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Ambient Backscatter Communications for Future Ultra-low-power Machine Type Communications:

Challenges, Solutions, Opportunities, and Future Research Trends

Ruifeng Duan, Xiyu Wang, Hüseyin Yiğitler, Muhammad Usman Sheikh, Riku Jäntti, and Zhu Han

Abstract—**The widespread applications of massive machine-type communications (MTCs) are limited by energy availability, spectrum congestion, and device costs. The emerging ambient backscatter communication (AmBC) not only addresses these bottlenecks but also opens the opportunities for new applications. This article aims to explore AmBC-enhanced future ultra low-power MTCs. In this context, we present the development trends in AmBC prototype designs and discuss potential applications, highlight the specific features of the AmBC technology, and review the AmBC receiver designs. Finally, we investigate and outline the future research challenges and trends from the practical aspects of AmBC systems.**

I. INTRODUCTION

Recent advances in wireless communications, and miniaturization in computing and sensing components enabled the development of ubiquitous systems that acquire and convey the information without human intervention, often referred to as IoT. For realizing pervasive connectivity among different devices, these systems aim at generating a common operational framework for different applications and services by utilizing machine-type communication (MTC). The same communication methodology is used for conveying the data among machines and MTC central servers for forming the common framework in the servers.

The scalability and flexibility of IoT deployment using MTC are mainly limited by three factors: 1) the connectivity of different devices is limited by their life span defined by the energy availability; 2) the cost of each device also constrains the number of devices that can be deployed for an application; 3) the link availability is limited by the congestion of the communication medium. The ambient backscatter communication (AmBC) technology provides a complete solution to these problems. Without need of a dedicated power infrastructure and a carrier emitter, AmBC enables devices to communicate by scattering ambient modulated RF signals existing in the air. For example, it can use the signals of terrestrial television broadcasts, cellular system transmissions, WiFi or Bluetooth transmissions [1]. It provides orders of magnitude of power efficiency better than that of the traditional radio communication systems, enables ultra-low cost manufacturing of communication devices by avoiding expensive and power-hungry radio components, and can operate in a spectrum allocated for other wireless transmissions.

An AmBC system integrates new ultra-low power communication systems into existing IoT connectivity infrastructure seamlessly. It leads to the evolution of 5G and beyond MTC solutions by opening new applications or by enriching the existing ones. The commercial potential is vast, and the expectation of generating both the theoretical and technological breakthroughs is high. Despite the advantages of the AmBC technology and the proposed solutions, this field of research is largely less explored, and there are various challenges arising from the practical implementations.

This article aims at providing a guideline for practitioners and researchers working in this area. For this purpose, we first introduce currently available AmBC designs and their application opportunities. We then identify the common features of AmBC before presenting the most important challenges and their mitigation methods. We present future research trends, and finally draw the conclusions.

II. AMBC SYSTEMS

A sustainable wireless communication has been identified as one of the key enabling technologies for the IoT. The cost and energy limitations of MTC-based IoT deployments have been driving the development of the IoT connectivity solutions such as IEEE 802.15.4, Bluetooth low energy (BLE), and more recently low power wide area radios such as SigFox, long range (LoRa), and narrowband IoT. These systems can operate for extended duration with finite energy, and their cost is significantly lower than that of the traditional wireless communication solutions. However, their operation is not optimized for self-sustainable operation, which would be desirable in many IoT deployments. Although the aforementioned systems along with

Ruifeng Duan, Xiyu Wang, Hüseyin Yiğitler, Muhammad Usman Sheikh, and Riku Jäntti are with Aalto University. Zhu Han is with University of Houston and Kyung Hee University.

