Guest Editorial Special Issue on Low-Latency High-Reliability Communications for the IoT

AS ONE of the key enabling technologies of emerging smart societies and industries (i.e., industry 4.0), the Internet of Things (IoT) has evolved significantly in both the technologies and applications. It is estimated that more than 25 billion devices will be connected by wireless IoT networks by 2020. In addition to ubiquitous connectivity, many envisioned applications of the IoT, such as industrial automation, vehicle-to-everything (V2X) networks, smart grids, and remote surgery, will have stringent transmission latency and reliability requirements, which may not be supported by the existing systems. Thus, there is an urgent need for rethinking the entire communication protocol stack for wireless IoT networks.

The response to our Call for Papers on this special issue was very strong, with 39 articles submitted from all over the world. During the review process, each paper was assigned to one responsible guest editor and reviewed by at least three experts in the relevant areas, with a rigorous two-round, and in some cases a three-round review process. Thanks to the courtesy of the Editor-in-Chief of IEEE INTERNET OF THINGS JOURNAL, Dr. Xuemin (Sherman) Shen, we were able to accept 13 excellent articles covering various aspects of low-latency high-reliability communications for the IoT. In the following, we are pleased to introduce these articles and highlight their main contributions.

In the survey article "High-Reliability and Low-Latency Wireless Communication for Internet of Things: Challenges, Fundamentals, and Enabling Technologies," the editorial board reviews the various application scenarios, fundamental performance limits, and potential technical solutions for high-reliability and low latency (HRLL) wireless IoT networks. The physical, medium access control (MAC), and network layers of wireless IoT networks, which all have significant impacts on latency and reliability, are discussed. For the physical layer, the fundamental information-theoretic limits for HRLL communications are discussed, after which a frame structure and preamble design for HRLL communications are introduced. Then, practical channel codes with finite block length are reviewed. For the MAC layer, the optimized spectrum and power resource management schemes and recently proposed grant-free schemes are discussed. For the network layer, an optimized network structure, optimal traffic allocation schemes, and network coding schemes that minimize the latency are presented.

Massive wireless connections are emerging in the IoT and will require cognitive radio technology, namely, cognitive IoT. Different from the conventional cognitive networks, the cognitive IoT will be dominated by short-packet transmissions, which suffer from a significant packet error rate even when the transmission rate is smaller than the Shannon capacity. In the paper "Joint Spectrum Sensing and Packet Error Rate Optimization in Cognitive IoT," a joint optimization of the spectrum sensing time and packet error rate to maximize the cognitive effective-throughput, which is defined as the effective transmission rate by considering the packet error rate, is introduced. First, an instantaneous effective-throughput maximization problem with the instantaneous channel state information (CSI) between cognitive transceivers is formulated, and a successive optimization algorithm is developed. Second, an average effective-throughput maximization problem with the statistical CSI between cognitive transceivers is formulated. Due to the complicated expression for the average effective-throughput, a closed-form expression is analyzed and an exhaustive search method is adopted to obtain an optimal solution. The numerical and simulation results reveal that the packet length has a significant impact on the optimal design. Moreover, the proposed algorithms can almost maximize the instantaneous/average effective-throughput.

Nonorthogonal multiple access (NOMA) provides a new solution for future V2X services to mitigate the traffic congestion and reduce latency. In "Cooperative NOMA Broadcasting/Multicasting for Low-Latency and High-Reliability 5G Cellular V2X Communications," the authors proposed two relay-assisted NOMA transmission schemes for 5G V2X communications, i.e., half-duplex relay-assisted NOMA (HDR-NOMA) broadcasting/multicasting and full-duplex relay-assisted NOMA (FDR-NOMA) broadcasting/multicasting and investigated the optimal power allocation problems for them. To improve the quality of service (QoS) for users with poor channel conditions and to guarantee fairness, power allocation problems are formulated to maximize the minimum achievable rate for all users. Even though neither of the formulated problems is concave nor convex, it is shown that the considered problems are quasi-concave. Hence, a bisection-based power allocation algorithm is proposed to obtain the optimal solutions. Numerical results demonstrate that the proposed schemes outperform the scheme with fixed power allocation significantly and achieve a considerable performance improvement with respect to a suboptimal fractional transmit power allocation (FTPA) method and an optimized time-division multiple access (TDMA) scheme. Furthermore,

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compared with HDR-NOMA, better performance can be achieved by FDR-NOMA when the self-interference is sufficiently suppressed.

