The research and development of information technologies have been evolving towards a sustainable society to effectively reduce energy consumption and carbon footprints resulting from the unprecedented expansion of the Internet. My interdisciplinary research is on protocol design and performance modeling of wireless networks supporting heterogeneous services for future sustainable societies. The main research objective is to improve the sustainability of communication networks to meet the ever-growing user demands by developing new green networking technologies that support much higher data rates at much lower energy consumption and cost. The new green technologies will further enable ubiquitous information infrastructure that lead to future sustainable societies. For example, low-cost, low-energy sensor networks can facilitate weather forecasting, natural resource exploration, disaster warning, environment safeguarding, and remote health care and tele-medicine; vehicular ad hoc networks allow communications among nearby vehicles and between vehicles and nearby roadside units, which will significantly improve road safety, energy and transportation efficiency, and reduce carbon emissions and pollution, etc. To support new green applications over green communication networks, substantially different constraints and demands should be considered, which motivates us to re-design and re-engineer the network protocols and algorithms. The following outlines my research interests and recent accomplishments.

1 Major Research Contributions

1.1 Protocol design for UWB and mmWave communication networks

The Federal Communications Commission (FCC) has authorized the unlicensed use of 3.1–10.6 GHz and 57–64 GHz frequency bands for ultra-wideband (UWB) and millimeter-wave (mmWave) communications, respectively, which opens numerous opportunities for supporting high rate (up to multi-Gigabit) applications that will create health and wealth, and change our daily life and our society. For example, UWB is considered an ideal candidate for vital signs and physiological signals monitoring in a medical healthcare system as its transmission power is much lower than traditional wireless systems. UWB can also be used for emergency services thanks to its precise localization and reliable communication capabilities.

Although UWB and mmWave communications have been hot topics in the communication society for several years, there are very limited works in the network protocol design for fully utilizing these sustainable communication technologies to enable new killer applications. The research works in [1]-[6] provide the first steps toward this direction. Our pioneer research work has effectively exploited the spatial multiplexing capabilities of the UWB/mmWave communication networks by considering the underlying physical layer features and channel propagation characteristics.

- Wireless network capacity is interference limited due to the broadcast nature of the wireless channel. Existing
protocols, e.g., IEEE 802.15.3, is inherently inefficient for spatial resource utilization by allowing one transmission at one time [1]. How to efficiently explore the spatial utilization of wireless channel to improve the network capacity is a challenging issue. Instead of studying the asymptotic capacity bounds of arbitrary networks which may be too loose to be useful in realistic networks, we have focused on deriving the expected capacity or transport capacity of a UWB network with random topology, and maximize them by fine tuning protocol parameters [2]. The analysis has revealed insight into the question of how spatial capacity of UWB networks can be effectively explored by allowing appropriate concurrent transmissions.

- Due to the stringent transmission power constraints and the limited transmission range of UWB communications, multi-hop relay is necessary and favorable to extend the communication coverage of UWB networks. A simple, scalable, and distributed UWB MAC protocol is of critical importance to efficiently utilize the large bandwidth of UWB channels to enable new applications cost-effectively. To address this issue, we have designed a distributed asynchronous exclusive regions (ER) based MAC for multi-hop UWB networks and derived the best ER size to maximize the network throughput [3].

- Since oxygen absorption peaks at 60GHz, the mmWave band is particularly desirable for high-dense, high data rate applications. By investigating the unique features of mmWave communications, i.e., high oxygen absorption and atmospheric attenuation, limited communication range, and the use of directional antenna to combat high path loss, we have derived the ER according to the different types of antennas employed by the transmitters and receivers and proposed a randomized ER based scheduling scheme to appropriately exploit the spatial multiplexing gain of mmWave WPANs [4]. An efficient admission control and concurrent scheduling scheme for Internet Protocol TV (IPTV) distribution using mmWave networks has been presented [5]. Furthermore, we have designed an optimal geographic routing and distributed MAC for multi-hop mmWave networks to maximize the network resource utilization [6].

1.2 Multimedia over WLAN: a low-cost solution

IEEE 802.11 based wireless local area networks (WLANs) become ubiquitous, thanks to its deploy simplicity and scalability, performance robustness, and licence-free wireless technologies. It is desirable to enable multimedia services over WLANs, which will be a solution for many applications that are cost-sensitive, e.g., remote health care and distance education in developing countries or rural areas.

