Guest Editorial
5G Wireless Communications With High Mobility

Ruisi He, *Senior Member, IEEE*, Fan Bai, *Fellow, IEEE*, Guoqiang Mao, *Fellow, IEEE*, Jérôme Härri, *Member, IEEE*, and Pekka Kyösti

THE fifth generation (5G) wireless communication networks are expected to support communications with high mobility, e.g., with a speed up to 500 km/h. Hence 5G communications will have numerous applications in high mobility scenarios, such as high speed railways (HSRs), vehicular ad hoc networks, and unmanned aerial vehicles (UAVs) communications [1]–[3]. The 5G systems will provide advanced communication platforms enabling reliable transmission for the Wireless Train Backbone (WLTB) or Wireless Train Control & Management System (WTCMS) [4], [5]. They will also enable new services or enhancements for vehicular communications in Intelligent Transportation System (ITS) [6]–[9]. The coordination and swarming control for UAVs will also benefit from 5G capabilities, as UAV-based 5G infrastructure modeling and improvement have begun receiving attention [10]. In general, high mobility communication is not only about how large is the maximum speed, it is more about the challenges caused by mobility. In high mobility scenarios, a wireless channel is rapidly time varying, Doppler shifts and spreads can be much larger than those in cellular communications, and if modeled statistically, the channel will be non-wide-sense stationary (non-WSS) over a short time period. In addition, network topology can change quickly, and switching among base stations (BSs) and/or peer nodes can be more frequent, not forgetting 5G challenges in cross-border mobility [11].

Even though mobile communications have been well developed during recent decades, many technical challenges still exist for wireless networks with high mobility support. Since 5G communications have ambitious requirements in many aspects such as data rate, reliability, latency, etc., investigations of the impact of high mobility on wireless system performance is of significant importance, as the time-varying radio channel can still be a major bottleneck to achieving 5G requirements. In order to provide high mobility support to 5G, there are still a number of technical issues to be investigated. This includes non-stationary wireless channel measurements and modeling theory [12], advanced signal processing for multiple physical and data link layer operations when high mobility is involved, such as channel estimation and equalization in time-varying fading channels, Doppler estimation and compensation techniques as well as Doppler diversity schemes [13]. It also includes transceiver structures, waveform and coding that can exploit the properties of high mobility, signal processing techniques that can harvest the benefits (e.g., Doppler diversity) and mitigate the impairments (e.g., carrier frequency offsets) in high mobility environments [14], error correction schemes, efficient mobility management and user mobility modeling [15], ultra-reliable and/or low-latency, massive MIMO and millimeter-wave technologies under high mobility scenarios, and new network architectures with high mobility support [16], [17]. Moreover, 5G and beyond challenges and applications for new vertical sectors subject to high mobility [18]–[24], such as railway, UAV, or automotive are still open.

All the above introduces challenges to realize reliable 5G communications with high mobility. Many mobility related research problems still exist, and can become major obstacles to the development of 5G and beyond. Therefore, this special issue aims to bring together researchers, industry practitioners, and individuals working on these related areas to share their new ideas, latest findings, and state-of-the-art results. The special issue attracted 77 high quality submissions. All articles received at least three reviews and the accepted articles went through at least one revision round. We eventually accepted 18 technical articles covering various aspects of 5G wireless communications with high mobility, categorized into five focus areas: "5G Network Architecture, Optimization, and Performance with High Mobility Support," "UAV Assisted Technologies for 5G High Mobility Communications," "Channel Coding, Estimation and Detection Techniques for 5G High Mobility Channels," "Massive MIMO for 5G High Mobility Communications," and "Millimeter-Wave based Technologies for 5G High Mobility Communications." The contributions of the articles are categorized and described as follows.

A. 5G Network Architecture, Optimization, and Performance With High Mobility Support

The article "A First Look at Disconnection-centric TCP Performance on High-speed Railways" conducts large-scale disconnection-centric measurement study of TCP performance

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over LTE on HSR. The authors perform extensive data collection obtaining 378.3 GB data collected over 56639 km of railroad, and measure some important performance metrics such as TCP goodput, latency and loss rate across different congestion control algorithm, mobile carrier, and different train speed. The LTE disconnection taxonomy is further developed. The findings in the article show the networking performance on the HSR environment, as well as identify several root causes of performance inefficiencies.

The article "Reservation Service: Trusted Relay Selection for Edge Computing Services in Vehicular Networks" develops a reservation service framework to enhance the edge service experience in vehicular networks. A trusted relay selection scheme is proposed for edge services to facilitate the proposed reservation service framework. The authors design the request relay mechanism based on the dynamic traffic status to guarantee the efficiency of the relay process. Then, the reputation management mechanism is presented to constrain the behaviors of vehicles. A reputation-based auction approach is further proposed to select relay vehicles to reduce the cost for the relay service. The results show that the proposed reservation service framework can lead to the lowest cost compared with the conventional schemes.

