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A Random Access Protocol with Multi-Packet Reception for Infrastructure-Less Wireless Autonomic Networks

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Abstract A random access protocol with multi-packet reception (MPR) capability for infrastructure-less wireless autonomic networks is introduced and analyzed. In these networks mobile nodes may communicate with each other directly without a central entity (base station), where each mobile node either will be in a transmitting mode or in a receiving mode or in an idle mode. The throughput per node and the packet retransmission probability depend exclusively on the MPR capability and the ratio of the transmission probability and the receiving probability of each mobile node. For a given ratio of the transmission probability and the receiving probability of each mobile node, throughput-delay performance increases with the increase of MPR capability. In the proposed infrastructure-less networks, mobile nodes can control the network traffic very precisely by controlling the three parameters. These three parameters are transmission probability, receiving probability and idle mode probability of each mobile node. Since each mobile node can control the network traffic very precisely to obtain the maximum throughput, the network is autonomic, i.e., self-optimizing. The optimum transmission probability of each mobile node to obtain the maximum throughput is evaluated. The throughput utility increases with the increase of MPR capability. On the other hand, the cost per mobile node also increases with the increase of MPR capability. Therefore the MPR capability should be optimized to provide reasonable trade-off between the throughput per node and the cost per mobile node. The results of this study may be used for a system design of an infrastructure-less contention-based multiple access schemes with MPR capability.

Keywords Ad hoc networks · Autonomic · Cost · Multi-packet reception · Node transmitting probability · Sensor networks · Slotted ALOHA

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1 Introduction

Selecting an efficient protocol for sharing a common broadcast wireless channel among a set of mobile nodes is a challenging task. The conventional and emerging wireless networks, such as satellite, cellular, wireless local area, ad hoc, sensor and wireless mesh networks, all face the same challenge. Among the protocols for random access through a common wireless channel, Slotted ALOHA is one of the most attractive medium access control (MAC) protocol due to its simplicity and low delay (under light load) for bursty traffic. The capacity of Slotted ALOHA system can be improved significantly by receiving multiple packets in a time slot [1]. Multiple packets can be received in a time slot using directional antennas and multiple receivers, with and without capture effect [2–4]. Direct sequence code division multiple access (DS-CDMA) is another random multiple access, where mobile nodes transmit packets in the same channels using different orthogonal (or quasi-orthogonal) spreading codes [5]. The multi-packet reception (MPR) capability can be achieved using direct sequence spread spectrum (DS-SS) Slotted ALOHA [6].

The channel state information (CSI) directly influences the quality of the physical (PHY) layer. The MPR capability can be enhanced in the PHY layer by the proper estimation of CSI. The performance of MAC layer can be improved by mutual interactive of MAC-PHY perspective [7,8]. The MPR capability in wireless network can be enhanced by collision resolution [9]. An infinite user population model for the analysis of random access protocols jointly assigned by MPR and retransmission diversity is proposed and analyzed in [10]. A centralized multi-queue service room MAC protocol (MQSR) can optimize the same protocol by avoiding unnecessary empty slots for light traffic and excessive collision for heavy traffic [11]. The optimized MQSR has superior throughput and delay performance as compared to, for example, the Slotted ALOHA with the optimal retransmission probability [11]. Another MPR, called the dynamic queue protocol, which offers a much simpler implementation and only marginal performance degradation [12]. Recently, optimum transmission policy using perfect decentralized CSI is introduced and analyzed [13]. Unfortunately, these MAC schemes [11–13] require a central controller to coordinate the transmissions of the client mobile nodes.

In all the above mentioned MPR protocols [1–13], mobile users transmit their packets to a central entity (base station). Recently, there has been an increasing interest in data transmissions over infrastructure-less wireless networks. In those networks, the communications between two nodes may be direct or via one or more other mobile nodes without the aid of a fixed infrastructure or centralized management. The nodes in those networks should form the network autonomic, i.e., self-optimized [14–17]. Ad hoc, sensor and mesh networks belong to those networks.

A random access protocol for infrastructure-less wireless autonomic networks is introduced and analyzed in this paper. In those networks each mobile node either will be in a transmitting mode or in a receiving mode or in an idle mode. If the mobile nodes can control the network traffic to obtain the maximum throughput, without requiring a central controller to coordinate the transmissions of the client mobile nodes, a network is autonomic, i.e., self-optimized.

