10. Impact of network density on number of VBSs.

clusterhead-formation protocol. Fig. 11 clearly shows, regardless of the value of THRESHOLD_1, that since VBS elects nodes based on their ID numbers, they remain as clusterheads for longer periods than in the case of PA-VBS. However, in practice, this cannot be achievable since clusterheads consume more power than other MTs, and their battery power drains quicker. Hence, VBS is more prone to undergo disorder. The results show that the clusterhead duration, on average, is between 2.5 and 4 times more in the case of VBS. This implies that using VBS will drain all the battery power of the clusterheads until they can no longer operate.

Fig. 12 shows that PA-VBS achieves load balancing amongst the nodes in the wireless ad hoc network. Every node is elected as a clusterhead at least once during the simulation run-time, regardless of the wireless transmission range. On the contrary, VBS elects a smaller fraction of the total number of mobile nodes as clusterheads during the entire simulation run-time. In addition, the total number of nodes elected as clusterheads decreases as the wireless range increases. This implies that VBS does not guarantee fairness amongst the wireless nodes in contrast to PA-VBS. As a result of increasing the wireless range, there was a 40% drop in the total number of VBSs in the case of 50 nodes, and around 29% with 75 and 100 MTs. This result proves that PA-VBS attains fair clustering.

In Fig. 13, the energy consumed by the lowest ID nodes running VBS was considerable as opposed to the energy drained by the rest of the nodes. For example, the MT with an ID equal to 1 consumed more than three times its MP when the wireless transmission range was equal to 10 units. However, most of the other MTs consumed less than their MP. The amount of consumed energy in

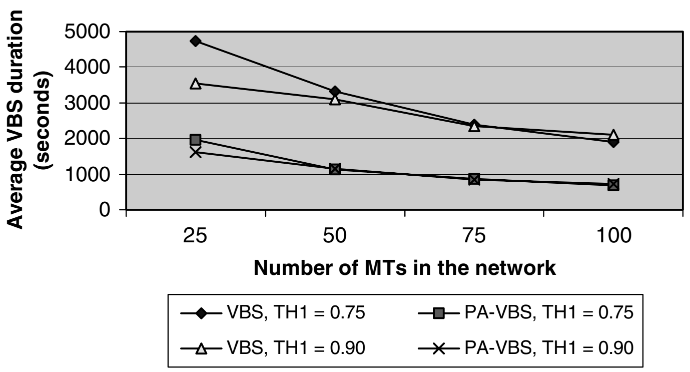


Fig. 11. Impact of network density on clusterhead duration.

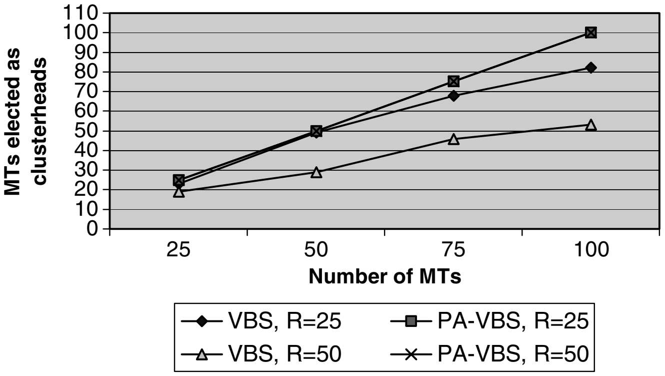


Fig. 12. Impact of network density on total number of elected clusterheads.

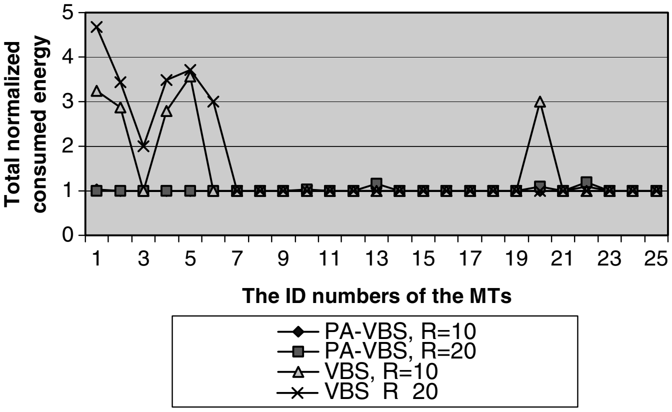


Fig. 13. Total consumed energy throughout the simulation by each MT.

the case of VBS increases when the wireless range is increased. On the other hand, the MTs running PA-VBS consume almost the same amount of energy throughout the simulation regardless of the wireless transmission range. This simulation experiment further proves that PA-VBS achieves load balancing. PA-VBS guarantees that a node will have a fair share of becoming a clusterhead, and that its power will be used gracefully, as compared to all the other MTs.

