GUEST EDITORIAL

MULTIHOP CELLULAR: FROM RESEARCH TO SYSTEMS, STANDARDS, AND APPLICATIONS


YING-DAR LIN


YU-CHING HSU


MAINAK CHATTTERJEE


THOMAS KUNZ

It has been more than a decade since the multihop cellular network (MCN) architecture was first proposed and analyzed in 2000 [1]. As the transmission range decreases k times, the number of simultaneous transmissions and hop count increase by k^2 times and k times, respectively, which leads to k times cellular capacity increase. Fundamental research projects have demonstrated the benefits of MCN in terms of system capacity, service coverage, and network connectivity. Many special issues have been devoted to this stream of research [2–6]. The actual concept behind the MCN architecture could be regarded as a hybrid of mobile ad hoc networks (MANETs) and cellular networks. This concept of "relaying within a cell" also pushed standard bodies to consider solutions embedded with mesh or ad hoc architectures, such as IEEE 802.11s [7], IEEE 802.15.5 [8], and IEEE 802.16j [9]. Now, in the recent standards of the Third Generation Partnership Project (3GPP), Proximity-Based Services (ProSe) [10, 11] related work items also cover the MCN concept. In addition to device-to-device (D2D) direct communications, user equipment (UE)–UE relay and UE–network relay are also supported features. Both infrastructural and infrastructureless architectures are considered. Among many use cases, the most urgent one is public safety. These show that MCN architecture realization is ongoing.

FROM STANDARDS TO SYSTEMS AND APPLICATIONS

From another aspect, there are various radio access technologies (RATs) enabling pervasive communications for people and devices to meet requirements in mobility, spectrum, and transmission distances. When devices equipped with single/multi-RATs reside in a local spot, considering cost effectiveness, bandwidth aggregation, and power saving, a multi-RAT MCN could be constructed by those devices and the infrastructure. As shown at Mobile World Congress 2013 in Barcelona, limited to the simple I/O interface of some devices, near field communication (NFC) could be used to trigger Bluetooth or Wi-Fi Direct communication for big file transmission, which might further trigger other communications for cloud access. As Wi-Fi-only devices could have Internet access via 3GPP/Wi-Fi dual-mode smartphones, multi-RAT MCN now offers more interesting service models and is starting to be applied to the real world.

After much research on protocols and architectures for the IEEE series, specifications have been created for single-RAT MCN based on analytical models and simulations, and other issues related to implementation, deployment, and operations have emerged. From the 3GPP aspect, many research issues are still pending, such as D2D discovery, path switching between direct/infrastructure link, ID allocation and mapping, authentication, and group management. For multi-RAT MCN, further research has to be done considering the RAT capabilities of devices. New business models, such as social networking, advertising, and machine-to-machine communications, could be foreseen.

IN THIS ISSUE

This Feature Topic serves as a state-of-the-art snapshot of these exciting developments. We present five original articles describing the current standardization status of 3GPP, D2D discovery, resource allocation for D2D communications, synchronization issues in relay-aided MIMO environments, and a dynamic graph framework for MCN modeling. Their brief summaries are listed below. We hope readers enjoy the interesting and insightful articles in this issue.

ARCHITECTURE IN 3GPP

In addition to IEEE series standards, MCN is an ongoing topic at 3GPP. Because of the fundamental differences, such as network architecture and management mechanisms, many issues need new consideration at 3GPP. "Direct Mobile to Mobile Communication: Paradigm for 5G" explains the architectural and technical challenges for D2D communications in the 3GPP standard. From the radio access network (RAN) aspect, modulation, frame structure, synchronization, hybrid automatic repeat request (HARQ), channel measurement, and power control are addressed. From the system architecture aspect, the protocol stack and bearer management are discussed. In addition, some real-life applications and use cases are described.

D2D DISCOVERY

In an MCN, before a device can communicate to its target device, it must first find, identify, and communicate with other proximate devices so that data can be routed to the final destination. "Device Discovery for Multihop Cellular Networks" first reviews the current solutions for the unlicensed band communications technique, such as IrDA, Bluetooth, and Wi-Fi Direct. However, for fundamentally different cellular networks, which operate on licensed band and centrally controlled radio resources, some issues need to be reconsidered to make the discovery scheme more efficient. This article addresses the discovery principles and unique design issues in a cellular network, and provides a practical device discovery design example for Long Term Evolution (LTE) systems, placing the emphasis on implementation complexity and energy efficiency.