The paper is organized as follows. Section 2 describes the system model and assumptions. The capacity of a mobile node with MPR capacity is described in Sect. 3. Section 4 provides optimum throughput for autonomic networks. The optimum number of MPR capability by considering the maximum gain is estimated in Sect. 5. Conclusions are provided in Sect. 6.

2 System Model and Assumptions

Let us consider an area, where mobile nodes are uniformly distributed. Assuming that each node can cover an area of a. If γ is the average number of nodes in the area a, then the distribution of nodes is Poisson Point Process. In infrastructure-less wireless networks, the distribution of mobile nodes as a Poisson Point Process is a widely accepted phenomena and used in many research papers [18,19,25].

The mobile nodes can be divided into three parts: transmitting nodes, receiving nodes, and idle nodes (neither transmitting nor receiving). The whole radio frequency is divided into equal parts. The number of radio frequencies (channels) is the same as the number of receiving mode nodes. All transmitting mode nodes know their receiving nodes and their corresponding channel.

Let us assume that the radio channels in a multi-hop infrastructure-less network is divided into time frames with equal duration called time slot. Each mobile node transmits its data packets by fitting those time slots. These data slots are used when few nodes are transmitting packets and few other nodes receive packets. Because of that, in infrastructure-less networks, mobile nodes cannot be in a transmission mode and in a receiving mode at the same time. Assume that each node is in the transmitting mode, receiving mode and idle mode with probability, *b, c* and *d*, respectively. The probability that *n* packets are ready to transmit to the direction of a given receiving node in a random access system without any central entity is [19]

$$Tr = \frac{(b/c)^n}{n!} e^{-(b/c)} \tag{1}$$

Equation (1) depends exclusively on the ratio of node transmitting probability *b*, and node receiving probability *c*. It is important to note that the probability equation derived in Eq. (1) is independent of the average number of transmitting nodes or receiving nodes within the range of operation (area *a*). The arrival model of aggregate traffic to the direction of any node or any receiving node for an infrastructure-less wireless network is given by Eq. (1), which is Poisson Point Process.

3 Capacity of a Mobile Node with MPR Capability

The MPR allows receiving multiple packets from several transmitters in a transmission slot. Let us assume that each mobile node has *M* MPR capacity. A mobile node can receive a maximum of *M* packets in each time slots. If more than *M* packets are transmitted to it, then all packets are unsuccessful. Ideally the MPR capacity, *M*, should be the same as the maximum number of packets transmitting to any receiver per time slot. This could require a large MPR capacity that could be too costly. On the other hand, if the MPR capacity is very low, then the packet unsuccessful probability will be high. Therefore, the question arises: what is a reasonable MPR capacity that will provide sufficient performance in an infrastructure-less network?

According to Eq. (1), we can also reduce the packet arrival to any mobile node by reducing the ratio of transmission probability of each mobile node and the receiving probability of each mobile node. The network traffic can be controlled very precisely by each mobile node, without any central information. Let us assume that each node can receive a maximum of *M* packets per time slot. The average number of received packet by each mobile node using MPR capability of *M* is

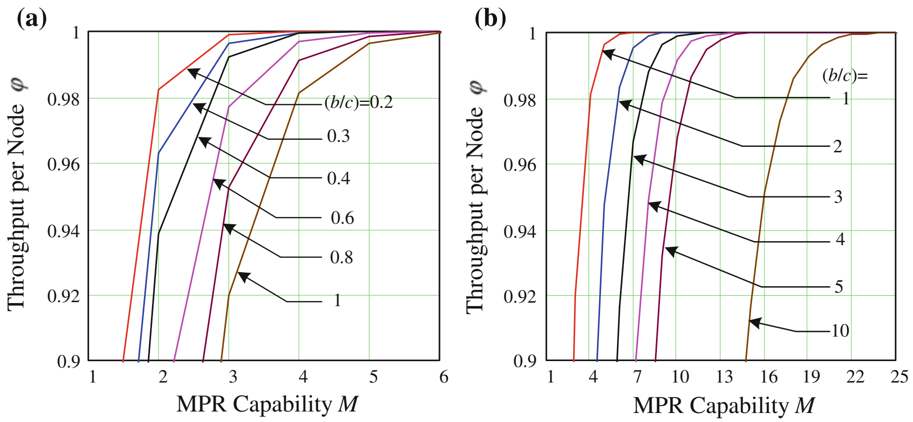

Fig. 1 Normalized throughput per node. **a** $(b/c) \leq 1$; **b** $(b/c) \geq 1$

$$\Gamma = \sum_{l=0}^{M} l \frac{(b/c)^l}{l!} e^{-(b/c)} = e^{-(b/c)} (b/c) \sum_{k=0}^{M-1} \frac{(b/c)^k}{k!} \tag{2}$$