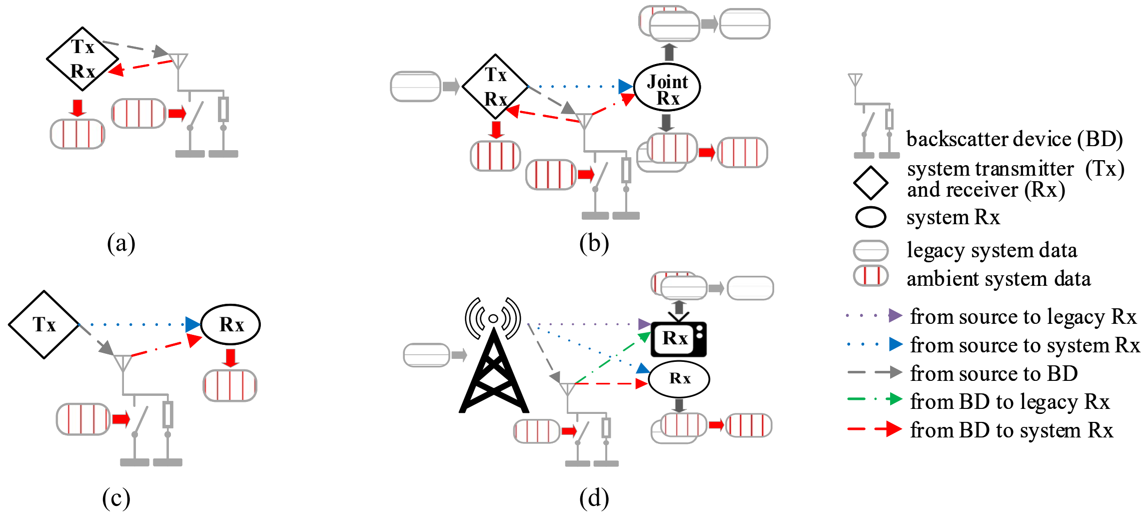

Fig. 1. Backscattering and AmBC configurations: a) mono-static backscattering; b) AmBC with a joint receiver; c) bi-static backscattering; d) AmBC with ambient and legacy receivers.

available and emerging energy harvesting technologies provide a solution for certain applications, their feasibility is limited to the use-case scenarios that can accommodate temporary energy storage and complicated radios.

Figure 1 depicts samples of backscattering communication (BC) and AmBC configurations. The mono-static BC configuration consists of a backscattering device (BD), and a co-located transmitter (Tx) and receiver (Rx) device. This configuration requires a carrier emitter, for example, for RFID or radar applications. In bi-static configuration, the Tx and the Rx are two separate devices. In AmBC, a BD modulates the ambient signal of the legacy system by scattering the RF energy impinging on its antenna in a controlled manner. An AmBC system, as shown in Figure 1, can operate in different configurations including mono-static, bi-static co-located, and bi-static dislocated configuration, while using joint receivers for both legacy and AmBC transmissions. One important feature of AmBC is that the ambient sources can be non-cooperative and completely unaware of the AmBC or can be co-operative to aid joint decoding at the receiver.

A. *Available AmBC systems*

MTC in AmBC system relies on existence of legacy systems such as LoRa, WiFi, FM radio or TV broadcast. The first approach available in the literature is to build an AmBC capable system by modulating the legacy signals using controlled scattering. Although the resultant energy variation due to operation of the BD can be used for decoding the signal when the BD data-rate is low, for high data-rate operation the systems are designed using frequency-shifting, which also enables easier mathematical analysis. This option requires a dedicated receiver to decode the data emitted by the BD. An alternative option is to alter the ambient signal from one communication technology waveform into the waveform of another technology, for instance, from continuous wave to BLE, from BLE to WiFi, from BLE to IEEE 802.15.4, to use commodity receivers to decode the backscattered signal. This option is only suitable when the deployment can satisfy the operation requirements of the commodity receivers, and does not scale well. For the sake of generality, in the remaining part of this article, we just consider the first option.