The article "Safety-Oriented Resource Allocation for Space-Ground Integrated Cloud Networks of High-Speed Railways" proposes a space-ground integrated cloud railway network consisting of space and ground cloud layers, where in the space, baseband units of low earth orbit satellites are collected and centrally-managed by geostationary earth orbit (GEO) satellites. To improve the mobility support, the authors establish an additional backup space C-plane connection between trains and GEO satellites. Under the architecture with diverse network resources, a safety-oriented resource allocation scheme is developed based on both the resource allocation priority of safety services and the network handover costs to deliver the safety-oriented services. Simulation results demonstrate that the proposed scheme can always meet the transmission requirements for safety services in HSRs.

The article "Performance Analysis of 5G Mobile Relay Systems for High-Speed Trains" investigates an asymmetric 5G mobile relay system for HSRs, where the mobile relay is deployed at the train to avoid high penetration loss of the direct link between the BS and the users (UE) inside carriages. The sub-6GHz frequency is utilized for the BS-relay link while the relay-UE link adopts the millimeter wave frequency. Therefore, the BS-relay link and the relay-UE link experience different fading. Moreover, the channel aging effect is considered due to the high mobility in HSRs. The authors first study the exact statistical characterizations of the end-to-end signal-to-noise ratios. Then, they derive exact closed-form expressions for some key performance metrics. The effects of channel aging, system and channel parameters on the mobile relay system are analyzed. The investigation shows that the mobile relay system is a promising network architecture for HSR communications and can provide steady and high-speed data provisioning to passengers against the significant bottleneck of channel aging.

The article "Deep Reinforcement Learning for Dynamic Uplink/Downlink Resource Allocation in High Mobility 5G HetNet" investigates the channel model in the high mobility and heterogeneous network, and proposes a novel deep reinforcement learning based intelligent Time Division Duplex (TDD) configuration algorithm to dynamically allocate radio resources in real-time. In the article, the deep neural network is employed to extract the features of the complex network information, and the dynamic Q-value iteration based reinforcement learning with experience replay memory mechanism is proposed to adaptively change TDD Up/Down-link ratio by evaluated rewards. The simulation results in the article show that the proposal achieves significant network performance improvement in terms of both network throughput and packet loss rate, comparing with conventional TDD resource allocation algorithms.

B. UAV Assisted Technologies for 5G High Mobility Communications

The article "Optimal UAV Caching and Trajectory in Aerial-Assisted Vehicular Networks: A Learning-Based Approach" investigates the UAV-aided edge caching to assist terrestrial vehicular networks in delivering high-bandwidth content files. Aiming at maximizing the overall network throughput, the authors formulate a joint caching and trajectory optimization problem to make decisions on content placement, content delivery, and UAV trajectory simultaneously. A deep supervised learning scheme is proposed to enable intelligent edge for real-time decision-making in the highly dynamic vehicular networks. The authors then design a deep supervised learning architecture of the convolutional neural network (CNN) to make fast decisions online. With the CNN-based model, a function which maps the input network information to the output decision can be intelligently learnt to make timely inference and facilitate online decisions. Extensive trace-driven experiments are conducted to demonstrate the performance.

The article "Energy Efficiency Optimization for NOMA UAV Network with Imperfect CSI" focuses on system performance optimization in non-orthogonal multiple access UAV network considering imperfect CSI between the UAV and users. A suboptimal resource allocation scheme including user scheduling and power allocation is designed for maximizing energy efficiency. Because of the nonconvexity of optimization function with a probability constraint for imperfect CSI, the original problem is converted into a non-probability problem and then decoupled into two convex subproblems. First, a user scheduling method is applied in the two-side matching of users and subchannels by the difference of convex programming. Then, based on user scheduling, the energy efficiency in UAV cells is optimized through a suboptimal power allocation algorithm by successive convex approximation method. The simulation results prove that the proposed algorithm is effective compared with existing resource allocation schemes.

The article "3D Channel Tracking for UAV-Satellite Communications in Space-Air-Ground Integrated Networks" explores the 3D channel tracking for a Ka-band UAV-satellite communication system. The authors firstly propose a statistical dynamic channel model called 3D two-dimensional Markov model for the UAV satellite communication system by exploiting the probabilistic insight relationship of both hidden value vector and joint hidden support vector. Furthermore, a novel 3D dynamic turbo approximate message passing algorithm is derived to recursively track the dynamic channel with the 3D two-dimensional Markov model priors. Numerical results show that the proposed algorithm achieves superior channel tracking performance to the state-of-the-art algorithms with lower pilot overhead and comparable complexity.