Equation (2) shows the average number of received packets by any mobile node using M MPR capacity. From Eq. (1), it can be shown that the average number of ready to send packets to a given receiving node is (b/c). Let us define the normalized throughput as the ratio of average received packets using MPR to the average number of packets transmitted to the direction of a given mobile node

$$\varphi = \frac{\Gamma}{(b/c)} = e^{-(b/c)} \sum_{k=0}^{M-1} \frac{(b/c)^k}{k!} \tag{3}$$

Figure 1 shows the normalized throughput with the variation of MPR capacity M using Eq. (3). The average number of unsuccessful packets by each mobile node per time slot is

$$\begin{aligned} \Delta &= \sum_{l=M+1}^{\infty} l \frac{(b/c)^l}{l!} e^{-(b/c)} = e^{-(b/c)} (b/c) \left[e^{(b/c)} - \sum_{k=0}^{M-1} \frac{(b/c)^k}{k!} \right] \\ &= (b/c) \left[1 - e^{-(b/c)} \sum_{k=0}^{M-1} \frac{(b/c)^k}{k!} \right] = (b/c)[1 - \varphi] \end{aligned} \tag{4}$$

Equation (4) shows the average number of unsuccessful packets by a given mobile node using M MPR capacity. Let us define the packet retransmission probability as the ratio of average unsuccessful packets using MPR to the average number of transmitted packets per time slot to the direction of a given mobile node

$$\delta = \frac{\Delta}{(b/c)} = 1 - e^{-(b/c)} \sum_{k=0}^{M-1} \frac{(b/c)^k}{k!} = 1 - \varphi \tag{5}$$

Figure 2 shows the packet retransmission probability per time slot per node using Eq. (5). Note that, Figs. 1 and 2 show that the average arrival traffic (b/c) plays a very important role for achieving higher normalized throughput and/or lower packet retransmission probability. In the proposed system model, this parameter $[(b/c)]$ can be controlled very easily. Using the

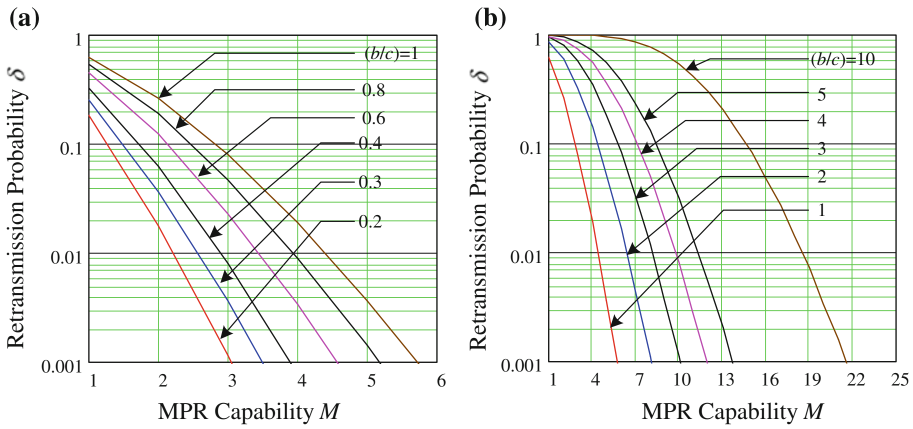

Fig. 2 Retransmission probability. **a** $(b/c) \leq 1$; **b** $(b/c) \geq 1$

technology described in [20], each mobile node can measure the network traffic or the traffic transmitted to it. Each mobile node is also able to transmit less traffic by reducing its ratio of transmission probability and receiving probability (b/c), without any central information.

