Guest Editorial
Multimedia Economics for Future Networks: Theory, Methods, and Applications

Wen Ji, *Senior Member, IEEE*, Zhu Li, *Senior Member, IEEE*, H. Vincent Poor, *Fellow, IEEE*,
Christian Timmerer, *Senior Member, IEEE*, and Wenwu Zhu, *Fellow, IEEE*

I. INTRODUCTION

A. Multimedia Data Is Becoming the Dominant Traffic in Communication Networks

WITH the growing integration of telecommunication networks, Internet of Things (IoT), and 5G networks, there is a tremendous demand for multimedia services over heterogeneous networks. According to recent survey reports, mobile video traffic accounted for 60 percent of total mobile data traffic in 2016, and it will reach up to 78 percent by the end of 2021. Users' daily lives are inundated with multimedia services, such as online video streaming (e.g., YouTube and Netflix), social networks (e.g., Facebook, Instagram, and Twitter), IoT and machine generated video (e.g, surveillance cameras), and multimedia service providers (e.g., Over-the-Top (OTT) services). Multimedia data is thus becoming the dominant traffic in the near future for both wired and wireless networks.

B. Monetizing Video Traffic Is Dominating the Multimedia and Networking Ecosystem

Operators are facing the challenge of effectively monetizing video traffic while developing profitable business models that support capital infrastructural expenditures for 5G and future networks. Nevertheless, the underlying system is a vast and complex network with various multimedia applications controlled by a variety of entities, such as Content Providers (CPs) who own or generate the content, and Service Providers (SPs) that operate the underlying network infrastructure. What is worse, such a system is dominated by demanding End Users (EUs) who request content applications with high Quality-of-Experience (QoE). Furthermore, the rise of online virtual reality (VR) and 360-degree content has also incurred inevitable CDN costs (e.g., storage/cloud costs) in Internet applications. At the same time, to satisfy the demands and expectations from worldwide users, profound changes need to be made in order to fit diversified network deployment, traffic dynamics, commercial structures, and economic formation in the ecosystem. As a consequence, finding ways to monetize video traffic efficiently is a leading research issue in both academia and industry.

C. Economic Considerations and Concepts Are Guiding Networking of Multimedia Traffic

The wireless spectrum and network resources are always limited and overly crowded. The exploding growth of both wireless and wireline data traffic is far beyond the growth of capacity. This conflict is exacerbated when video data are operated under such limited and uncertain environments. Thus, today's multimedia communications and networking practices are tightly coupled with economic considerations. Economic theories, such as game theory and incentive theory, become promising as they can capture many of the intrinsic features from these multimedia networked systems.

Therefore, this IEEE JSAC Special Issue (SI) on "Multimedia Economics for Future Networks: Theory, Methods and Applications" is intended to give a comprehensive and in-depth view of the challenging economic issues for multimedia frontier applications, future network design, transmission optimization, and scientific studies of heterogeneous networks. The main goal of this SI is to bring together leading researchers from both academia and industry from diversified backgrounds to reexamine the mathematical foundations of multimedia, beyond classical models and solution concepts, and eventually provide guidance for the development of new generations of Internet and networks.

There are a total of 15 technical papers included in this special issue. The issues covered in the papers can be categorized into five focus areas: "Theoretical foundations and novel economic architectures", "Pricing and economic models in multimedia markets", "Optimization and

performance", "Multimedia economics in 5G", and "Recent emerging applications". The following describes accepted papers classified by these thematic areas.

II. SUMMARY OF ACCEPTED TECHNICAL PAPERS

A. Theoretical Foundations and Novel Economic Architectures

For the past decades, multimedia communication has been confronted with two major flaws. One is the large theoretical gap between macro multimedia applications and micro inter-processing analysis, and the other is the growing rates of both original resolutions and transmitted compressed data. It is accepted that multimedia research imported information theory for multimedia compression, introduced network technology for multimedia networking, and used pattern recognition and data mining for multimedia content analysis. By contrast, conventional multimedia research seldom developed its unique theory when it met practical requirements from markets.

The paper "Multimedia crowdsourcing with bounded rationality: A cognitive hierarchy prospective" addresses the bounded rationality analysis from the perspective of a cognitive hierarchy. Conventional literature in this area concentrated on automatic tasks assignment. This work discusses how workers select the multimedia sensing tasks and studies how the workers' cognitive rationality affects the reward and performance of a multimedia crowdsourcing system. The authors conduct a novel theoretical analysis using cognitive hierarchy theory.

When multimedia data are transmitted in conventional edge-cloud architectures, the unique challenge is that the supply and communication capability on the cloud side may not match the demands from mass edge devices. A new paradigm should be examined to support an improved and integrated user experience across all devices. Moreover, economic considerations dominate the practical network deployment, quality of users' experience, and technology development.