However, supporting multimedia applications over wireless networks poses significant challenges due to the inherent impairments of wireless communications at the licence-free bands, e.g., time-varying fading, shadowing and interference, and limited radio resources, which result in difficulties in network planning, admission control, and quality of service (QoS) provisioning.

- Asynchronous distributed channel access has been a key factor to the overwhelming success of the IEEE 802.11 WLANs. However, the contention nature of distributed coordination function (DCF) renders quantitative QoS control, particularly the delay control, very difficult. To meet the stringent QoS requirements of multimedia applications over a distributed WLAN, it is necessary to determine the network capacity, in terms of the maximum number of multimedia connections that can be supported with satisfactory user-perceived quality. Previous WLAN performance analysis assumed homogeneous and saturated traffic load of all nodes, including the WLAN access point (AP) and mobile nodes, which are not applicable for realistic infrastructure WLANs.
supporting multimedia applications. Therefore, we have developed a novel analytical framework to study the network capacity of infrastructure WLANs supporting non-persistent unbalanced multimedia flows[7], which has been cited more than 70 times since it was published in 2006. The analytical results can be applied to design effective admission control to guarantee the QoS of multimedia applications and maximize the utility of the network.

• In response to the demand for higher performance WLANs to support broadband multimedia applications, the next generation WLANs will employ enhanced physical layer and medium access control (MAC) protocols to improve system capacity and reliability. We have analytically investigated the performance of the new MAC features, such as frame aggregation and bidirectional transmissions, in the IEEE 802.11n standard [8]. To explore the physical layer multiple-input multiple-output (MIMO) capability, we have further proposed a distributed MIMO-aware multi-user (MU) MAC protocol [9]. By exploiting the multi-user degree of freedom in a MIMO system, the proposed MU MAC can effectively minimize the AP-bottleneck effect in legacy infrastructure WLANs and significantly improve network capacity.

• To support multiple classes of applications with different QoS requirements, a multiclass distributed channel access has been developed to provide service differentiation via contention window adaptation. But how to optimize the system parameters was an open issue. To address this, we have proposed a cross-layer framework to integrate the network-layer queueing analysis with the extended multiclass DCF model for WLAN network capacity planning and contention window design [10]. Given the QoS requirements, e.g. the stochastic delay bound or delay outage probability of real-time traffic, both the network capacity and the optimal contention windows for the AP and the mobile nodes can be jointly solved from our cross-layer framework.

1.3 QoS provisioning in wireless multimedia networks

Future wireless networks are expected to integrate diverse networks and access technologies to provide ubiquitous QoS-guaranteed multimedia services to end users. We have also studied QoS-based service provisioning in various wireless multimedia networks.

• Next generation wireless networks are expected to integrate diverse network architectures and multimedia services. The network heterogeneity, coupled with channel fading, user mobility, and multi-hop relay, could result in severe variations in the end-to-end throughput and delay, which makes QoS provisioning extremely challenging. To tackle this problem, we have developed an analytical framework to study the impacts of network dynamics on the user-perceived video quality [11]. Based on the derived closed-form expressions of the video quality, we have proposed distributed call admission control, adaptive playout buffer management, and quality-driven network resource allocation schemes to guarantee the user-perceived media quality and efficient network resource utilization.

• For cellular and IEEE 802.16 (WiMax) networks, multicast transmission is an efficient solution to disseminate multimedia data to multiple users simultaneously. But without an acknowledge scheme, multicast is inherently unreliable. Previous approaches typically improved the multicast reliability at the cost of reduced throughput. In [12], we have applied cooperative transmission techniques in a channel-aware multicast scheduling scheme to achieve high reliability, throughput, and good fairness performance, taking advantages of user cooperation and spatial diversity of wireless channels.
To improve cooperative driving in inter-vehicle communication (IVC) system, it is of critical importance to quickly disseminate safety-related information among nearby vehicles. We have proposed efficient yet reliable broadcast and MAC protocols for emergency message dissemination in IVC [13, 14]. By jointly considering geographical locations, physical-layer channel conditions, and moving velocities of vehicles, the best relayer is selected to forward the message in the desired propagation direction. IEEE 802.11e has also been applied to further assure the QoS provisioning to safety-related services. Our proposed protocol can not only minimize the broadcast message redundancy but also quickly and reliably deliver emergency messages in IVC.