The direct communications between mobile nodes have also been studied in [21–24]. The optimum transmission probability of each mobile node to obtain the maximum throughput, without using of any central information, has not been studied in [21–24]. The authors believe that the study in this paper is the first attempt to combine the five factors together. These five factors are: autonomic (i.e., self-optimizing), half-duplex, Slotted ALOHA, MPR capability and infrastructure-less network.

4 The Optimum Throughput for Autonomic Networks

In an infrastructure-less wireless network, the mobile nodes in transmitting modes transmit their packets to the direction of mobile nodes in the receiving modes. Each mobile node in receiving mode can receive a maximum of M packets in a time slot [15]. According to Eq. (2), it can be said that for a given value of MPR capability M, the throughput, Γ, increases initially, with the increase of arrival rate, (b/c). It reaches its maximum value in a certain value of arrival rate, (b/c). We will call this value as optimum arrival rate, $(b/c)_{\text{opt}}$. The throughput, Γ, again starts to decrease and goes to finally zero, when the arrival rate, (b/c), increases further.

To obtain the optimum arrival rate, $(b/c)_{\text{opt}}$, differentiate Eq. (2), with respect to (b/c)

$$\frac{d\Gamma}{d(b/c)} = \begin{cases} e^{(b/c)} - (b/c)e^{-(b/c)} & \text{for } \ M = 1 \\ e^{-(b/c)} \left\{ \sum_{k=0}^{M-1} \frac{(b/c)^k}{k!} - \frac{(b/c)^M}{(M-1)!} \right\} & \text{for } \ M > 1 \end{cases} \tag{6}$$

We can evaluate the optimum traffic load, $(b/c)_{\text{opt}}$, by setting $\frac{d\Gamma}{d(b/c)} = 0$, in Eq. (6). The optimum arrival rates, $(b/c)_{\text{opt}}$ and the corresponding maximum throughputs, Γ_{opt}, for different values of MPR capability, M, are evaluated numerically and provided in Table 1.

The optimum packet arrival rate, $(b/c)_{\text{opt}}$ can be considered as the ratio of optimum transmission probability of each mobile node, b_{opt} and the optimum receiving probability of each mobile node, c_{opt}. Therefore, we can write

Table 1 The maximum throughput and other parameters to obtain the maximum throughput

M	$(b/c)_{\text{opt}}$	$b_{\text{opt}}/(1-d)$	S_{opt}
1	1	0.5	0.368
2	1.618	0.618	0.84
3	2.27	0.694	1.371
4	2.945	0.747	1.942
5	3.64	0.784	2.544
6	4.349	0.813	3.168
7	5.071	0.835	3.812
8	5.804	0.853	4.472
9	6.546	0.867	5.145
10	7.297	0.879	5.831
20	15.116	0.938	13.131
30	23.285	0.959	20.907
40	31.661	0.969	28.956
50	40.18	0.976	37.191
60	48.805	0.98	45.561
70	57.515	0.983	54.038
80	66.293	0.985	62.602
90	75.129	0.987	71.237
100	84.014	0.988	79.934

$$\frac{b_{\text{opt}}}{c_{\text{opt}}} = (b/c)_{\text{opt}} \tag{7}$$

Now we will evaluate the optimum transmission probability of each mobile node, b_{opt}. Since $b_{\text{opt}} + c_{\text{opt}} + d = 1$, thus the Eq. (7) can be rewritten as

$$b_{\text{opt}} = (1-d)\frac{(b/c)_{\text{opt}}}{1+(b/c)_{\text{opt}}} \tag{8}$$

Since the maximum throughput can be obtained without any centralized feedback information, Eq. (8) can be considered as a basic equation for infrastructure-less wireless autonomic networks. The ratio of the transmission probability of each mobile node and the inverse of a mobile node is in an idle mode, $b_{\text{opt}}/(1-d)$, for a given MPR capability, M, is fixed and is given in Table 1.

Let us consider an optimum random access protocol for infrastructure-less wireless autonomic network design example. Each mobile node has 3 MPR capabilities. According to Table 1, $(b/c)_{\text{opt}}$ is equals to 2.27. We will consider two separate cases for this design model.

In the first case, each mobile node has sufficient traffic to transmit. Then the probability that a mobile node in an idle mode, d, can be set equals to zero. The optimum transmission probability of each mobile, b_{opt}, will be set as $(2.7)/(1+2.7) = 0.73$. The optimum receiving probability of each mobile node, c_{opt}, will be set as $c_{\text{opt}} = 1 - b_{\text{opt}} - d = 1 - 0.73 - 0 = 0.27$.