Observing the simulation results of Fig. 14 shows that PA-VBS achieves load balancing between the wireless nodes, regardless of the routing load carried by the clusterheads. However, the total energy drained from the batteries of the MTs does increase with the increment of the routing load. For example, a 67% increase in the carried routing load results in more than double the amount of consumed battery capacity. The difference between the total energy consumed by any two MTs was never more than 14%. Further, in most cases, the wireless nodes consumed an equal amount of battery capacity.

As shown in Fig. 15, the amount of consumed energy by the wireless nodes is affected by the value assigned to the association threshold. This is attributed to the fact that the nodes initially elected as clusterheads, and whose instantaneous energy values were well over the association threshold, will remain as clusterheads for very long periods of time. Consider, for example, a node whose initial normalized energy was equal to 90%. This node may, in the worst case, operate as a clusterhead until it consumes 65% of its battery

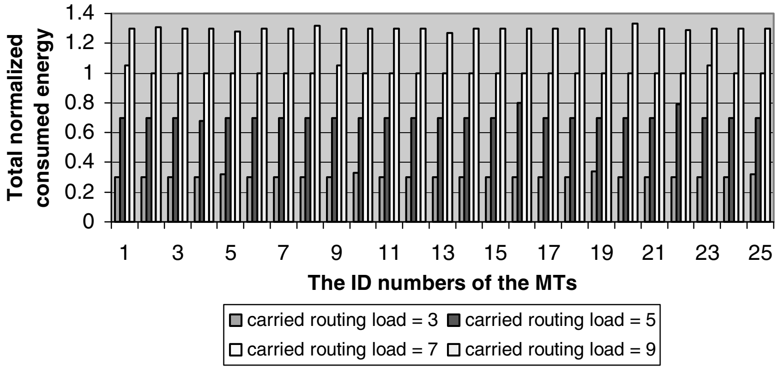


Fig. 14. The impact of the carried routing load on the total consumed energy.

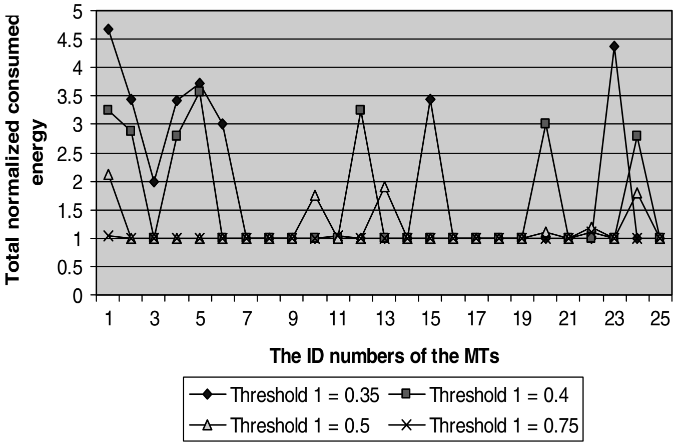


Fig. 15. The impact of the association threshold on the total consumed energy.

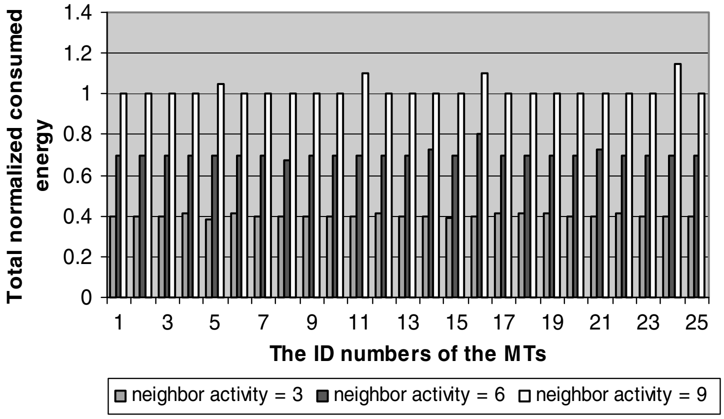


Fig. 16. The impact of the neighbor activity factor on the consumed energy.

