Theme Article

Edge Caching and Computing in 5G for Mobile AR/VR and Tactile Internet

Sukhmani Sukhmani
University of Ottawa

Mohammad Sadeghi
University of Ottawa

Melike Erol-Kantarci
University of Ottawa

Abdulmotaleb El Saddik
University of Ottawa

***Abstract*—As a result of increasing popularity of augmented reality and virtual reality (AR/VR) applications, there are significant efforts to bring AR/VR to mobile users. Parallel to the advances in AR/VR technologies, tactile internet is gaining interest from the research community. Both AR/VR and tactile internet applications require massive computational capability, high communication bandwidth, and ultra-low latency that cannot be provided with the current wireless mobile networks. By 2020, long term evolution (LTE) networks will start to be replaced by fifth generation (5G) networks. Edge caching and mobile edge computing are among the potential 5G technologies that bring content and computing resources close to the users, reducing latency and load on the backhaul. The aim of this survey is to present current state-of-the-art research on edge caching and computing with a focus on AR/VR applications and tactile internet and to discuss applications, opportunities and challenges in this emerging field.**

Augmented reality and virtual reality (AR/VR) technologies have recently gained noticeable attention both from academia and industry. The concept of AR is to present virtual information over the reality such as deformation of real images, whereas in VR, the main idea is to place users in a virtual environment. In some applications, it is possible to observe a mix of AR and VR technologies where virtual and actual environments are smoothly combined.[1] Despite the technology leap in the recent years, current

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state-of-the-art AR and VR technologies suffer from various deficiencies. For instance, the headsets are not able to track eye movements, facial expression and senses cannot be detected in details. More importantly, current AR and VR systems are widely limited to offline streaming where 360° navigable scenes are rendered using a powerful external computer to which the AR/VR device is attached to a cable. In addition, the majority of AR/VR applications do not support real-time interaction of multiple mobile users which is due to technology bottleneck in today's wireless networks. Mobile AR/VR applications require intensive computational capability and massive communication bandwidth with ultra-low latency to transmit high resolution/frame-rate videos that cannot be handled with current wireless infrastructure [i.e., long term evolution (LTE) networks].

Another recently emerging, related technology is the tactile internet that will enable transmitting haptics signals, hence the feeling of touch. The applications of tactile internet can extend to entertainment, healthcare, robotics, autonomous driving, and many more. Similar to AR/VR, the tactile internet demands massive communication bandwidth with ultra-low latency which is not supported by current wireless mobile networks. The tactile internet requires 1 ms of latency due to the nature of haptic signals and human perception. However, today's LTE networks can only support latency of 25 ms approximately. In this context, the fifth generation (5G) wireless mobile networks are expected to outperform LTE and provide a suitable infrastructure for mobile AR/VR and support enhancements that can lead to tactile internet.[2] Standard bodies have set the target date of 2020 for the first rollout of 5G technologies. Among the promising technologies that are considered for 5G are: millimeter wave (mmWave), polar codes, nonorthogonal multiple access and massive MIMO, in addition to architectural evolution over LTE. The new 5G architecture will benefit from edge caching and edge computing. These unique additions within 5G will enable mobile AR/VR and tactile internet applications to benefit from the "anytime-anywhere connectivity" promise of modern wireless mobile networks. In this paper, we particularly focus on edge caching and computing and discuss how they enable mobile AR/VR and tactile internet.

Edge caching aims to bring frequently accessed content, such as videos of major sports events, viral videos over the social networks, etc., closer to the users. Bringing the content each and every time from the Internet servers results in unnecessary traffic over the backbone and it increases the latency. When the users are geographically close, caching the content at the base stations or access points enhances the performance. On the computation side, cloud computing enables access to a shared pool of services and resources. The idea of cloud computing in the wireless mobile networks has led to mobile cloud computing and cloud radio access networks. Edge computing urges the deployment of computing resources closer to the end users, in particular, at the nodes of the mobile network. The edge device can be a base station, an access point, a vehicle or a user device. Heavy applications with intense computing tasks can still be sent to the cloud. However, edge computing allows offloading light tasks to the edge devices. In turn, the latency associated with access is reduced since edge devices are closer than cloud servers.