B. *Applications and opportunities*

To promote the sustainable backscatter based IoT applications, researchers from the University of Washington have developed, for instance, a living IoT platform, a battery-free high-definition video streaming system and a battery-free cellphone. The success of IoT depends on the sustainability of deployments and their resilience to the emerging application demands. In this regard, the AmBC systems benefit the overall IoT architecture in two ways: first, these systems provide a local access to ultra-low power or passive ‘things’, and second, they improve the capacity and the reliability of other wireless IoT solutions with zero or negligible cost in terms of energy and complexity. In the following, we summarize various conceptually proven application verticals of the AmBC technology such as medical science, environmental monitoring and network communications.

a) Medical applications: AmBC has rich application opportunities in healthcare because of its battery-free operation and small form-factor. An AmBC-enabled on-body and battery-less temperature sensors can be designed as a comfortable wearable gadget. A more challenging application of communicating with smart contact lens using a commodity WiFi or with Bluetooth radios have already been demonstrated. More importantly, in-vivo smart medical devices with extremely low-power and small form-factor energy harvesting components can be realized for accessing deep-tissue micro implants. The experiments have shown that implantable neural recording devices can communicate with mobile devices within a short communication distance.

b) Environmental applications: The AmBC technology has various environmental applications, for instance, wireless humidity sensing, agricultural monitoring, and indoor space sensing applications. The BDs in these applications are distributed over a large area, and thus have long distance between the ambient source and the BD. These applications utilize, for instance, the ambient FM broadcasting signals, and augment the receiver by adding relay stations to improve the signal strength.

c) Generic Machine Type Communication applications: The AmBC technology enables MTC, card to card, or even multi-hop communications [2]. The work in [3] has developed a passive LoRa-enabled AmBC system relying on opportunistic uplink and downlink piggybacking schemes to utilize intermittent LoRa signals. Moreover, the AmBC technology can promote vast applications for wearable devices.

d) Network enhancements: The AmBC technology not only improves the energy-efficiency of the IoT devices but also improves the network performance as a whole. Authors in [4] have concluded that AmBC improves the spectral efficiency of the channel as an AmBC link can co-exist with a legacy wireless system under certain conditions. Another networking enhancement provided by AmBC is on improved security as presented in [5].

III. CHARACTERISTICS OF AMBC

Since the advantages of the AmBC systems stem from the scattering mechanism used by the BD, we present the impact of the scattering mechanism on the fading and propagation channels, discuss the spectral properties of the AmBC, and address the energy-related considerations.

A. Propagation and fading

The BC channel is a concatenation of the channel from the Tx to the BD and the channel from the BD to the Rx, which is a two-way keyhole channel [4]. This type of channel has main characteristics: deeper small-scale fades than that of a conventional one-way channel even in the line of sight (LOS); keyhole characteristic remains in both LOS and non-LOS conditions. Any keyhole channel can be modeled as the cascade of two channels; *keyhole diversity* is available in a rich scattering environment caused by modulating a backscatter signal with multiple antennas. Since a backscattering channel is a spatial keyhole channel, where each RF backscattering antenna acts as a keyhole, backscatter readability is a serious problem due to deep signal fading.

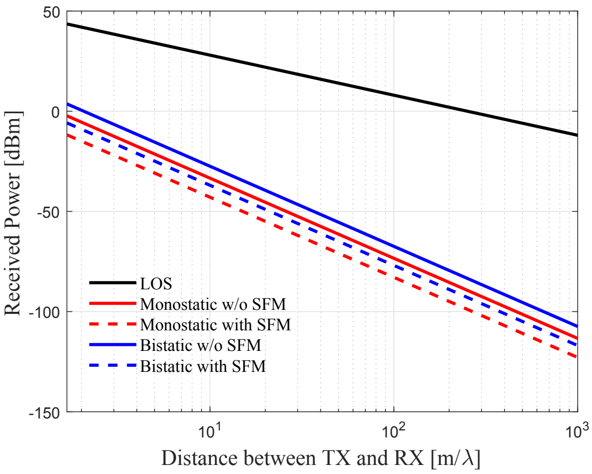

Fig. 2. Received power as a function of the separation between the Tx and the Rx for several AmBC configurations. The transmit power of the ambient source is 10 kilowatts. The SFM is 9.5 dB.