RESOURCE ALLOCATION FOR D2D COMMUNICATIONS

"Fine-Grained Resource Allocation for Cooperative Device-to-Device Communication in Cellular Networks" proposes to adopt cooperative communication (CC) for D2D communications. However, new challenges, such as relay selection, channel allocation, and transmission scheduling, are raised for efficient resource allocation. By dividing each CC transmission into broadcast and relay phases, which can be scheduled individually, the fine-grained resource allocation scheme exploits the benefits of slot-by-slot scheduling by both space-division and frequency-division multiplexing. Based on this scheme, the authors study the problem of maximizing the minimum rate among multiple wireless links by jointly considering relay assignment, transmission scheduling, and channel allocation.

SYNCHRONIZATION ISSUE FOR RELAY-AIDED COOPERATIVE MIMO

A relay-assisted cooperative MIMO network is proved to improve the cell edge performance in perfect initial synchronization scenarios. However, practical cooperative systems cannot guarantee reliable operation near the cell edge without robust synchronization techniques. In "Synchronization Issues in Relay-Aided Cooperative MIMO Networks," various cooperative initial synchronization procedures corresponding to a variety of relay-assisted cooperative MIMO scenarios are analyzed. The authors characterize the mean acquisition time (MAT) and mean frame acquisition time (MFAT), as well as the relaying delay of DS-CDMA and OFDMA/TDD, respectively. In addition, both the detrimental and beneficial factors affecting the attainable synchronization performance in relay-aided cooperative non-coherent MIMO environments are highlighted. The design guidelines proposed will be beneficial to both researchers and practicing engineers involved in investigating or implementing cooperative communication systems.

MCN MODELING FRAMEWORK

To investigate the MCN performance is a continuous effort. However, existing works considered this issue under a small-scale network. "A Dynamic Graph Optimization Framework for Multihop D2D Communication Underlying Cellular Networks" aims to investigate theoretical performance limits and study the optimal system design for large-scale systems. By using the reformulation linearization technique (RLT), the objective flow maximization and the associated constraints of flow conservation and resource allocation are transformed into linear expressions of decision variables. Thus, the formulated maximization problem falls into the category of linear programming problems. In addition, the authors use a realistic cellular network deployment to quantitatively analyze and assess the capability of the proposed framework.

REFERENCES

[1] Y.-D. Lin and Y.-C. Hsu, "Multihop Cellular: A New Architecture for Wireless Communications," *IEEE INFOCOM*, Tel Aviv, Israel, Mar. 2000.

[2] G. Bianchi *et al.*, Eds., Special Issue on Multihop Wireless Mesh Networks, *IEEE JSAC*, Nov. 2006.

[3] P. H. J. Chong *et al.*, Eds., Special Issue on Technologies in Multihop Cellular Networks, *IEEE Commun. Mag.*, Sept. 2007.

[4] Z. Dawy *et al.*, Eds., Special Issue on Multihop-Based Cellular Networks, *EURASIP J. Advances Sig. Proc.*, Feb. 2008.

[5] R. Boutaba, S. Murphy, and A. Banchs, Eds., Special Issue on Wireless Multi-Hop Networking for Infrastructure Access, *Computer Networks*, 2010.

[6] C. Wang *et al.*, Eds, Special Issue on Device-to-Device Communications in Cellular Networks, IEEE *JSAC*, 3rd qtr., 2014.

[7] IEEE Std for Information Technology — Telecommunications and Information Exchange Between Systems — LAN/MAN — Specific Requirements, "Part 11: Wireless Medium Access Control (MAC) and Physical Layer (PHY) specifications: Amendment 10: Mesh," Sept. 2011.

[8] IEEE Recommended Practice for Information Technology-Telecommunications and Information Exchange between Systems — Local and Metropolitan Area Networks — Specific rRequirements, "Part 15.5: Mesh Topology Capability in Wireless Personal Area Networks (WPANs)," May 2009.

[9] IEEE Std for Local and Metropolitan Area Networks, "Part 16: Air Interface for Broadband Wireless Access Systems Amendment 1: Multihop Relay Specification," June 2009.

[10] 3GPP TS 23.303, "Proximity-Based Services (ProSe); Stage 2; Release 12," v. 12.1.0, June 2014.

[11] 3GPP TR 23.713, "Study on Extended Architecture Support for Proximity-Based Services; Release 13," v. 0.1.0, July 2014.