In AR/VR applications and tactile internet, some scenes might be frequently requested such as backgrounds. In those cases, edge caching has the potential of reducing delay and using network resources more efficiently. Moreover, it is not very feasible to transmit large amounts of data over long distances to the cloud servers for computation purposes, due to the low latency required for these applications. Thus, edge computing could be used again for latency reduction. Figure 1 illustrates the next-generation wireless network along with haptics, AR, VR users, and device-to-device (D2D) communications.

Despite the fact that there are various studies on edge caching and computing, their use for AR/VR applications and tactile internet has been explored less.[3] In this tutorial paper, we first survey the few studies on edge caching and computing that target AR/VR and tactile internet. Then, we focus on general edge caching and computing studies and discuss their suitability to the AR/VR and tactile internet domain. We also present a detailed discussion on the

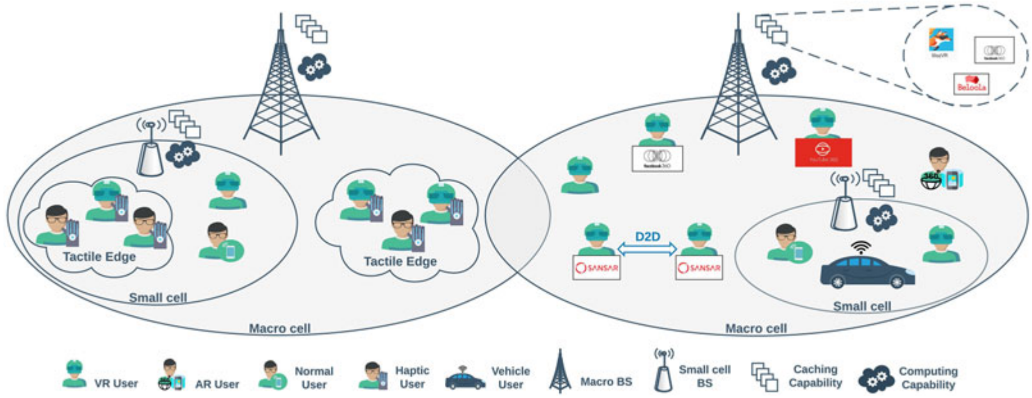

Figure 1. Overall block diagram of the edge computing in AR and VR systems.

opportunities and challenges in this emerging field while drawing future directions. This paper will serve as a roadmap for researchers in this emerging field.

EDGE CACHING FOR AR/VR AND TACTILE INTERNET

Caching at the edge exploits the idea of storing content in a temporary storage closer to the mobile user than the content servers over the Internet. Caches can be placed at macrocell base stations or small cell base stations or user devices. In general, edge refers to the devices within the radio access network. In the literature, edge caching has been implemented at small base stations[4,5] and the user terminals[6] and has been shown to reduce the overall energy consumption and traffic over the backhaul. The advantages of edge caching have led several demanding applications such as AR/VR and haptic communications to explore its potential. The rest of this section provides a detailed survey of these studies.

Edge Caching for AR and VR Applications

In AR/VR applications, selection of what to cache and where to cache are crucial problems. The first problem is related to the popularity of a content. In AR/VR, the content popularity has different patterns than the popularity of streaming video content or other conventional applications used on today's smart devices. For instance, it is effective to cache viral videos but for AR/VR it might be useful to cache background scenes instead of the bulk videos. Furthermore, content caching for AR/VR should also be coupled with encoding techniques. Thus, cache-friendly encoding, as well as chunking techniques, are required.

Since latency is a major concern in mobile AR/VR applications, the selection of where to cache, i.e., whether at the radio access network or the core network, is even more critical than other mobile applications. Furthermore, due to the directivity of communications, it becomes more challenging to address caching in 5G wireless networks that use millimeter wave (mmWave). The directivity can cause retrieval and connection delays when accessing caches.[7] It may become necessary to increase redundancy of the cached content to reduce latency.