Author in [6] have validated the link budget models for mono-static and bi-static AmBC configurations. The work concludes that a close match can be achieved between the simulated and the measured values by considering different factors of backscatter signal propagation along with realistic system parameters. Different margins, slow fading margin (SFM) and fast fading margin, play a vital role in modeling the backscattering link. Figure 2 shows the link budget with and without the SFM for the monostatic and bistatic dislocated configurations, considering the BD is located in the middle of the ambient source and the receiver. The LOS curve denotes the link budget of the direct path between the ambient transmitter and the receiver. It confirms that there exists significant difference between the power of the direct path and the backscatter link. Therefore, it is a challenging task to design an AmBC receiver capable of recovering the desired signal in the presence of a strong direct path interference.

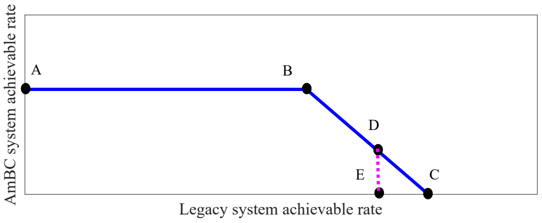

Fig. 3. An illustration of achievable rate regions: A-B-D-E for two active spectrum-sharing the spectrum, and A-B-D-C for AmBC system sharing the bandwidth with a legacy link.

B. *Spectrum efficiency enhancement*

AmBC can be viewed as a spectrum sharing method, where the AmBC device co-exists with a legacy system that generates the ambient signal. Figure 3 illustrates the two achievable rate regions. The region A-B-D-E depicts the scenario that two active transmitters sharing the spectrum. The region A-B-D-C illustrates the case of the AmBC system sharing the spectrum with a legacy system. The rate region of the AmBC case is fundamentally different in comparison with the active transmitter scenario as the AmBC device in certain conditions increases the rate of the legacy system (point C) compared to what it can achieve alone (point E) [4]. The transmission rate of the AmBC system incurs different interference to the legacy receiver. If an AmBC symbol duration is much longer than the legacy system frame duration, the legacy system is able to track the channel variations caused by the AmBC and treat AmBC signal just as an additive multipath component. Hence, AmBC can be used to improve the communication quality of the legacy system by transmitting, for example, known pilots. On the other hand, if an AmBC symbol duration is short, the legacy receiver is not able to track the channel variations caused by the AmBC device and the AmBC-modulated signal paths appear as an interference for the legacy receiver (point B).

C. *Energy harvesting and rate-energy tradeoff*

The battery-free or semi-passive tags require energy for transferring and/or decoding information operations, which can be harvested from the ambient RF signals. The amount of energy harvested from the ambient RF signals depends on the RF source, the distance between the source and the backscatter device and the time duration for harvesting. For instance, up to 61 micro Watts can be obtained from 680 MHz TV signal of a tower located 4.1 km away from a BD [7].

One of the critical problems is to achieve better trade-off between the harvested energy and the decoded information rate, as practical BD circuits are unable to decouple the RF energy required for encoding the information from the RF energy for harvesting. The schemes of allocating the RF energy, such as time splitting, static power splitting and on-off splitting, have been studied through analyzing the rate-energy curves for different scenarios [8]. It is consistent with the result in work [2], which suggests different operation modes among RF energy harvesting and information transformation according to the SNR obtained by the devices. For the BD close to the ambient Tx or to the Rx, i.e., in the high SNR region, static power splitting is preferable; while in intermediate SNR cases, the on-off splitting is the optimal scheme.

IV. CHALLENGES AND SOLUTIONS

Since AmBC systems piggyback their information onto an ambient signal in the air, the AmBC receiver operates with the signals from two sources: first the signal transmitted by the legacy system, and second, the signal modulated by the BD. This problem poses itself as the primary challenge for decoding AmBC signal, which we refer to as *direct path interference*. The direct path interference defines the signal to interference plus noise ratio (SINR) operating point for the AmBC receivers, which raises stringent constraints on the receiver design. In this section, we first present the direct path interference problem, and its available solutions. Then, we summarize three different ambient signal decoding schemes of AmBC receivers.