The article "Access Points in the Air: Modeling and Optimization of Fixed-Wing UAV Network" models and evaluates the performance of a fixed-wing UAV network, where UAV access points (APs) provide coverage to ground users (GUs) with millimeter wave backhaul. Firstly, it shows that network spatial throughput (ST) is independent of the hover radius under real-time closest-UAV association, while linearly decreases with the hover radius if GUs are associated with the UAVs, whose hover center is the closest. Secondly, network ST is shown to be greatly degraded with the over-deployment of UAV APs due to the growing air-to-ground interference under excessive overlap of UAV cells. Finally, aiming to alleviate the interference, a projection area equivalence (PAE) rule is designed to tune the UAV beamwidth. It is found that network ST can be sustainably increased with growing UAV density and independent of UAV flight altitude if UAV beamwidth inversely grows with the square of UAV density under PAE.

C. Channel Coding, Estimation and Detection Techniques for 5G High Mobility Channels

The article "Multi-dimensional Spectral Super-Resolution with Prior Knowledge with Application to High Mobility Channel Estimation" is concerned with estimation of multiple frequencies with prior knowledge from incomplete and/or noisy samples. Suppose that it is known a priori that the frequencies lie in some given intervals, the authors develop efficient super-resolution estimators by exploiting such prior knowledge based on frequency-selective atomic norm minimization. The multidimensional Vandermonde decomposition of block Toeplitz matrices is studied restricting the frequencies to lie in given intervals. The authors then propose to solve the frequency-selective atomic norm minimization problems for the low-rank spectral tensor recovery by converting them into semidefinite programs based on the multidimensional Vandermonde decomposition. Extensive simulation results are presented to illustrate the high performance of the proposed methods.

The article "Decoding Binary Linear Codes over Channels with Synchronization Errors" develops a systemic approach to decode general binary linear codes over binary symmetric channels with synchronization errors in which the lack of synchronization is modeled as the deletion channel model. The maximum likelihood decoding problem for binary linear codes over deletion channels is first formulated as a nonlinear optimization problem, in which a set of linear constraints are employed to characterize the input-output relationship of a deletion channel. It turns out that both the objective function and the constraints of this optimization problem are nonlinear, which poses significant challenges against the design of efficient decoding algorithms. As a remedy, the authors first replace the nonlinear objective function of this optimization problem via a lower bound, and prove this lower bound is a linear function in the special case that the input is binary. The linear programming relaxation approach is applied to obtain an approximate solution to the proposed nonlinear optimization problem. It is found that the proposed decoding algorithm can achieve close-to-optimal bit error rate decoding performance at moderate computational complexity.

The article "Backscatter Aided Wireless Communications on High Speed Rails: Capacity Analysis and Transceiver Design" introduces backscatter technology into HSR wireless communications, which can address the fast time-varying channel and large penetration losses, and yet have low complexity of signal processing and low cost of circuit implementation compared with traditional solutions such as relaying or beamforming. The authors propose a backscatter aided wireless transmission (BAWT) scheme and demonstrate that it outperforms the existing direct wireless transmission (DWT) scheme. The upper and lower bounds of channel capacity are derived for BAWT and the authors prove that it exceeds that of DWT on certain conditions. They also propose the transceiver design for both BAWT and DWT, including joint carrier frequency offset and channel estimator, and signal detector. It is found that BAWT, rather than DWT, can obtain the channel statistical information in practical applications due to fixed train antennas and unchanged tracks, which can be utilized to facilitate channel estimation.

The article "Iterative Doppler Frequency Offset Estimation in Satellite High-Mobility Communications" proposes a novel method to solve the high Doppler frequency offset and low signal-to-noise ratio circumstances in satellite high-mobility communications. The method is named GP-MASO-MLE, which consists of a coarse estimation algorithm based on the Gaussian process (GP) model and Newton-Raphson method, and a fine correction algorithm based on the improved maximum likelihood estimation (MLE) jointly with turbo decoding iterations. Simulation results show that the proposed algorithm can approach to the bit error rate performance bound of ideal Doppler frequency offset correction within 0.1 dB, which can be well applied in code-aided satellite high-mobility communication systems. In addition, the computational complexity of the proposed algorithm is lower than other traditional turbo synchronization algorithms.

D. Massive MIMO for 5G High Mobility Communications

The article "High-Mobility Massive MIMO with Beamforming Network Optimization: Doppler Spread Analysis and Scaling Law" considers the high-mobility massive MIMO systems, where Doppler shifts compensation can usually be combined with beamforming network to effectively suppress the channel time variation, and the key of the beamforming network lies in the optimization of the common configurable amplitudes and phases (CCAP) parameter. The authors demonstrate that the CCAP parameter optimizes the beamforming network to reduce channel time variation and approximates in a semi-sinusoidal form. Then, a scaling law between the asymptotic Doppler spread and the number of antennas M is derived, showing that the asymptotic Doppler spread decreases at a rate of 1/M. It is proved that the optimal CCAP parameter obtained from Jakes' channel model can be directly applied to more general cases, while the inverse proportionality between the resulting asymptotic Doppler spread and the number of antennas remains valid. Numerical results confirm the correctness of the theoretical analysis in the article.