Besides challenges, one of the opportunities for AR/VR applications arises from distributed caching. As the number of nodes/devices close to the user increases, distributed caching of chunks of content at user devices becomes possible. Nomadic users can further help to opportunistically distribute the content, as such when a user hands over and carries a desired content with the device. In that case, rather than downloading the content from the base station, content can be shared using D2D communications, which facilitates faster communication and efficient use of network resources. This exchange of cached content with D2D, as in studies by Golrezaei, *et al.*[4] and Liu and Lau,[8] requires direct communications between the users. Meanwhile, D2D video distribution and the impact of video size is also an important aspect.[9]

In edge caching, the caching strategy can be reactive or proactive. In reactive caching, the content is brought to the cache or updated based on user demand. In proactive caching, the content to-be-demanded is predicted and brought to the cache. An example of a proactive caching algorithm is introduced by Park *et al.*,[10] based on the scalable data management for the distributed virtual environment. Distributed virtual environments facilitate the user to explore the virtual ambiance while interacting with the objects in the real world. In order to have an immersive experience, the virtual environment is often replicated at the client side. In some instances, the size of the virtual environment is increased, thereby inducing significant transmission overhead. One way to overcome this challenge is to partially generate the virtual environment and dynamically obtain the objects that are demanded by the user. For efficient replication with minimum overhead, they propose prioritizing the transfer of objects and prefetching strategies. Park *et al.*[10] focus on caching at the user side. However, similar prioritized caching might be considered for edge caching.

In the study by Chakareski,[11] the author aims to address the challenge of caching large files of 360 videos in the wireless network. They propose to partially cache and stream the 360 videos based on user's viewpoint rather than caching and streaming the entire video to the user. This is based on the assumption that the user only navigates a small subset of the entire video at a point of time.

In the study by Chen *et al.*,[12] the problem of edge caching is studied for VR network to reduce the backhaul traffic and meet the delay requirements for the VR users. In their proposed scheme, unmanned aerial vehicles are employed to collect the VR contents which are requested by users and transferred to the small base stations for caching purposes. The goal of this scheme is to maximize the reliability of the VR user by choosing the format of the cached contents (visible contents consist of 120° horizontal and vertical frames or 360° contents). A deep learning algorithm is implemented to find the best caching strategy.

Edge Caching for Tactile Internet

Implementing haptic communications over wireless networks is quite challenging since the required delay for haptics is 1 ms. The state-of-the-art in tactile internet focuses on real-time interaction where the idea of caching is not practical. However, it may be also desired to replay haptic content as discussed in by El Saddik *et al.*[13] This might be useful for training applications that rely on haptic feedback. When a recorded haptic content is served to the mobile users, edge caching will play an important role. Bastug *et al.*[14] have focused on the predictive text caching that can intelligently serve the predicted user demands efficiently. A similar artificial intelligence engine can be used to determine the most viable content that needs to be stored for the haptic experience in the future tactile internet.

EDGE COMPUTING FOR AR/VR AND TACTILE INTERNET

Edge computing also known as mobile edge computing has recently emerged to overcome the computational limits of mobile devices in the face of increasing number of computationally-intensive applications.[15] Edge computing helps to reduce the pressure on the network resources by offloading workload to distributed computing clusters. Despite the fact that, cloud computing enables users to access a shared pool of servers and allows them to offload heavy computations to the cloud, the delay in accessing cloud servers is still high. This is one of the major reasons why edge computing emerges as a promising capability for mobile AR/VR and tactile internet.

Edge Computing for AR and VR Applications

In the study by Chakareski,[11] the author has exploited edge computing to overcome the computational limitation of the VR devices by enabling users to offload the computation tasks to edge servers. The authors have aimed to minimize the computation and transmit power consumption using a Lyapunov stochastic optimization model, subject to cochannel interference, reliability and delay constraints. Meanwhile, in the report by Yang *et al.*,[16] the authors propose to reach the required communication throughput by using cache and computation resources at users. Two different computing mode has been introduced. In the "MEC computation mode," when a task is requested by the

Table 1. Comparison of edge caching and computing studies for AR/VR and tactile internet.

	Evaluated Parameters						Applications
	Network Delay	Through-put	Caching capacity	Response time	Computing capability	Energy consumption	
Chakareski[11]		✓	✓			✓	AR/VR networks
Chen *et al.*[12]	✓	✓	✓				VR video streaming
Yang *et al.*[16]	✓	✓	✓				VR video streaming
Elbamby *et al.*[17]	✓	✓			✓		VR gaming
Zhang *et al.*[18]	✓				✓		VR Multiplayer Gaming
Ateya *et al.*[19]	✓			✓			Tactile Internet
Maier *et al.*[20]				✓			Tactile Internet

VR user, the MEC server computes the contents and sends the task; whereas, in the "local computation mode," MEC server sends contents that are not available at the mobile VR device and the computation of the received contents takes place at the user device. Then, the authors present an optimal task scheduling strategy to efficiently operate the aforementioned modes in order to minimize the use of communication resources while satisfying delay constraints.

