Special Issue—Advances in Molecular Communications: Theory, Experiment, and Application

MOLECULAR communications (MC) broadly defines information exchange using (bio-)chemical signals over multiple scales. The research in this area addresses various fields where MC plays an important role. Notable examples include 1) the modeling of living systems, which aims to gain new insights into biological systems; 2) their interface with the outer world, aiming to develop techniques to control biological systems; and 3) synthetic MC, focusing on the design, analysis, and implementation of human-made MC systems at different scales.

In recent years, the Workshop on Molecular Communications (https://molecularcommunications.eu) has become an important annual event in the community where researchers from various disciplines come together to present and discuss their latest research results. The fifth version of this event was planned to be held from 18 – 20 May 2020 in Tampere, Finland. However, due to the global outbreak of the coronavirus disease 2019 (COVID-19), we decided to cancel the workshop this year. We also agreed to not go for an online event, since the lively exchange among the participants is an important part of the workshop. At the time when we decided to cancel the event, the submission process was already completed, so we were looking for a way to publish the most significant contributions, and decided to organize a special issue in the IEEE TRANSACTIONS ON MOLECULAR, BIOLOGICAL AND MULTI-SCALE COMMUNICATIONS (T-MBMC). We would like to thank the Editor-in-Chief Prof. Chan-Byoung Chae for fully supporting this idea from the beginning. Since the workshop only required the submission of a 2-page abstract, we asked the authors to extend their submitted abstracts to letter submissions for T-MBMC. After a standard peer-review process, we selected eight papers for inclusion in this special issue. As briefly summarized below, the papers address important MC research themes, such as simulation, experiments, and theoretical design/analysis of synthetic MC systems as well as modeling of biological systems.

The first two papers address simulation and experimental issues in macroscale MC. In the paper "Using Vector Fields for Efficient Simulation of Macroscopic Molecular Communication," Stratmann *et al.* present an efficient simulation approach for macroscale MC systems with complex flow profiles. The proposed Pogona simulator first computes a vector field of the flow characteristics using computation fluid dynamics (CFD) simulations. Then, the vector field is used in a particle-based simulation, which simulates the information transmission using signaling particles. The simulation results are successfully validated against wet-lab measurements. Moreover, the simulation of binary information transmission using on-off keying (OOK) and pulse position modulation (PPM) is demonstrated, recreating practical effects such as intersymbol interference (ISI). The proposed simulator complements various diffusion- and uniform flow-based simulators by enabling different flow speed vectors at every point in space.

In the paper "Investigation of Multiple Fluorescent Dyes in Macroscopic Air-Based Molecular Communication," Damrath *et al.* present an air-based macroscopic MC testbed using fluorescent dye compounds, namely Uranine and Rhodamine 6G, as information carriers. The testbed uses an industrial sprayer, a 2 m long tube, and a high-speed camera as transmitter, transmission channel, and receiver, respectively. The authors implemented and analyzed OOK, molecular concentration shift keying (MCSK), and molecular shift keying (MoSK). The latter two modulation schemes can be used to improve the error performance and/or increase the bit rate, exploiting the additional degree of freedom in the form of different colors of the signaling particles. The authors showed that a bit rate of 40 bit/s over a distance of 2 m is possible. The proposed platform also offers the opportunity for a first practical implementation of multi-user communication.

The following three papers explore the modeling of biological systems based on MC paradigm. In the paper "Larger Connection Radius Increases Hub Astrocyte Number in a 3-D Neuron-Astrocyte Network Model," Lenk *et al.* investigate the effect of the astrocyte network topology on neuronal network activity. Astrocytes, a glial cell type in the brain, are tightly connected to neurons, and thus have bidirectional communication. In the study, they varied the distance between pairs of astrocytes in a 3-D space. Using a graph theory approach, the results indicate that a shorter distance between two cells yielded a higher number of active astrocytes and shorter paths. The number of connected cell pairs was instead lower. Thus, longer distances between cells suggest a centralized information transmission.

In the paper "Intercellular Communication as a Series of Narrow Escape Problems," Hughes *et al.* describe the intercellular exchange of nutrients and signals in plants as a narrow escape problem. Plant growth, development, and responses to the environment all depend on intra- and intercellular transport across membranes. The coordination of cellular programs requires the information exchange between cells and many of

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these signals are thought to go through specialized channels called plasmodesmata, which enable symplastic connectivity between cells. Computing how diffusing molecules in a cell find these exits can be described as a narrow escape problem. Analytical solutions to such problems exist but only for idealized geometries such as spheres. Here, the authors investigate the applicability of such idealized geometries for studying MC in plant tissue. Their initial results suggest that a volumetric correction factor can be used to scale analytical narrow escape solutions to non-spherical geometries.

In the paper "Modeling the Role of Inter-Cellular Communication in Modulating Photosynthesis in Plants," Awan *et al.* investigate the impact of MC on the process of photosynthesis. They build a system model that considers an external stimulus and plant-internal components to capture the key processes of photosynthetic reactions and transport in the form of diffusion. Numeral solutions are developed for solving this intercellular MC description of a core biological process, demonstrating the importance of communication in plants.

Finally, the last three papers address theoretical aspects in the design and analysis of synthetic MC systems, including the analysis of the channel capacity and the design of new signaling and transmission schemes. In the paper "Bounds on the Constrained Capacity for the Diffusive Poisson Molecular Channel With Memory," Ratti *et al.* present analytical upper and lower bounds on the constrained channel capacity of a diffusion-based MC system with a point transmitter and a fully absorbing spherical receiver, where the received signal is approximated as a Poisson random variable (i.e., Poisson channel). Through numerical evaluations of the derived expressions, it is shown that the channel capacity has a non-proportional decrease as the level of ISI increases. Moreover, for binary modulation schemes the bounds are quite tight, so accurate estimation of the channel capacity is possible. In contrast, for non-binary modulation schemes, the bounds are looser and the channel capacity estimate becomes less accurate with increasing ISI.

In the paper "Equilibrium Signaling in Spatially Inhomogeneous Diffusion and External Forces," Egan *et al.* present a new signaling scheme, so-called equilibrium signaling, which enables the derivation of simple expressions for the receiver statistics even in complex MC environments. These expressions can be used to obtain a near-optimal detection rule for sufficiently large symbol intervals. The authors apply this approach to an MC system with reflective boundaries, a passive receiver, a spatial inhomogeneous diffusion coefficient, and external forces. Through numerical results it is shown that the equilibrium statistics are already obtained for moderate symbol intervals.

In the paper "TDMA-MTMR-Based Molecular Communication With Ligand-Binding Reception," Rudsari *et al.* introduce a framework for time division multiple access (TDMA)-based MC with multiple transmitters and a single receiver. Each transmitter sends a specific type of molecule and the receiver can receive different types of molecules. Moreover, the reception process is based on ligand-binding reception and the receiver has a switching delay. The authors study the influence of the ISI length on the signal-to-interference ratio. Moreover, different drug release management methods are studied for the proposed framework, and it is shown that it significantly improves the performance in terms of bit error rate compared to state-of-the-art methods.

As summarized above, this special issue addresses important research questions in the emerging and expanding field of MC. The collected papers on the one hand highlight recent results in MC research and on the other hand provide directions for possible future research. To conclude the editorial remarks, we would like to thank Prof. Chan-Byoung Chae, Editor-in-Chief of T-MBMC, to allow us to organize this special issue and for his support. Moreover, we also would like to thank Christina Tang-Bernas, Editorial Assistant of T-MBMC, for her help and guidance throughout the process of creating this special issue. Finally, we would like to thank all authors and reviewers that contributed to this special issue.

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