In the paper entitled: "Front-end smart visual sensing and back-end intelligent analysis: A unified infrastructure for economizing the visual system of city brain," the authors propose transmitting compact features instead of original multimedia data. They introduce economic methods to organize hybrid features and data transmission among massive numbers of devices. For instance, the authors build their model and optimization approach into the economic architecture, where the economic communication is based on incremental model compression. Further, the authors test their architecture on a smart city, namely, the visual system of a city's "brain".

B. Pricing and Economic Models in Multimedia Markets

Video data have increased at an enormous rate in today's global Internet networks, such as videos on demand, cloud-based video streams, and social media video sharing. Comparing with conventional data markets, video-streaming services are challenged by the bandwidth-heavy and dynamic time-dependent difficulties. As a result, how to design a corresponding pricing plan in consideration of users' positive responses challenges Internet Service Providers (ISPs).

The paper "Time-dependent pricing for multimedia data traffic: Analysis, systems, & trials" addresses bandwidth-hungry streaming applications and explores the necessary time-dependent pricing method. This work devises a holistic approach for designing the efficiency of a time-dependent pricing scheme for multimedia-rich data traffic. The deduction of economic principles and system settings outlined in this work provide a path for researchers to design other pricing schemes in future multimedia networks.

Real markets, which charge CPs, SPs, and EUs for accessing the Internet, have been introduced as a useful modeling method for both SPs and CPs to manage their profits from EUs. Revenues may be temporarily low for unstable real-time requirements in multiuser video transmission systems because EUs randomly cancel their subscriptions due to the large traffic requirement caused by video data. Conventional market models and tools in networking, such as pricing, resource allocation, profit-incentive schemes, become more unstable for video services.

The paper entitled "Filling two needs with one deed: Combo pricing plans for computing-intensive multimedia applications" addresses the unique needs of computing intensive multimedia applications in real markets, and it studies new plans with consideration of both communication and computing costs. The authors analyze the prevailing pricing schemes, such as pay-as-you-go payment, upfront data plans and upfront combo plans, and propose a randomized online scheme to probabilistically reserve plans based on a recent usage of resources. The authors design attractive plans offering joint communication and computing resources, and show how to allow service providers to derive threshold value in a combo plan to provide attractive pricing for consumers.

When economic schemes are deployed in multimedia markets, the challenges come from two aspects. One is effective resource forecasting on the operator side. The other is the overhead of resource specifications, price discovery and budget constraints on the user side. The paper "Procuring spontaneous session-level resource guarantees for real-time applications: An auction approach" addresses the use of auctions to handle the spontaneous demands and session-level performance guarantees in wireless networks. The authors present an auction model for increasing social welfare and operator revenues based on sharing the radio channel between competitive user multimedia sessions. This work employs economic policies to provide reliable QoEs for multimedia flows and particularly exhibit the advantages of auction designs.

C. Optimization and Performance

Since video occupies nearly 80% of the data in the modern Internet, a massive amount of resources are consumed by video data. The research focus has shifted from making a connection in communication networks to delivering multimedia content in future networks. Modern communication systems are almost overwhelmed by video data - merely one type of multimedia. However, current communication and network theories barely tackle practical problems, e.g., how multimedia sources are utilized. Moreover, how QoE with consideration of

video data should be measured accurately in communication systems, and what quantitative analysis for delays, complexity, and transmitted power should be conducted, under realistic delay constraints, such as high-speed wireless video data, are important issues.

The paper entitled: "Rebuffering optimization for DASH via pricing and EEG-based QoE modeling," first, this paper presents an electroencephalography (EEG) based QoE assessment model. It is known that since most QoE models are built based on the subjective scores of users, the uncertain accuracy due to users' personal preference limits the final QoE results. This work uses EEG measurements to capture human response to video and directly captures the first reaction of the human brain to video. This method avoids the negative affect due to users' variable emotion and fatigue. As a result, the proposed method benefits to improve the performance of QoE for video sources. Secondly, this work presents a price-based bandwidth allocation scheme for mitigating the effect of video rebuffering on QoE in a Dynamic Adaptive Streaming over HTTP (DASH) system, and gives a Stackelberg game solution to jointly maximize the revenue of the DASH server and the individual utility of DASH clients.

Currently, resources in heterogeneous networks face low utilization coupled with several problems, including exponentially increasing demands, unbalanced transmission pipes, uncertain network performance, traffic-intensive multimedia applications, energy inefficiency in wireless communication, statistical delay-bounded QoS guarantees, time-sensitive multimedia streaming, and large-volume multimedia data. Future studies are expected to yield innovations that achieve significantly high utilization and rapid optimization for different networks and users.