A. *Direct path interference*

The AmBC system deployments can be in a mono-static or bi-static configuration shown in Fig. 1. In a mono-static configuration, the receiver can be designed to mitigate the leakage of the transmitted signal. In the bi-static case, however, the backscatter-modulated signal is superimposed with the direct path signal at the receiver. In practical deployments, the direct path signal strength is several orders of magnitude higher than that of the scattered signal component. Hence, in bi-static AmBC systems, a receiver needs to operate at a large dynamic range to be able to reach acceptable performance in terms of Bit Error Rate (BER).

The analog front-end of a commodity-communication-system receiver is usually configured to capture the desired signal as good as possible. This operation utilizes the dynamic range of the analog-to-digital converter (ADC) by pushing the undesired components and noise sources to a few least significant bits. Since the AmBC signal is restrained to a few least

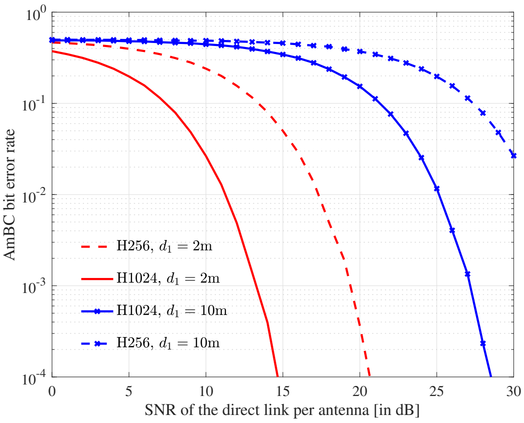

Fig. 4. BER as a function of the received SNR of the direct link.

significant bits of the ADC output, such operation, however, is not suitable for decoding the weak AmBC signal along with the strong direct signal, which results in high packet error rate. This issue can be mitigated by first eliminating the strong direct path ambient signal, and then decoding the AmBC information.

One approach to mitigate the direct path interference is to use hybrid analog-digital domain null-steering beamforming techniques [10]. The direct path signal is attenuated in the analog domain by steering the null of the multiple receiver antennas toward the direct path direction, so that the automatic gain control unit of the receiver operates at the level of the weak AmBC signal. This allows the usage of a common ADC to sample the received signal. Thereafter, the digital samples of the weak AmBC-modulated signal buried in the residual direct path signal and the noise can be decoded using a non-coherent receiver. To further improve the performance of the receiver, the BD adopts orthogonal channelization codes, for instance, Hadamard codes, to avoid requiring the knowledge of the instantaneous channel state information (CSI).

Figure 4 shows the BER of an AmBC system as a function of the received SNR per antenna of the direct link [10]. The considered carrier frequency of the ambient RF signal is 500 MHz. The linear receive antenna array has 8 elements with a half-wavelength spacing of the carrier, and the angle of arrival (AoA) estimation is carried out by using the Bartlett method [10]. The ambient RF source is located at 60°, and the backscatter is located at 90°. The notation H_M denotes a length-M Hadamard codeword and d_1 is the distance between the AmBC device and the receiver. The results confirm that the proposed novel design allows the AmBC receiver to non-coherently detect the non return to zero binary phase shift keying (BPSK) signals of the BD without decoding the ambient RF signals for a large distance between BD and Rx. The achieved BER is in the order of 0.001 without applying error correction techniques.

B. Receiver design

Receivers extract the backscatter data using the available information at the receiver. For AmBC systems, attenuating the direct path signal increases the SINR of the signal in the digital domain. However, the improvement in SINR is limited by two factors. In addition to the keyhole effect of the backscattering link, the legacy system causes the AmBC link to experience very fast fading because the unknown legacy signals might have much higher data-rate transmission compared to the rate of BD. The first factor also limits the performance of the signal processing methods adopted by the receiver, for instance, for AoA estimation and beamforming. The second factor limits the use of the coherent modulation schemes such as BPSK. The rest of this section summarizes available receiver designs for AmBC systems. We first summarize coherent (including semi-coherent) receivers, and then, the non-coherent receivers. Thereafter, recent emerging machine-learning based algorithms are presented.