In the second case, each mobile node has not sufficient traffic to transmit. The optimum transmission probability of each mobile, b_{opt}, is 0.6. According to the system model, the optimum arrival rate, $(b/c)_{\text{opt}}$ should be 2.7. According to Eq. (7), the optimum receiving probability of each mobile node, $c_{\text{opt}} = \frac{b_{\text{opt}}}{(b/c)_{\text{opt}}} = \frac{0.6}{2.7} = 0.22$. Finally, the probability that a mobile node is in an idle mode, d, will be set as $d = 1 - b_{\text{opt}} - c_{\text{opt}} = 1 - 0.6 - 0.22 = 0.18$.

From the above mentioned two cases, it can be said that although the optimum transmission probability of each mobile, b_{opt}, are different, the throughputs will be same. According to Table 1, the throughputs will be 1.371. The reason is that we are able to optimize the arrival rate, $(b/c)_{\text{opt}}$, is equals to 2.7.

5 Maximizing the Gain Considering Performance and Cost

It is already shown that the network and nodes performance increases with the increase of MPR capability. On the other hand, the cost (including research and manufacturing) of each mobile node increases with the increase of MPR capability. In general the optimal MPR capability of a mobile node is a function of the throughput performance and the network cost.

Let us consider a throughput utility function, $U(M)$, that corresponds to the level of satisfaction from the throughput and the network cost utility function, $C(M)$, that corresponds to the level of dissatisfaction from the network cost. Then the optimal operating point would correspond to the MPR capability that gives maximum positive difference between the level of satisfaction and dissatisfaction. Since each node has MPR capability, it is convenient to consider the throughput utility function, $U(M)$ as the optimum throughput per node. Therefore

$$U(M) = e^{-(b/c)_{\text{opt}}} \sum_{k=0}^{M-1} \frac{(b/c)_{\text{opt}}^k}{k!} \tag{9}$$

Let the node cost has a constant component equal to the cost of a node with a receiver of one MPR capability and a component proportional to the cost of a MPR capability that grows exponentially with receiver capacity due to increased complexity and power consumption. Then, assuming that the dissatisfaction from the cost is proportional to the cost we consider the following cost utility function form

$$C(M) = \lambda + \mu M^{\omega} \tag{10}$$

Figure 3a shows the throughput utility function that is compared with the cost utility function: $C_1(M)$ with $\lambda = 0.36$, $\mu = 0.003$, $\omega = 2$. Obviously the cost utility function parameters λ, μ, and ω depend on many factors and will change in time so the given examples are for illustration purposes only. According to Fig. 3a, the optimum MPR capability is 5, since it provides maximum positive gain over cost.

Figure 3b shows the throughput utility function that is compared with the cost utility function: $C_2(M)$ with $\lambda = 0.5$, $\mu = 0.0025$, $\omega = 2$. In the considered example, the optimal MPR capability, corresponding to the maximum net-satisfaction level is 6. Note that in the second example of the cost utility function, the receiver capacity equal to one is not acceptable since the net-satisfaction level is negative. This example illustrates that mobile node without MPR capability allows applying more expensive nodes due to the negative-gains in the network throughput.