The paper entitled "Joint pricing and cache placement for video caching: A game theoretic approach" addresses the caching problem within a large-scale mobile video distribution network from an economic point of view. The authors describe a game-theoretic algorithm for finding the price equilibrium between mobile network operators and a video provider. The process of finding balance points of the best rental price and the corresponding equilibria solution could be applied to finding other similar equilibriums.

D. Multimedia Economics in 5G

When multimedia data are transmitted in 5G networks, large bandwidth requirements increase the burden of resource utilization. Caching has been widely considered as a promising technique to facilitate multimedia services in mobile communication networks. However, in cache-enabled heterogeneous networks, base-stations and mobile-stations are quite different to those in traditional heterogeneous networks without caching, which should consider not only the radio resources but also the availability of multimedia content.

The paper entitled "Economically optimal MS association for multimedia content delivery in cache-enabled heterogeneous cloud radio access networks" addresses cache-enabled heterogeneous networks, and optimizes mobile-station (MS) association for multimedia content delivery in cache-enabled heterogeneous cloud radio access networks. The proposed MS association optimization considers both the content caching location and the wireless channel quality in heterogeneous environment. Through formulating the optimal MS association in an economic manner, the total profit defined as the difference between the incomes and serving costs, and the ratio of MSs with satisfied QoS are improved.

The paper "Joint radio communication, caching and computing design for mobile virtual reality delivery in fog radio access networks" discusses how to design mobile VR for Fog radio access networks in 5G scenarios. The major challenge of immersive VR experience is the latency because mobile VR applications need heavy radio communication, caching, and computing costs. The authors model the gap between computing and caching as a type of economic resource utilization. Through modeling of the tradeoff among communications-caching-computing resources in an economic way, the latency performance can be optimized in mobile VR applications.

The paper "Economical caching for scalable videos in cache-enabled heterogeneous networks" addresses economic modeling for multimedia transmission over heterogeneous networks. The authors propose an optimized economical caching scheme in cache-enabled heterogeneous networks to deliver multimedia video services with personalized viewing qualities to mobile users. The proposed economical efficiency optimization covers communication, energy consumption, and cache access models. Their proposed SVC-based caching scheme could relieve the traffic burden of backhaul links and lower the service delay in 5G networks.

The paper "Intelligent scheduling and power control for multimedia transmission in 5G COMP systems: A dynamic bargaining game" addresses multimedia communication in 5G scenarios. The authors propose a user-centric dynamic framework including downlink transmission scheduling and a power control for improving the performance of edge users in 5G coordinated multi-point (COMP) systems. This work provides a dynamic bargaining framework so as to select scheduled edge users, cluster the cooperative base stations, and determine the transmit power. The optimal users' throughput and transmission delay can be obtained through the unique Nash bargaining solution.

E. Recent Emerging Applications

Next-generation content distribution networks have deployed the "edge-cloud" structure to improve scalability. This structure consists of vast numbers of highly capable end-user devices, such as smart phones and tablets. A potential application is real-time multimedia transmission in IoT systems. However, IoT video communication over heterogeneous networks is difficult as it requires supporting stringent requirements in limited capability (such as low power and low available bandwidth) in end-systems. Besides, it also needs to provide stable and reliable transmission for variable amounts of devices.

Conventional video communication schemes assume that video data complies with specific distribution and could be predicted, and assume caching the video on the edge cloud is free. However, since the edge cloud is small, the practical video varies with the users and the environments. Besides,

since service providers are primarily interested in profits, most video caching schemes are infeasible in practical systems due to limited storage and computation resources on the edge-cloud side. The paper "Profit maximization for video caching and processing in edge clouds" analyzes how to cache and process videos on edge-clouds so as to offer maximized profits to video service provides. In particular, considering that the users' request to the edge cloud is usually unknown to the video provider, the authors design an online learning-based decision-maker based on multi-arm bandit theory.

The paper entitled "Power rationing for tradeoff between energy consumption and profit in multimedia heterogeneous networks" focuses on power control mechanisms in heterogeneous cellular networks with the aim to achieve revenue optimization. The work provides a method to measure the tradeoff among costs, QoS and profit management for both multimedia service providers and heterogeneous-cellular-networks operators. The authors explain cost-effective and profit-driven resource utilization for multimedia services from power control via pricing and game theory.

Understanding the QoE of users has been widely considered as a cornerstone task for various multimedia applications. However, in the era of economic multimedia networking, more and more service providers and content providers are also concerned about users' privacy issues because providers cache and preserve the users' private information. The privacy-aware and privacy-preservation schemes have attracted considerable attention from YouTube, Netflix, etc.