1) Coherent receiver: A cooperative maximum likelihood (ML) detector can be utilized at the AmBC receiver with the availability of all the CSI. In particular, the work in [11] has proposed a coherent and a partly coherent detector for AmBC, where the CSI needs to be estimated by sending the pilot sequences from the Tx and from the BD. Such requirements limit the use-case scenarios that may allow the coherent reception in practice. Ambient signals that have been generated using OFDM modulation have a repeating structure that can be exploited in the AmBC waveform and receiver design as suggested in [12].

2) Non-coherent receiver: A non-coherent detection avoids the necessity of tracking sensitive phase knowledge of the received signal, which degrades the performance of the AmBC system in general. Considering the OOK or differential BPSK modulation schemes at the BD, several works realized non-coherent demodulation by energy detector and ML detector. Due to the error floor issue of an energy detector, coding methods have been applied to improve the BER of an energy detector, such as Manchester coding, or spread coding. In [13], we proposed a time domain covariance matrix based method that allows demodulation of BPSK data without explicit knowledge of the ambient signal phase. For constant envelope ambient RF signals, a ML detector for AmBC modulated symbols has been proposed in [9].

3) Machine learning-based receivers: In certain deployment scenarios of the AmBC systems, the receiver cannot access or estimate the CSI and the constellation of the legacy system. In such cases, machine learning methods for detecting and/or estimating some latent variables is an attractive option, since it relaxes the system design constraints. Authors in [14] have designed a receiver based Gaussian mixture model when the modulation information of the ambient signal is available at the receiver. Authors in [15] have proposed a detection method of the desired AmBC signals using classification algorithms. The design enables the AmBC system to retrieves the BPSK-modulated information with practically acceptable performance without having the knowledge of the CSI and the constellations of the legacy system. Although machine learning-based receiver designs can be used in several components of the receivers, their applications to AmBC is still in its early stage.

V. FUTURE RESEARCH TRENDS

Recent AmBC developments have shown that the technology has great potential for enabling sustainable IoT deployments. However, as the new application areas are emerging, new research trends come forth to address certain practical aspects of the technology. This section presents potential future research trends.

A. Strong direct path interference and weak AmBC signal recovery

Various AmBC signal recovery techniques proposed and studied in literature are subject to some limitations. In addition, the current designs require a large number of samples or some knowledge of the backscatter channels or the noise variance. The sample covariance matrix distance-based method in [13] also has some limitations. If the BD modulates the ambient OFDM signal at a very high rate, the backscattered path frequency response will shift to another band in the frequency domain. If the receiver has a sharp and narrow band-pass filter, the AmBC signal can be filtered out. In case of a wideband receiver, an AmBC transmission will cause severe adjacent band interference.

B. Feedback/downlink channel design

The physical layer protocol design for AmBC integration calls both for the downlink signaling channel and uplink data channel. The downlink signaling is constrained by the capabilities of the AmBC nodes to act as a receiver. For an energy detector, the symbol length used by the OOK must be much larger than the symbol length used by the legacy communication system in order to average out the under-laying modulated signal. A non-coherent receiver is likely to be simpler than a coherent one, and thus is a more attractive option for the power constrained AmBC nodes. Hence, solutions are needed to build a downlink control channel that can be superimposed on the legacy data symbol in the downlink.

C. Intermittent transmission and synchronization

For an AmBC system using legacy systems with intermittent transmissions, the ambient signal must be tracked by the BD to successfully piggyback its information. For this purpose, the BD should be time synchronized to the Tx and know in advance when to start its transmission. Such a requirement results in a challenging design problem for the battery-free devices which requires efficient algorithms instead of traditional power-hungry detectors. For instance, the ambient LoRa signals are intermittent in nature so that the BDs need to ask for novel packet detection methods to synchronize with the ambient LoRa symbols [3].