BIOGRAPHIES

YING-DAR LIN [F'13] is a Distinguished Professor of Computer Science at National Chiao Tung University (NCTU) in Taiwan. He received his Ph.D. in computer science from the University of California, Los Angeles in 1993. He served as the CEO of the Telecom Technology Center during 2010–2011 and a visiting scholar at Cisco Systems in San Jose, California during 2007–2008. Since 2002, he has been the founder and director of the Network Benchmarking Lab (NBL, www.nbl.org.tw), which reviews network products with real traffic. He also cofounded L7 Networks Inc. in 2002, which was later acquired by D-Link Corp. His research interests include design, analysis, implementation, and benchmarking of network protocols and algorithms, quality of services, network security, deep packet inspection, wireless communications, embedded hardware/software co-design, and recently software defined networking. His work on multihop cellular was the first along this line, and has been cited over 600 times and standardized into IEEE 802.11s, IEEE 802.15.5, IEEE 802.16j WiMAX, and 3GPP LTE-Advanced. He is an IEEE Distinguished Lecturer (2014 and2015) and a Research Associate of the Open Networking Foundation (ONF). He is currently on the editorial boards of *IEEE Transactions on Computers*, IEEE Computer, *IEEE Network*, *IEEE Communications Magazine* — Network Testing Series, *IEEE Wireless Communications*, *IEEE Communications Surveys and Tutorials*, *IEEE Communications Letters*, *Computer Communications*, *Computer Networks*, *Journal of Network and Computer Applications*, and *IEICE Transactions on Information and Systems*. He has guest edited several special issues in IEEE journals and magazines, and co-chaired symposia at IEEE GLOBECOM '13 and IEEE ICC '15. He published a textbook, Computer Networks: An Open Source Approach (www.mhhe.com/lin) with Ren-Hung Hwang and Fred Baker (McGraw-Hill, 2011). It is the first textbook that interweaves open source implementation examples with protocol design descriptions.

YU-CHING HSU received her Ph. D. degree in 2002 from the Department of Computer Science at NCTU. Her Ph. D. dissertation on multihop cellular networks has been cited over 600 times. Since 2002, she has been with the Information and Communications Laboratory (ICL), Industrial Technology Research Institute (ITRI), where she was a vice technical manager from 2005 to 2010. In addition, she has been the Editor-in-Chief of the *ICL Journal* since 2010 and joined the Intellectual Property Committee of ICL serving as a patent reviewer from 2003. Her research interests include protocols above the MAC layer over WiFi/WiMAX/3GPP wireless networks, including mobility management, session management, routing, and security. She has dedicated herself to work related to the 3GPP standard body from 2012. She has applied for more than 30 patents, with more than half issued. Among those patents, one was adopted in IEEE 802.16j. The invention enables packets to be sent without the tunneling overhead in a multihop path.

MAINAK CHATTERJEE is an associate professor in the Department of Electrical Engineering and Computer Science, University of Central Florida, Orlando. He received his B.Sc. degree in physics (Hons.) from the University of Calcutta, his M.E. degree in electrical communication engineering from the Indian Institute of Science, Bangalore, and his Ph.D. degree from the Department of Computer Science and Engineering, University of Texas at Arlington. His research interests include economic issues in wireless networks, applied game theory, cognitive radio networks, dynamic spectrum access, and mobile video delivery. He has published over 125 conferences and journal papers. He got the Best Paper Awards at IEEE GLOBECOM '08 and IEEE PIMRC '11. He is the recipient of the AFOSR sponsored Young Investigator Program (YIP) Award. He co-founded the ACM Workshop on Mobile Video (MoVid). He serves on the editorial board of Elsevier's *Computer Communications* and *Pervasive and Mobile Computing* journals. He has served as the TPC Co-Chair of several conferences including IEEE WoWMoM '11, WONS '10, IEEE MoViD '09, the Cognitive Radio Networks Track of IEEE GLOBECOM '09, and ICCCN '08. He also serves on the Executive and Technical Program Committees of several international conferences.

THOMAS KUNZ [SM] received a double honors degree in computer science and business administration in 1990 and his Dr. Ing. degree in computer science in 1994, both from Darmstadt University of Technology, Federal Republic of Germany. He is currently a professor of systems and computer engineering at Carleton University. His research interests are primarily in the area of wireless and mobile computing. The main thrust is to facilitate the development of innovative next-generation mobile applications on resource-constrained handheld devices, exploring the required network architectures (MANETs, wireless mesh networks, wireless sensor networks), network protocols (routing, Mobile IP, QoS support), and middleware layers. He has authored or co-authored over 200 technical papers, received a number of awards, and is involved in national and international conferences and workshops. He is a Senior Member of ACM.