In summary, my research work includes both theoretical analysis and practical protocol design, which are important for next-generation wireless networks to enable ubiquitous multimedia services for future sustainable societies. The resource management schemes proposed in [2, 3, 4] are the first steps towards maximizing the spatial capacity of high-rate wireless networks to support as many users as possible, and they open a door to numerous research in this area. The analytical framework developed in [7, 10] provides an in-depth insight into the capacity of WLANs in supporting multimedia applications. The admission control, buffer management, and scheduling algorithms proposed in [5, 11, 12] further pave the way of supporting multimedia applications in next generation wireless networks. Furthermore, the analytical frameworks developed in [7], [2] and [11] introduce new methodologies and tools and provide guidance and insights into network research and engineering. The research results have been published in archival journals and premier conferences in the fields of wireless networking. I have also been actively involved in writing grant proposals related to my research work. I believe that my interdisciplinary research experience allows me to be an effective communicator and researcher, and enables me to establish solid research programs and to collaborate with researchers working in different areas.

2 Future Research Plan

The previous research work has laid down a solid foundation which allows me to explore many new exciting areas including the following.

2.1 Green communication network

Driven by the steady increase of relevant global CO₂ emission and energy cost, researchers have been striving to find green approaches for reducing energy consumptions of communication and networking infrastructure and promoting environment conditions, including energy-efficient network capacity planning, power-aware network architecture and protocol design, renewable energy, green spectrum access (i.e., opportunistic spectrum access without causing harmful interference pollution), and environment-friendly green services and utilities, etc. Green communication and networking solutions can not only improve the efficiency of energy consumption and resource utilization, but also benefit for the sustainable society and global environment. To improve energy and spectrum efficiency of green communication networks, protocol design across the multiple layers in OSI model should be involved. I will revisit my previous research work of protocol design in power-efficient wireless networks and investigate how to revise or invent new protocol design for green communication networks, considering particular features of green applications and services. In specific, I will study spectrum-aware MAC and routing protocols by jointly considering optimal power control, opportunistic green spectrum access, and adaptive resource management to improve the overall efficiency of spectrum utilization and QoS performance of diverse green multimedia applications.


2.2 UWB-based biomedical sensor network

Wireless sensor networking is a promising technology for a wide range of applications. With the advance as of miniature, lightweight, and ultra low-power biosensors, wireless telemedicine becomes an emerging interdisciplinary field that calls for innovations in communications and networking technologies to facilitate reliable, secure, and quality remote health care services. The IEEE 802.15 Task Group 6 (WBAN) has been recently formed to develop a communication standard optimized for low power devices and operation on, in or around the human body to serve a variety of applications including medical and other personal entertainment. Due to the ultra low-power level of UWB enabled biosensors, the communication range is very limited (e.g., 2 to 5 meters), and multi-hop relaying might be necessary. In addition, biomedical sensor networks are expected to be integrated with other WPAN/WLAN/WiMAX networks to form a telemedicine system that enables remote medical services. How to guarantee the secure, timely and reliable delivery of the life-critical data over a heterogeneous sensor network is an open issue. Thus motivated, the next step of my ongoing research is to study advanced across-layer protocol design for integrated UWB-based biomedical sensor networks. I will jointly consider energy-efficient and QoS-aware routing and resource management, physical layer interference mitigation, and explore security mechanisms to meet various QoS and security requirements of multimedia medical services (e.g., data, image, voice, and video). Furthermore, I will tackle the challenging issues in a vehicular environment in addition to hospital or home networks. The high mobility results in more stringent requirements for QoS adaption, which is critical for medical services in an ambulance.

2.3 Next-generation multimedia network

The revolutionary advances in wireless communication technologies (e.g., UWB, mmWave) and the proliferation of consumer electronics (CE) lead to tremendous increase of multimedia applications, such as video conferencing, live multimedia streaming, high definition TV (HDTV) broadcasting, and video gaming. The next-generation multimedia networks are envisioned to enable users to create and access large volumes of rich multimedia information on a variety of personal mobile devices across different networks. However, the available wireless resources for supporting these killer multimedia applications are at premium. In addition, various multimedia applications have different QoS requirements. For example, interactive media such as voice calls are very delay-sensitive while video streaming is more bandwidth intensive but can tolerate a certain level of startup latency. Therefore, proper QoS control and network resource management are necessary to provide QoS satisfaction for various multimedia services. I will continue to work on wireless multimedia service provisioning and extend our previous work to study QoS control and network capacity planning in next-generation heterogeneous networks by investigating different network characteristics and QoS demands of various emerging multimedia applications.

References