The number of studies that combine caching and computing for AR/VR is limited. Only recently, the authors Elbamby *et al.*[17] propose a proactive caching and computing scheme to satisfy the high reliability and low latency requirement of VR gaming. In this scheme, the information about users' movements and game actions are utilized to precompute the next video frames and cache them to minimize the latency, while multiconnectivity is applied to guarantee the reliability. In the report by Zhang *et al.*,[18] the application of edge computing in VR gaming is extended to a massively multiplayer online scenario. In this scenario, the main challenges are low latency, high bandwidth, and precise scaling of large numbers of online players. The authors employ a hybrid edge cloud scheme that exploits edge computing to manage updating and rendering of view changes.

Edge Computing for Tactile Internet

According to Simsek *et al.*,[2] the tactile edge needs to be equipped with intelligence of interpolation/exploration of human actions, along with content prediction/proactive caching, in order to increase the range of tactile services. In the study by Ateya *et al.*,[19] the authors have proposed an approach towards a multilevel cloud-based cellular system. Here, edge computing facilities are made available through micro cloud units that are connected with the small cells. The concept of connecting the mini clouds to the core network has been shown to reduce the network congestion and round-trip latency. Meanwhile, Maier *et al.*,[20] uses edge computing within a fiber-wireless architecture to bring down the latency to the desired levels of tactile internet. In Table 1, we summarize the studies that offer edge caching and computing solutions to AR/VR applications and tactile internet.

OPPORTUNITIES AND CHALLENGES

Edge caching and computing bare many opportunities for AR/VR applications and tactile internet, while they come with several challenges. In the following sections, we discuss the opportunities that arise from the adoption of AR/VR and tactile internet in the entertainment, education, culture, arts, medicine and autonomous cars domains, as well as their related challenges.

Future Application Domains and Opportunities

Entertainment Online gaming is among the driving sectors of AR/VR in setting up user requirements and demands. In particular, new generation online VR gaming that lets users to experience a multiplayer game in a virtual environment sets an ideal example. Today, online VR games are implemented as web-based games that require players to be equipped with complex head mounts. Providing a virtual online gaming experience for the users on their mobile devices is still a challenge due to limited computing capabilities of devices and the throughput-delay limitations of the wireless networks. The computational overhead of AR/VR arises from several factors: higher refreshing rate to provide two synchronized images for both eyes (60–120 frames per second), 120° of visual field which is two times more than traditional games and most importantly, the need for immediate feedback due to frequently changing point of view. As for the feedback, it is also the factor that puts pressure on the wireless networks since less than 30 ms of end-to-end latency is expected in online VR games.[18] When computing and communication requirement are jointly considered, the computing capacity of the cloud emerges as a promising solution, while the delay to reach the cloud becomes the roadblock. Therefore, employing edge computing for online VR gaming bares many opportunities.

Education AR/VR technologies have been used for education in the past decade, in particular in the field of medicine and pilot training via flight simulators. Meanwhile, tactile internet can introduce a new method of interactive education by allowing haptic interaction of the students with the subjects remotely. This can be applied to various educational procedures such as the cases when students and educators participate in a laboratory experiment or remote surgeries. It can also be useful for musical bands to perform and practice remotely. To accomplish these examples, a precise synchronization of audio, video, and haptic interactions is necessary that impose ultra-low latency requirement over the underlying network. In most cases, the users might not be mobile hence not need the wireless networks. Nevertheless, the popularity of smart mobile devices indicates that in the close future all of the above educational activities could be demanded on mobile devices. In that case, edge caching and computing will become handy to facilitate such applications.

Art and Culture In several museums and art galleries, AR/VR technologies are already being utilized to enhance the experience of visitors, although mobile AR/VR experience has not been implemented yet. In the mobile AR/VR case, the augmented information will be highly localized and the information will need to be updated at a fast rate as the user moves to the next object. In the future, more computationally intensive applications are expected to emerge such as synchronized dancers/performers with the help of AR/VR. Clearly, as the scale and the range of the activity enlargers, the role of the mobile network escalates. Providing high-throughput, low-latency communication to users when there are hundreds or thousands of participants located in a geographically large area is challenging. An example would be an art installation in a metropolitan area that enables the residents to participate and interact with the scenes and with each other in the augmented environments. Such wide-scale applications can benefit from edge caching and computing immensely.