Another paper addressing vehicular networks is entitled "A Low-Latency Content Dissemination Scheme for mmWave Vehicular Networks." To improve the content dissemination performance, the authors proposed an information-centric network (ICN)-based mmWave vehicular framework together with a decentralized vehicle association algorithm to realize low-latency content dissemination. In this framework, by using the ICN protocol, content items are cached and retrieved at the edge of the network, thereby reducing the content retrieval latency. To enhance the content dissemination rate, a vehicle association algorithm, which jointly considers the content segment diversity, the relative velocity between vehicles, and the transceiver's beamwidth, is operated in every vehicle. Considering the blindness of directional mmWave links, a common control channel operating at low frequency bands with omnidirectional coverage is used to share information related to vehicle associations. The simulation results demonstrate that the proposed algorithm can improve the content dissemination efficiency and reduce the content retrieval latency.

In "Evaluating the Suitability of IEEE 802.11ah for Low-Latency Time-Critical Control Loops," the authors evaluated the IEEE 802.11ah for low-latency time-critical control loops. A network setting for adjusting network dynamics to low latency control loops is proposed, enabling limited jitter and high reliability. The scalability of IEEE 802.11ah networks hosting both control loops and monitoring sensors periodically transmitting measurements is explored. Assigning the control loop end-nodes to dedicated restricted access window (RAW) slots results in over 99.99% successful deliveries. Furthermore, interpacket delay is concentrated around the cycle-time in the following or preceding beacon interval in case the beacon interval is at least half of the value of the shortest cycle-time. Adjusting the beacon interval to the fastest control loop in the network ensures the latency requirements at the cost of the maximum achievable throughput and energy consumption.

Massive IoT has been proposed for 5G networks to serve the sporadic traffic generated by devices operating under tight resource constraints. In these applications, the overhead for synchronization and control functions is comparable to the data size. Hence, the control/data ratio is very unfavorable. The authors of the article "Ultra-Reliable Energy-Efficient Cooperative Scheme in Asynchronous NOMA With Correlated Sources" proposed the techniques to take advantage of the fact that transmitters are privy to all data in order to boost the spectral and power efficiency, while increasing reliability. Identical content transmission over NOMA (ICToNOMA) for transmitters with correlated sources is also proposed. ICToNOMA cooperatively combines and transmits identical messages over consecutive data packets. The potency of successive interference cancellation (SIC), as the main block in current NOMA receivers, is proposed in asynchronous channels. By applying water-filling and geometric power allocation, it is shown that the SE degradation is caused by SIC. Moreover, it is demonstrated that the SE is improved in asynchronous NOMA and ICToNOMA, by managing the memory of channels and correlation instead of cancelling it. In addition, an iterative joint detection and decoding (IJDD) receiver is proposed to outperform SIC in asynchronous NOMA receivers. Extensive simulations show that ICToNOMA can outperform NOMA by providing a considerable boost in the channel reliability with increasing the spectral and power efficiency.