D. Smart antennas for AmBC

Multi-antenna technologies have been applied in various wireless communication systems including AmBC systems to boost the performance. The field of smart antennas for AmBC is yet relatively unexplored. Unlike the current state-of-the art solutions, the new smart antennas for AmBC systems should allow the antenna to tune to the characteristics of the ambient signal. Multiple antennas per device should be exploited in an efficient yet low complexity manner. Hence, novel antenna and device designs, communication schemes (algorithms, protocols and their implementation), and novel scalable data aggregation schemes for multi-antenna BDs are the topics for the future research.

E. Security and Privacy

The security and privacy issues are critical in all IoT applications. The special challenge in AmBC case is the limited computational and communication resources which dictates that the used authentication and encryption methods need to be lightweight. Additional security for the AmBC links can be obtained by using physical-layer security (PLS) methods. Despite, several works have investigated the PLS, higher layer security and privacy preserving protocols for RFID systems, only a little has been done for AmBC due to the power and design limitations of the low cost AmBC devices.

VI. CONCLUSIONS

The AmBC technology has the potential for revolutionizing the current IoT connectivity by enabling sustainable applications. In this article, we presented the trends of AmBC from the aspects of practical implementation, communication features and detection techniques. An overview of important challenges and the corresponding potential research for future AmBC system design have been presented. Through numerical simulation, we have demonstrated the superiority of applying hybrid beamforming and coding techniques for the AmBC system. This can be a potential solution for the large dynamic range problems suffered by a simple AmBC receiver to recover desired information.

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Ruifeng Duan [M'14] (ruifeng.duan@aalto.fi) received his M.Sc. and D.Sc.(tech.) degrees in 2008 and 2014, respectively. Since August 2014, he has been with Aalto University. His current research interests include extreme value theory, ambient backscatter communication, and ultra-reliable low latency communication.

Xiyu Wang (xiyu.wang@aalto.fi) received her B.Eng. and M.Sc. degrees in computer science in 2015 and 2018, respectively. She is currently pursuing a Ph.D. degree in Aalto University. Her research interests include machine learning for wireless communication, Internet of Things, and 5G communication. She is a grant recipient awarded by the China Scholarship Council.

Hüseyin Yiğitler (huseyin.yigitler@aalto.fi) received his B.Sc. and M.Sc. both in electrical and electronics engineering in 2004 and 2006, respectively. He received his Ph.D. from Aalto University in 2018. He holds a Post-Doctoral Researcher position at Aalto University, and taking the CTO role at Biyomod, Ankara. His research interests include RF propagation, localization and tracking, signal processing, and design and implementation of embedded (wireless) systems.

Muhammad Usman Sheikh (muhammad.sheikh@aalto.fi) received his M.Sc. and D.Sc. degrees from Tampere University of Technology in 2009 and 2014, respectively. Currently, he is working as a post-doctoral researcher at Aalto University. His general interests include network planning and optimization, future mobile technologies, 3D ray tracing, advanced antennas and innovative cellular concepts.

Riku Jäntti [SM'07] (riku.jantti@aalto.fi) received his D.Sc. degree (with distinction) in automation and systems technology in 2001. He is a full professor of communications engineering and the head of the Department of Communications and Networking at Aalto University. He is an associate editor of IEEE TVT. He is also IEEE VTS Distinguished Lecturer (Class 2016). His research interests include machine-type communications, cloud-based radio access networks, ambient backscatter communication and quantum communication.

Zhu Han [F'14] (hanzhu22@gmail.com) received his B.S. from Tsinghua University in 1997 and his Ph.D from the University of Maryland, College Park in 2003. He is a full professor in the Electrical and Computer Engineering and Computer Science Departments at the University of Houston. He received the NSF Career Award in 2010, the Fred W. Ellersick Prize of IEEE Communication Society in 2011, and the IEEE Leonard G. Abraham Prize in the field of Communications Systems in 2016. Currently, he is ACM distinguished member. He was a 1 percent highly cited researcher since 2017 according to the Web of Science.