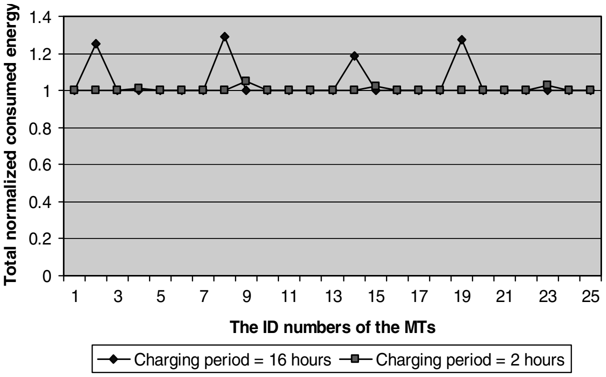


Fig. 17. The impact of the charging period on the consumed energy.

capacity. When the association threshold was raised to 0.5, a considerable decrease in the consumed energy was noted. Fewer discrepancies in the values of the consumed energy can be seen.

The simulation results of Fig. 16 show that PA-VBS achieves load balancing between the wireless nodes, regardless of the neighbor activity experienced by the wireless nodes. However, the total energy drained from the batteries of the MTs does increase with the increment of the neighbor activity factor. For example, a 100% increase in the neighbor activity results in a 75% increase in the amount of consumed battery capacity. The total energy consumed by any two MTs was never remarkably different. In most cases, the wireless nodes consumed an equal amount of battery capacity.

In Fig. 17, the energy consumed by the wireless nodes running PA-VBS with varying charging periods was examined. The amount of drained energy was found to be sometimes considerably different under a long charging period (16 h). Once nodes were elected as PA-VBSs, some were forced to remain PA-VBSs for longer periods in case their neighbors were being charged.

5. Conclusions

In this paper, we introduced a novel infrastructure-creation scheme for wireless mobile ad hoc networks, namely PA-VBS. The paper also provides an in-depth explanation of the operation of our proposed PA-VBS infrastructure-creation protocol. Moreover, packet-level simulation experiments of wireless mobile ad hoc networks, with variable node densities, were conducted, and the results were examined. PA-VBS surpasses VBS in balancing the load amongst the nodes of the wireless mobile ad hoc network. Unlike other clustering protocols, PA-VBS allows the mobile nodes to use their valuable battery power fairly. Contrary to VBS, PA-VBS does not drain all the battery capacity of the clusterheads since clusterheads do not accept any more merge requests when below THRESHOLD_1. Plus, PA-VBS introduces the concept of service denial. Our experiments showed that PA-VBS always elects 100% of the wireless nodes as clusterheads; hence, it attains fair clustering. All the nodes will serve as a clusterhead, at least once, during their lifetime. Most importantly, PA-VBS keeps the total consumed energy by the MTs almost constant. This guarantees fair energy consumption amongst the wireless mobile nodes.

PA-VBS balances the load amongst the wireless nodes regardless of the carried routing load. Consequently, PA-VBS can be utilized as a basis for routing in ad hoc networks. Moreover, PA-VBS can form the cornerstone for the wise distribution of the network load amongst all the viable paths between a source and destination pair.

References

[1] A. Safwat, H. Hassanein, H. Mouftah, Power-aware wireless mobile ad hoc networks, in: Handbook of Ad hoc Wireles, CRC Press, Boca Raton, FL, 2002.

[2] V. Rodoplu, T. Meng, Minimum energy mobile wireless networks, IEEE Journal on Selected Areas in Communications 1 (2000) 22–31.

[3] D. Baker, A. Ephremides, The architectural organization of a mobile radio network via a distributed algorithm, IEEE Transactions on Communications COM-29 (1) (1981) 56–73.

[4] A. Ephremides, J. Wiselthier, D. Baker, A design concept for reliable mobile radio networks with frequency hopping signaling, Proceedings of the IEEE 75 (1) (1987) 56–73.

[5] M. Ettus, System capacity, latency, and power consumption in multihop-routed SS-CDMA wireless networks, Proceedings of 1998 IEEE Radio and Wireless Conference (RAWCON '98), pp. 55–58.

[6] T. Meng, V. Rodoplu, Distributed network protocols for wireless communication, Proceedings of the 1998 IEEE International Symposium on Circuits and Systems (ISCAS'98), vol. 4, pp. 600–603.

[7] T. Shepard, Decentralized channel management in scalable multihop spread spectrum packet radio networks, Tech. Rep. MIT/LCS/TR-670, July 1995.

[8] M. Bhardwaj, A. Chandrakasan, Bounding the lifetime of sensor networks via optimal role assignments, Proceedings of IEEE Infocom, 2002.

[9] C.R. Lin, M. Gerla, A distributed architecture for multimedia in dynamic wireless networks, Proceedings of IEEE GLOBECOM, New York, 1995, pp. 1468–1472.

