

Guest Editorial

Special Section on Graph Theory and Its Application in Vehicular Networking

THE LAST TWO decades have witnessed unprecedented growth in telecommunications, particularly in the area of wireless communications. This development in telecommunications opens doors to many sophisticated complex systems, e.g., social networks, smart grids, vehicular networks, and sensor networks, which previously were not feasible. Graph theory is among the most widely used tools for modeling and analyzing the many types of interactions, relations, and dynamics in these systems. Many problems of practical interest can be represented by graphs.

The use of graph theory in vehicular networks or, more broadly, highly dynamic networks is of particular interest. The complex interactions among vehicles, between vehicles and roadside infrastructure, combined with the high mobility of vehicles and fast changing network topology, present some unique challenges in network modeling and performance analysis, network design, resource management, communication protocol development, security protocol design, and localization.

This Special Section aims at highlighting recent advances in graph theory that are applicable to highly dynamic networks, particularly vehicular networks, identifying challenges in the area and presenting possible solutions, and furthermore unveiling the significant potential of graph theory in the domain of vehicular networks. We received a total of 22 paper submissions, and all of them were of exceptionally high quality. Unfortunately, we are only able to accept eight papers for publication in this Special Section due to space limitations.

The paper titled “Application of Graph Theory to the Multicell Beam Scheduling Problem” by Dartmann *et al.* applies combinatorial optimization techniques to joint optimization of the beamforming vectors, power control, and beam scheduling along with multiuser scheduling to improve the downlink transmission in a multicell network where performance is limited by intercell interference. This joint optimization problem is called the beam scheduling problem in the paper, which is formulated as a graph-theoretic problem, more specifically, as a multidimensional assignment problem. The authors further propose four algorithms, each having different advantages, to solve the problem.

The paper titled “Interference Graph-Based Resource-Sharing Schemes for Vehicular Networks” by Zhang *et al.* studies the resource sharing problem in vehicular ad hoc networks (VANETs) using an interference graph-based approach. Both vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) links are considered. They show that better sum rates can be achieved using the graph-based approach, which allows V2V and V2I links to coexist, compared with orthogonal communi-

cations. Further, the proposed algorithm is proven to have low complexity, and simulation results corroborate their findings.

The paper titled “A Graph-based Cooperative Scheduling Scheme for Vehicular Networks” by Zheng *et al.* uses a graph-theoretic approach to solve the cooperative scheduling problem in VANETs. The authors suggest the use of a bipartite graphical model to efficiently find high-performing scheduling schemes for V2I and V2V links and both one- and two-hop connections. Their algorithm is derived from the polynomial-time Kuhn–Munkres algorithm, which makes it much more efficient than an exhaustive search, with almost the same performance, as is shown in simulation results. Through a comparison with non-cooperative schemes, it is also shown that cooperative communication can significantly improve the throughput in VANETs.

The paper titled “Adaptive Traffic Signal Control with Vehicular Ad hoc Networks” by Pandit *et al.* proposes to use VANETs to collect and aggregate real-time speed and position information on individual vehicles to optimize traffic signal control at road intersections. The conflicts among traffic movements at a road intersection are modeled using a conflict graph. On that basis, the traffic signal control problem is transformed into and solved as a job scheduling problem on processors. An online algorithm, called the oldest-job-first algorithm, is presented to minimize the delay across the intersection. The algorithm is shown to have a delay less than or equal to twice the delay of an optimal offline scheduling algorithm with perfect knowledge of traffic arrivals. The performance of the algorithm has also been studied using simulations.

The paper titled “Tour Planning for Mobile Data-Gathering Mechanisms in Wireless Sensor Networks” by Ma *et al.* considers the use of single or multiple mobile sensors to patrol through a static sensor network to gather data with the objective of minimizing the length of each data gathering tour. For the single mobile sensor case, the problem is solved by first determining a set of points, termed polling points, to visit during the tour and then by designing an optimal tour with minimal length to visit all these polling points. The second problem is similar to the well-known traveling salesman problem. In the paper, the problem is formulated as a mixed-integer programming, and a spanning-tree covering algorithm is proposed to solve the problem. The case of multiple mobile sensors is solved by letting the sensors traverse several shorter subtours concurrently.

The paper titled “Analysis of Wireless Localization in Non-Line-of-Sight Conditions” by Liu and Lee presents an analysis of the mobile user localization problem when non-line-of-sight (NLOS) beacons are involved. It is shown that, although NLOS paths cause problems for conventional localization algorithms, they are essential for localization, in particular if a user is outside the convex hull of the beacons. Shortcomings of existing algorithms are pointed out, and an improved algorithm is

proposed, which includes an efficient scheme to detect whether a user is inside the convex hull. Detailed simulations on a cellular-type network confirmed the theoretical findings.

The paper titled “An Evolving Graph-Based Reliable Routing Scheme for VANETs” by Eiza and Ni uses the theory of evolving graphs to capture the dynamics of the communication graph in VANETs. The evolving graphs are based on a novel link reliability model that explicitly takes into account vehicular movements. They are used to find reliable routes that satisfy quality-of-service constraints. Simulation results are provided, which indicate that the proposed routing scheme outperforms other protocols in the literature. One main advantage is that route requests do not need to be broadcast each time a new route needs to be discovered.

The paper titled “Graph-Based Metrics for Insider Attack Detection in VANET Multihop Data Dissemination Protocols” by Dietzel *et al.* considers the problem of insider attack detection in VANETs by exploiting redundant information dissemination. More specifically, if multiple packets are received from both honest and malicious vehicles, inconsistency in the received information makes it possible to detect the attacker. In the paper, three graph-based metrics are proposed to gauge the redundancy. Extensive simulations are carried out to validate the three metrics and to evaluate the potential of data redun-

dancy as a possible approach to future data integrity protection methods.

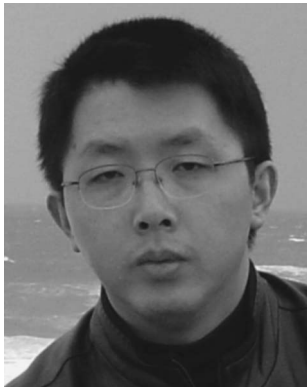
In conclusion, this Special Section includes eight papers that cover the use of graph theory in resource management, tour planning, localization, routing, and network security. We hope that these papers stimulate new research in graph theory that can lead to both theoretical advances and practical applications.

ACKNOWLEDGMENT

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Dr. Haenggi served as a Distinguished Lecturer for the IEEE Circuits and Systems Society from 2005 to 2006, as a General Cochair for the International Workshop on Spatial Stochastic Models for Wireless Networks in 2009 and for the Center for Discrete Mathematics and Theoretical Computer Science Workshop on Connectivity and Resilience of Large-Scale Networks in 2012, and as a Technical Program Committee Cochair for the Communication Theory Symposium of the IEEE International Conference on Communications in 2012. He served as a member of the Editorial Board of the *Elsevier Journal of Ad Hoc Networks* from 2005 to 2008, as an Associate Editor for the IEEE TRANSACTIONS ON MOBILE COMPUTING (TMC) from 2008 to 2011 and for the *Association for Computing Machinery Transactions on Sensor Networks* from 2009 to 2011, and as a Guest Editor for the IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS from 2008 to 2009. He is currently a Steering Committee Member of TMC. He received the ETH medal for both his M.Sc. and Ph.D. theses, the CAREER award from the U.S. National Science Foundation in 2005, and the IEEE Communications Society Best Tutorial Paper Award in 2010.