In "Dynamic Social-Aware Computation Offloading for Low-Latency Communications in IoT," by leveraging social ties in human social networks, optimal dynamic computation offloading mode selection to jointly minimize the execution latency of total tasks and the energy consumption of mobile smart devices in MEC-aided low-latency IoT is investigated. Different from the previous studies, which mostly focus on how to exploit social tie structure among mobile smart device users to construct the permutation of all the feasible modes, the authors consider dynamic computation offloading mode selection with social awareness-aided network resource assignment, involving both the computing resources and transmit power from heterogeneous mobile smart devices. On the one hand, the paper formulates the dynamic computation offloading mode selection into the infinite-horizon time-average renewal-reward problems subject to time average latency constraints on a collection of penalty processes. On the other hand, an efficient solution is also developed, which elaborates on a Lyapunov optimization-based approach, i.e., a drift-plus-penalty (DPP) algorithm. The numerical simulations are provided to validate the theoretical analysis and assess the performance of the proposed dynamic social-aware computation offloading mode selection method considering different configurations of the IoT network parameters.

A novel control-aware communication design to the low-latency resource allocation problem is proposed in "Control Aware Radio Resource Allocation in Low Latency Wireless Control Systems." In this proposed method, it incorporates both control and channel state information in scheduling transmissions across time slots, frequency bands, and data rates using the next-generation Wi-Fi scheduling architecture. Control systems that are closer to instability or further from a desired range in a given control cycle are given higher packet delivery rate targets to meet. Rather than a simple priority ranking, the authors derive precise adaptive packet error rate targets for each system needed to satisfy control-specific performance requirements. Then these adaptive rate targets are used to make scheduling decisions that reduce total transmission time. The resulting control-aware low latency scheduling (CALLS) method is tested in numerous simulation experiments that demonstrate its effectiveness in meeting control-based goals under tight latency constraints relative to control-agnostic scheduling.

In "Transmission Early-Stopping Scheme for Anti-Jamming Over Delay-Sensitive IoT Applications," the authors proposed a jamming detection scheme that uses the packet transmission time as a statistic to make detection decisions. The key insight behind the proposed scheme is that a long transmission/retransmission time for a certain packet indicates an abnormal condition such as jamming. Therefore, the authors

devised an optimal transmission-time threshold that, when exceeded, detects a jammer. Unlike most existing detection schemes where, in case of a detection error, retransmission could continue until the deadline is reached, our scheme aims to detect the jammer earlier than the deadline such that the remaining time (until the deadline) could be utilized in retransmitting the packet over a safe channel. The proposed detection scheme is a general framework that can be applied to many situations. After conducting a thorough analysis, the authors applied the proposed early-stop jamming detection framework to the distributed coordinated function (DCF) medium access mechanism specified by the 802.11 standard. The simulation results show significant performance gains achieved by the proposed scheme.

A novel modulation scheme termed orthogonal frequency-division multiplexing with subcarrier number modulation (OFDM-SNM) is proposed as a promising candidate modulation scheme for next generation networks in "Enhanced Orthogonal Frequency-Division Multiplexing With Subcarrier Number Modulation." Although OFDM-SNM is capable of achieving a higher spectral efficiency (SE) than OFDM with index modulation (OFDM-IM) and plain OFDM under certain conditions, its reliability is relatively inferior to these existing schemes because the number of active subcarriers varies. In this regard, the authors proposed an enhanced OFDM-SNM scheme, which utilizes the flexibility of placing subcarriers to harvest a coding gain in the high signal-to-noise ratio (SNR) region. In particular, the authors stipulated a methodology that optimizes the subcarrier activation pattern (SAP) by subcarrier assignment using instantaneous channel state information (CSI) and, therefore, subcarriers with higher channel power gains will be granted activation priority, if the number of subcarriers is fixed. The authors also analyzed their proposed enhanced OFDM-SNM system in terms of outage and error performance. The average outage probability and block error rate (BLER) are derived and approximated in the closed-form expressions, which are further verified by numerical results generated by Monte Carlo simulations.