Health Care AR/VR and tactile internet have vast applications in health care. For instance, remote surgery for the individuals in remote locations, where the specialized surgeons cannot travel or places such as war zones, is one of the fundamental applications. Besides remote surgery, AR/VR is used for patients suffering from multiple sclerosis where walking abilities of patients have been significantly improved with the help of visual-feedback from VR devices.[21] Similarly, tactile internet can be used as a supportive tool in physical therapy for disabled patients. Among these applications, remote surgery is the most demanding procedure and the role of computations and the availability of resources is quite essential for achieving the required spontaneous services.

Intelligent Transportation and Autonomous Vehicles Realizing the birds-eye view of a particular environment is important for fully autonomous vehicles. 360° navigable scene generated by an autonomous car can be shared with a mobile edge server such that it is merged and streamed to other autonomous vehicles in order to enhance their situational awareness. AR/VR can be used for training the autonomous cars on virtual environments. Apparently, driverless cars will need to be tested before they actually start driving on real roads. Therefore, simulated environments can be used for training the autonomous cars.

Challenges and Open Issues

Despite many opportunities, the use of edge caching and computing for AR/VR and tactile internet still faces various challenges. In the following section, these issues are pointed out.

Cache Size, Cache Management, Caching, and Computing Cost One of the limitations for edge caching is the cache size and the associated problem of cache management. Although memory is inexpensive, the media content is becoming richer and hungrier for storage. Therefore, cache size still remains as a challenge. In addition, cache management; simply which content to cache and where to cache needs careful study. There is a vast literature on this topic, and various strategies are exploited to achieve the results by analyzing the response latency, cache hit ratio, remote on-demand requests, and energy consumption. Yet, most of the studies focus on video and not on navigable scenes. More research work is required to understand the usage of 360 videos, AR/VR and haptic devices, and offer tailored caching management strategies. In addition, caching and computing capability comes with an additional cost. Considering dense deployments of 5G, this could easily escalate the capital and operational expenditures of the wireless operators tremendously. Hence, strategic placement of caching and computing is an open research area.

Quality of Experience (QoE) Model Current research work on edge caching and computing focuses mostly on network quality of service (QoS), i.e., throughput and latency performance. However with the AR/VR applications and tactile internet, QoE needs to be merged with QoS. For instance, in a highly localized scenario, precise tracking of users and objects is critical. Failing to locate objects precisely results in degraded QoE even though QoS requirements might be satisfied. Therefore, network QoS and user QoE needs to be jointly considered. QoE may be further improved by emotional feedback according to Chen *et al.*,[22] where 5G and mobile could computing has reconsidered under emotional data collection, emotional data analysis, resource cognition, and emotion-aware action feedback.

Fairness in Offloading Given the cost of computing, it is reasonable to assume the devices will not have infinite computational resources. In that case, mobile AR/VR and tactile internet users will compete on accessing these resources, in which some users may dominate computing services by frequently offloading while others may be left with no or little resources. Future research work needed to ensure fair access mechanisms, both considering selfish behavior of users and network related unfair treatment of users that may arise from cell edge users being given less opportunity for offloading due to their poor channel conditions.

Correlated Content Model In AR/VR applications, most of the time, the requested scenes or data from different users are highly correlated with location. For instance, when a group of people participates in a multiplayer soccer game through VR, the same 360 videos provided for a specific user can be delivered to other users with rotation according to the viewer's location and viewing angle. When correlated content models are used, there can be a huge decrement in computation load. Yet, the processing of the correlated content at the edge computing devices for increased efficiency is still an open issue.

Heterogeneous Users In the literature, most of the studies on AR/VR assume that users are homogeneous. However, in practice, users will not be identical due to a different kind of available headsets. Some users could be mounted with headsets with limited resources while the other users may be equipped with headsets capable of performing complex computational tasks. Providing computation resources at edge based on users' local capabilities remains an open issue.