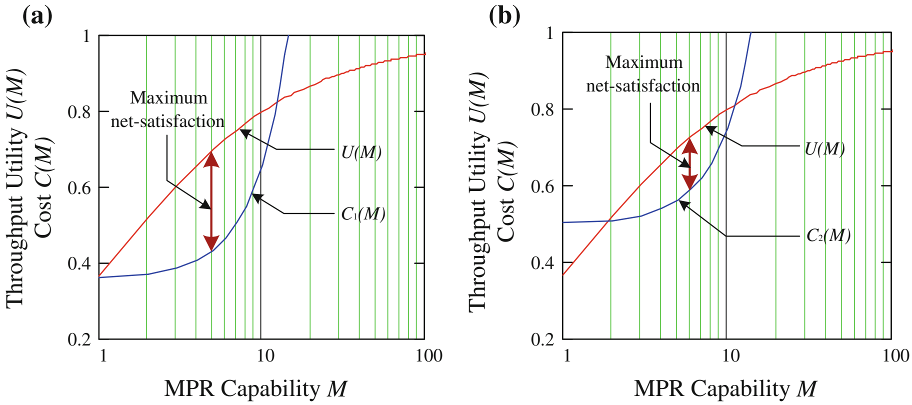

Fig. 3 **a** Max. gain for $M = 5$; **b** Max. gain for $M = 6$

6 Conclusions

A new random access protocol with MPR capability for infrastructure-less wireless autonomic networks is introduced and analyzed. In an infrastructure-less wireless autonomic network, mobile nodes may communicate with each other directly without a central entity (base station), using the proposed random access protocol. The average traffic arrival rate to each mobile node is the ratio of the transmission probability of each mobile node and the receiving probability of each mobile node. For a given average traffic arrival rate, the normalized throughput per mobile node, φ, increases with the increase of the MPR capability, M. The reason is that the probability of success increases with higher number of the MPR capability. Therefore, the packet retransmission probability, δ, also decreases with the increase of the MPR capability.

The average traffic arrival rate to each mobile node plays an important role for the performance of infrastructure-less wireless networks. Each mobile node is able to calibrate its ratio of transmission probability and receiving probability to control the network traffic load very precisely to obtain the maximum throughput. Table 1 shows the parameters for the proposed random access protocol that can be used for infrastructure-less wireless autonomic networks.

The throughput utility, $U(M)$, and thus the satisfaction level increases with the increase of the MPR capability. On the contrary, the cost utility, $C(M)$, increases and thus dissatisfaction level increases with the increase of the MPR capability. The optimum number of MPR capability can be considered by considering the highest satisfaction gain. The difference between the throughput and cost utilities defines the net-satisfaction for given MPR capability and the optimal MPR capability should maximize this metric. It is also shown that for some cases it may be not practical to implement an infrastructure-less network without the MPR capability.

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Hussein T. Mouftah (F'90) received the Doctor of Science degree in electrical engineering from Laval University, Quebec, Canada, in 1975. He has been with the School of Information Technology and Engineering (SITE), University of Ottawa, Canada, since September 2002 as a Tier 1 Canada Research Chair in Optical Networks, where he became a University Distinguished Professor in 2006. He is the author or coauthor of 6 books, 32 book chapters, more than 950 technical papers, and 10 patents. Dr. Mouftah served the IEEE Communications Society as Editor-in-Chief of the IEEE *Communications Magazine* (1995–1997), Director of Magazines (1998–1999), Chair of the Awards Committee (2002–2003), Member of the Board of Governors (1997–2000 and 2006–2007), Director of Education (2006–2007), Distinguished Speaker (2000–2007), and founding Chair of two Technical Committees (TCs): Optical Networking TC (2002–2004) and Ad Hoc and Sensor Networks TC (2005–2007). Dr. Mouftah is the recipient of the 1989 Engineering Medal for Research and Development from the Association of Professional Engineers of Ontario and of the 2002 Ontario Distinguished Researcher Award of the Ontario Innovation Trust. He has also received nine Outstanding/Best Paper Awards (CCECE'2009, 2 at ISCC'2008; ICC'2005; CITO Innovators Showcase'2004; IEEE Communications Magazine in 1993; SPECTS'2002; HPSR'2002; ISMVL'1984), the IEEE Canada Outstanding Service Award (1995), the CSIM Distinguished Service Award (2006) and the AHSN Distinguished Service Award (2009) both of the IEEE Communications Society (2006). In 2004 Dr. Mouftah received the IEEE Communications Society Edwin Howard Armstrong Achievement Award and the George S. Glinski Award for Excellence in Research from the Faculty of Engineering, University of Ottawa. In 2006 he was honored with the IEEE McNaughton Gold Medal and the Engineering Institute of Canada Julian Smith Medal. In 2007 he was the recipient of the Royal Society of Canada (RSC) Thomas W. Eadie Medal. Most recently, Dr. Mouftah received the University of Ottawa 2007–2008 Award for Excellence in Research and the ORION Leadership Award of Merit (2008). Dr. Mouftah is a Fellow of the IEEE (1990), Fellow of the Canadian Academy of Engineering (2003), Fellow of the Engineering Institute of Canada (2005) and Fellow of the Royal Society of Canada RSC: The Academy Science of Canada (2008).