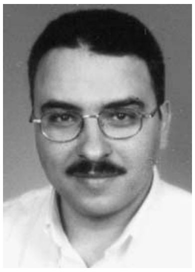
[10] C.-C. Chiang, H.-K. Wu, W. Liu, M. Gerla, Routing in clustered multihop, mobile wireless networks with fading channel, Proceedings of the IEEE Singapore International Conference on Networks, 1997, pp. 197–211.

[11] A. Safwat, H. Hassanein, Infrastructure-based routing in wireless mobile ad hoc networks, The Journal of Computer Communications 25 (3) (2002) 210–224.

[12] H. Hassanein, A. Safwat, Virtual base stations for wireless mobile ad hoc communications: an infrastructure for the infractructure-less, The International Journal of Communication Systems 14 (2002) 763–782.

[13] A. Safwat, H. Hassanein, Structured routing in wireless mobile ad hoc networks, Proceedings of the 6th IEEE Symposium on Computers and Communications (ISCC), 2001, pp. 332–337.

Ahmed M. Safwat was born in Egypt. He received his B.Sc. with Honours in computer science and digital electronics from Kuwait University. In May 2000, he received his M.Sc. degree in computer science from Queen's University, Canada, and he is presently very close to acquiring his Ph.D. degree in computer science from the School of Computing at Queen's University, Canada. His master's research was in the area of wireless mobile ad hoc networks. In his doctoral research he pioneered energy-efficient technologies for multi-hop and 4G wireless systems. He is the first author of a number of book chapters, journal publications, and refereed conference publications. He plans to file a number of patents for his novel work on power-aware wireless infrastructures, energy-constrained wireless systems, and wireless multi-hop ad hoc networks. His research interests are in the areas of wireless communications, wireless ad hoc and sensor networks, 4G wireless mobile systems, energy-conserving wireless systems, RF and microwave IC design, ubiquitous and pervasive computing, optical networks, performance evaluation of communication networks, and communication protocols and algorithms. He is the Co-Chair of the technical program committee for the workshop on Energy-Efficient Wireless Communications and Networks (EWCN) 2003. He is the finalist and runner-up in Canada's prestigious Student Technology Venture Challenge for 2002. He is also the recipient of the Distinguished Master's Thesis Award for the year 2000 from the Department of Computing Science at Queen's University. Moreover, he is a recipient of Kuwait University and the Ministry of Higher Education Scholarship.



H. Hassanein is a leading researcher in the School of Computing at Queen's University in the areas of broadband, wireless and optical networks architecture, protocols, control, and performance evaluation. He is the founder and director of the Telecommunication Research (TR) Lab in the School of Computing at Queen's. Dr. Hassanein has more than 100 publications in reputable journals, conferences and workshops in the areas of computer networks and performance evaluation. He has served on the program committee of a number international conferences and workshops. Dr. Hassanein is the editor of the IEEE 802.6e standard for Slot Reuse in Distributed Queue Dual Bus networks in 1992. He is the recipient of the 1993 IEE "Hartee Premium" best paper award, for the IEE proceedings on Computers. Dr. Hassanein was born in Cairo, Egypt and obtained his Ph.D. in Computer Science from the University of Alberta, Canada in 1990.

Hussein Mouftah joined the School of Information Technology and Engineering (SITE) of the University of Ottawa in September 2002 as a Full Professor and a Canada Research Chair (CRC) Tier 1 in Optical Networks. He has been with the Department of Electrical and Computer Engineering at Queen's University since 1979, where he was prior to his departure in August 2002, a Full Professor and the Department Associate Head, after three years of industrial experience mainly at Bell Northern Research of Ottawa (now Nortel Networks). He has spent three sabbatical years also at Nortel Networks (1986–1987, 1993–1994, and 2000–2001), always conducting research in the area of broadband packet switching networks, mobile wireless networks and quality of service over the optical Internet. He served as Editor-in-Chief of the IEEE Communications Magazine (1995–1997) and IEEE Communications Society Director of Magazines (1998–1999). Dr. Mouftah is the author or coauthor of three books and more than 650 technical papers and 8 patents in this area. He is the recipient of the 1989 Engineering Medal for Research and Development of the Association of Professional Engineers of Ontario (PEO). He is the joint holder of the Best Paper Award for a paper presented at SPECTS'2002, and the Outstanding Paper Award for papers presented at the IEEE HPSR'2002 and the IEEE ISMVL'1985. Also he is the joint holder of a Honorable Mention for the Frederick W. Ellersick Price Paper Award for Best Paper in the IEEE Communications Magazine in 1993. He is the recipient of the IEEE Canada (Region 7) Outstanding Service Award (1995). Dr. Mouftah is a Fellow of the IEEE (1990).