The article "Addressing the Curse of Mobility in Massive MIMO with Prony-Based Angular-Delay Domain Channel Predictions" proposes a novel form of channel prediction method to deal with the high mobility in massive MIMO, named Prony-based angular-delay domain (PAD) prediction, which is built on exploiting the specific angle-delay-Doppler structure of the multipath. In particular, the method relies on the high angular-delay resolution which arises in the context of 5G. The theoretical analysis shows that when the number of BS antennas and the bandwidth are large, the prediction error of the PAD algorithm converges to zero for any UE velocity level, provided that only two accurate enough previous channel samples are available. Moreover, when the channel samples are inaccurate, the authors propose to combine the PAD algorithm with a denoising method for channel estimation phase based on the subspace structure and the long-term statistics of the channel observations. Simulation results show that under a realistic channel model of 3GPP in rich scattering environment, the proposed method is able to overcome this challenge and even approaches the performance of stationary scenarios where the channels do not vary at all.

E. Millimeter-Wave Based Technologies for 5G High Mobility Communications

The article "Air-to-Ground Wireless Links for High-Speed UAVs" designs robust air-to-ground (A2G) wireless links for high speed UAVs, where conjunct power control is developed together with switched beamforming to maximize the power efficiency and minimize the fluctuation of A2G wireless links of millimeter wave (mmWave) signal transmission. The authors first present channel models for A2G wireless links of high-speed UAVs, which can be virtually seen as MIMO channels. To maximize the power efficiency, a conjunct power control problem is formulated to allocate powers for wireless links between antenna arrays on UAVs and APs. For switched beamforming, beamformers are designed to provide a certain time-invariant signal-to-interference-plus-noise ratio (SINR) to minimize the SINR fluctuation of A2G wireless links. From theoretical analysis and numerical results, it is shown that the proposed architecture is able to provide robust and high quality A2G wireless links for high-speed UAV mmWave communication systems.

The article "Empirical Study on Directional Millimeter-Wave Propagation in Railway Communications Between Train and Trackside" presents empirical studies based on the raw mmWave data obtained from extensive HSR measurement campaigns. Two classic environments in railway traffic are considered: the traditional train station and the HSR tunnel. Analyses of the mmWave channel measurement results at 37 GHz, including the received signal strength, power delay profile, root-mean-squared delay spread, and channel non-stationarity are presented. Based on the measured data, the authors further generalize the widely-used close-in free space path loss model. Finally, the performance gap between perfect dynamic beamforming and fixed beamforming is evaluated based on the generalized model and the measured data. The results show that the average throughput of dynamic beamforming is only 4% higher than that of fixed beamforming in the HSR tunnel, but 21% higher in the train station when severe beam misalignment is present.

The article "Network Massive MIMO Transmission Over Millimeter-Wave and Terahertz Bands: Mobility Enhancement and Blockage Mitigation" investigates network massive MIMO transmission for mmWave/THz downlink in the presence of mobility and blockage. Considering the mmWave/THz propagation characteristics, the authors first propose to apply per-beam synchronization for network massive MIMO to mitigate the channel Doppler and delay dispersion effects. Then network massive MIMO downlink transmission strategies are investigated with only the statistical channel state information available at the BSs. It is found that the beam domain is favorable to perform transmission, and BSs can work individually when sending signals to user terminals. Based on these insights, the network massive MIMO precoding design is reduced to a network sum-rate maximization problem with respect to beam domain power allocation. By exploiting the sequential optimization method and random matrix theory, an iterative algorithm with guaranteed convergence performance is further proposed for beam domain power allocation. Numerical results indicate that the proposed network massive MIMO transmission approach with the statistical channel state information can effectively alleviate the blockage effects and provide mobility enhancement over mmWave and THz bands.

By compiling these articles, we hope to enrich our readers and researchers with respect to 5G high mobility wireless communication techniques. We sincerely thank all the authors and reviewers for the tremendous efforts, and of course the Editor-in-Chief, Senior Editors and Staff Members of IEEE JSAC for their great help. Finally, we hope that readers of this special issue will find it to be useful to them in their work.

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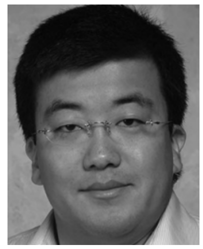

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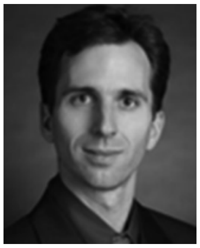

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