In "Energy Efficient Designs of Ultra-Dense IoT Networks With Non-Ideal Optical Front-Hauls," the authors considered an optimum design of the downlink of user-centric ultradense IoT networks with fiber-wireless communications (FWC). A large number of low power radio access points (RAPs) are densely deployed in the network to provide service to spatially distributed IoT physical devices (PDs). The RAPs are connected to a central unit (CU) through optical fiber front-hauls. Radio-frequency-over-fiber (RFoF) is employed in the optical front-hauls to reduce RAP complexity, cost, and energy consumption. With RFoF front-hauls, wireless signals received by PDs are subject to distortions accumulated through the optical and wireless links, including optical loss, optical chromatic distortion, optical and thermal noises, wireless pathloss, and small-scale fading. The optimum designs are performed across the optical and wireless domains with the help of a newly developed model that quantifies the combined effects of the optical and wireless links. One of the main challenges faced by the design of an ultradense IoT network is the high energy consumption due to dense RAP deployment. The objective of this paper is to minimize the total energy consumption of the entire IoT network, including both optical and wireless links, by jointly optimizing RAP power allocation and RAP-PD association, subject to QoS constraints for each PD. A low complexity suboptimum binary forcing gradient search (BFGS) algorithm is also proposed, which performs a gradient-based search based on the unique structure of the problem. The simulation results show that the optical front-hauls have significant impacts on the performance and design of ultradense IoT networks.

Transmission latency is a key performance metric in most wireless sensor network (WSN) applications. Nodes in a WSN often keep their radio transceivers off, and turn them on periodically using a duty cycling mechanism. The latter is a major source of delay in the network, because transmissions must wait for the next receiver wake-up. In "A Wave-Based Request-Response Protocol for Latency Minimization in WSNs," the authors presented a cross-layer approach to minimize latency of a request–response (RR) protocol adopted in an IEEE 802.15.4-based WSN, where the IPv6 routing protocol for low-power and lossy networks (RPL) is used. Extra wake-ups are generated dynamically to match the predicted arrival time of the response packet, in order to reduce the duty cycling delay. The proposed approach is verified with the Cooja simulator, relying on the Contiki Operating System. The observed experimental results show a shorter RR delay with respect to a phase alignment (PA) approach.

The serious security threat to industrial control systems and sensors has become a major challenge with the rapid development of the Industrial IoT (IIoT). Man-in-the-Middle (MITM) attacks are a very common intrusion method, which will create a significant security threat in the application of IIoT. In an IIoT scenario, lightweight safety certification can play a very important role in the development of data-intensive and decentralized applications running on billions of sensors and devices, preserving their security. To counter this threat, in "New Security Mechanisms of High-Reliability IoT Communication Based on Radio Frequency Fingerprint," a low-latency high-reliability security mechanism is proposed to avoid MITM attacks in IIoT settings. First, combining radio frequency fingerprint (RFF) technology with IIoT applications, a lightweight IIoT security architecture is proposed. Based on the proposed IIoT security architecture, the process of device access authentication and communication service is illustrated. Second, according to the requirement of IIoT identification, a method for access authentication of a device is proposed based on its RFF. Feature extraction, classifier design, and access authentication are discussed in detail in the article. According to the simulation results, the new security mechanisms based on RFF can be used to avoid the MITM attacks in IIoT settings.

In closing, we thank all the authors for their excellent contributions. We also thank all the reviewers for their efforts in reviewing the papers, and for their valuable comments and constructive suggestions to improve the quality of the articles. Finally, we are grateful for the advice and support of Prof. Xuemin (Sherman) Shen, the Editor-in-Chief of the IEEE INTERNET OF THINGS JOURNAL, for his help throughout the publication process.

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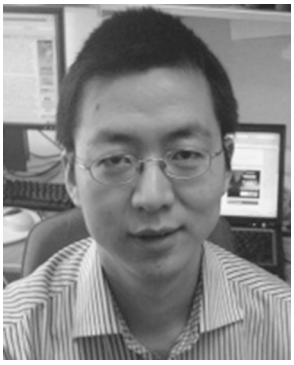

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