Flexible Networks and SDN In general, edge computing calls for the flexible allocation of resources as well as the flexible organization of the network. Thus, the interaction of SDN and 5G networks has been explored in the study by Huo *et al.*[23] The authors have proposed using an SDN controller that is capable of managing the entire topology including caching and computing at every node, as well as providing forwarding strategies. Yet, the interaction of flexibly organized networks with AR/VR and tactile internet needs to be further explored.

Users Privacy and Security Issues AR/VR and tactile internet applications carry a rich set of information about an individual including the locations they visit, their interaction with the environment, their interaction with the other individuals, etc. When edge caching and computing is used, such content may be shared with other users causing privacy and security concerns. The tradeoff between the utility arising from reusing common content and user privacy needs to be carefully explored.

The opportunities and applications of edge caching and computing for AR/VR and tactile internet are wide. However, more research work is needed to address the challenges that are outlined above.

CONCLUSION

In this paper, we surveyed edge caching and computing studies that target performance improvements in mobile AR/VR and tactile internet. The differences and corresponding architectures and advantages of each method are pointed out. The most current applications of edge caching and computing are explained and the opportunities and challenges in these areas are identified. This paper will serve as a roadmap for researchers working in the field of edge caching and computing and for researchers aiming to enhance the reliability and latency performance of wireless networks to serve AR/VR applications and the tactile internet more efficiently.

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Sukhmani Sukhmani is currently working as 4G/5G System Developer with Ericsson Inc, Canada. She received the Bachelor’s degree in electronics and communication from Chandigarh Engineering College, Ajitgarh, Punjab, and the Master’s degree in electrical and computer networks from the School of Electrical Engineering and Computer Science, the University of Ottawa, Ottawa, ON, Canada. During this study, she was working under the supervision of Dr. Melike Erol-Kantarci.

Mohammad Sadeghi is currently working toward the Ph.D. degree at Electrical and Computer Engineering, University of Ottawa, Canada, working under the supervision of Dr. Melike Erol-Kantarci. His research interests include machine learning for smart grid applications, cooperative communications and underwater acoustic communications. He received the B.Sc. degree in electrical engineering from the University of Isfahan, Isfahan, Iran, in 2015, and the M.Sc. degree in electrical engineering from Ozyegin University, Istanbul, Turkey, in 2017.

Melike Erol-Kantarci is an Assistant Professor with the School of Electrical Engineering and Computer Science, the University of Ottawa, Ottawa, ON, Canada. She is the Founding Director of the Networked Systems and Communications Research laboratory. She is also a Courtesy Assistant Professor with the Department of Electrical and Computer Engineering, Clarkson University, Potsdam, NY, USA. She has more than 100 peer-reviewed publications that have been cited over 3000 times and she has an h-index of 28. She is the coeditor of two books: *Smart Grid: Networking, Data Management, and Business Models* (CRC Press) and *Transportation and Power Grid in Smart Cities: Communication Networks and Services* (Wiley). She has delivered seven tutorials and more than 20 invited talks around the globe. Her main research interests are 5G and beyond wireless networks, Tactile Internet, smart grid, cyber-physical systems, Internet of things and wireless sensor networks. She was the recipient of the IEEE Communication Society Best Tutorial Paper Award and the Best Editor Award of the IEEE Multimedia Communications Technical Committee in 2017. She is an Editor of the IEEE Communications Letters and IEEE Access. She is a Senior Member of the IEEE. She is currently the Vice-Chair of Green Smart Grid Communications special interest group of IEEE Technical Committee on Green Communications and Computing.

Abdulmotaleb El Saddik (F'09) is a Distinguished University Professor with the University of Ottawa, Ottawa, ON, Canada. He is an internationally recognized scholar who has made strong contributions to the knowledge and understanding of multimedia computing, communications, and applications. His work looks toward the establishment of Digital Twins using Artificial Intelligence, AR/VR and, tactile internet that allow people to interact in real time with one another as well as with their digital representation. He has been extremely productive of high-quality research and impact. He has authored more than 500 peer-reviewed articles and five patents. He is the author of the book *Haptics Technologies: Bringing Touch to Multimedia*. He was the recipient of several awards including the Friedrich Wilhelm Bessel Award, the IEEE Instrumentation and Measurement Society Technical Achievement Award and IEEE Canada C.C. Gotlieb (Computer) Medal and A.L. McNaughton Award. He is a Fellow of the IEEE, the Canadian Academy of Engineering, and the Engineering Institute of Canada.