The paper entitled "Seeing isn't believing: QoE evaluation for privacy-aware users" focuses on investigating the impacts of privacy issues on cloud media users' behavior, and evaluating the users' true QoE. Accurately assessing the users' QoE with consideration of privacy is important because privacy issues have a significant impact on the multimedia users' behavior and consumption habits. This work connects privacy-aware control to QoE control, and as a result, a systematic and privacy-aware QoE evaluation scheme in the framework of cloud mobile media is proposed. The proposed privacy-aware QoE evaluation can easily deal with the online implementation requirements in Internet or mobile data markets.

Net neutrality has recently been a hot research topic in the Internet because it is extensively debated as a potential regulation of the future Internet. The paper entitled "Regulating monopolistic ISPs without neutrality" considers the problem from different perspectives. The authors focus on regulating monopolistic access without imposing net neutrality regulations. The authors use standard economic methods, such as welfare analysis and desirable regulations, to support their views.

Wen Ji (M'09–SM'16) received the M.S. and Ph.D. degrees in communication and information systems from Northwestern Polytechnical University, China, in 2003 and 2006, respectively.

From 2014 to 2015, and in 2018, she was a Visiting Scholar with the Department of Electrical Engineering, Princeton University, USA. She is currently a Professor with the Institute of Computing Technology (ICT), Chinese Academy of Sciences (CAS), Beijing, and the Peng Cheng Laboratory, Shenzhen, China. Her research interests include multimedia communication and networking, video coding, channel coding, information theory, optimization, network economics, and ubiquitous computing. She holds over 20 patents and has more than 80 refereed publications in journals, conference proceedings, and book chapters related to her areas of interest. She was the General Chair of GameNets 2014. She served or serves on various editorial boards, including as a Guest Editor for the *ACM Transactions on Embedded Computing Systems* and the IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS.

Zhu Li (SM'07) received the Ph.D. degree in electrical and computer engineering from Northwestern University, Evanston, IL, USA, in 2004. He was a Principal Staff Research Engineer with the Multimedia Research Laboratory (MRL), Motorola Labs, from 2000 to 2008, an Assistant Professor with the Department of Computing, The Hong Kong Polytechnic University, from 2008 to 2010, a Senior Staff Researcher/Senior Manager with the Multimedia Standards Research Laboratory, Samsung Research America, Richardson, TX, USA, from 2012 to 2015, and a Senior Staff Researcher/Media Analytics Group Lead with the Media Laboratory, FutureWei (Huawei) Technology, Bridgewater, NJ, USA, from 2010 to 2012. He is currently an Associate Professor with the Department of Computer Science and Electrical Engineering (CSEE), University of Missouri–Kansas City, Kansas City, and the Director of the NSF I/UCRC Center on Big Learning (CBL). He has 48 issued or pending patents and more than 100 publications in book chapters, journals, conference proceedings, and standards contributions related to his areas of interest. His research interests include audio–visual analytics and machine learning with its application in large-scale video repositories annotation, mining, and recommendation, as well as video adaptation, source-channel coding, and distributed optimization issues of the wireless video networks. He was a recipient of the Best Poster Paper Award at the IEEE International Conference on Multimedia and Expo, Toronto, ON, Canada, in 2006, and the Best Paper (DoCoMo Laboratories Innovative Paper) Award at the IEEE International Conference on Image Processing, San Antonio, TX, USA, in 2007. He was the elected Vice-Chair of the IEEE Multimedia Communication Technical Committee from 2008 to 2010.

H. Vincent Poor (S'72–M'77–SM'82–F'87) received the Ph.D. degree in electrical engineering and computer science from Princeton University in 1977.

From 1977 to 1990, he was on the faculty of the University of Illinois at Urbana–Champaign. Since 1990, he has been on the faculty of Princeton University, where he is currently the Michael Henry Strater University Professor of Electrical Engineering. From 2006 to 2016, he served as the Dean of Princeton's School of Engineering and Applied Science. His research interests include information theory, statistical signal processing and stochastic analysis, and their applications in wireless networks and related fields. Among his publications in these areas is the book *Information Theoretic Security and Privacy of Information Systems* (Cambridge University Press, 2017). He is a member of the National Academy of Engineering and the National Academy of Sciences and a Foreign Member of the Royal Society. He is also a fellow of the American Academy of Arts and Sciences, the National Academy of Inventors, and other national and international academies. He received the Marconi and Armstrong Awards from the IEEE Communications Society in 2007 and 2009, respectively. Recent recognition of his work includes the 2016 John Fritz Medal, the 2017 IEEE Alexander Graham Bell Medal, and several honorary doctorates and professorships, including Honorary Professorships from Tsinghua University and Peking University, both conferred in 2017, a D.Sc. *(honoris causa)* from Syracuse University awarded in 2017, and a D.Eng. *(honoris causa)* from the University of Waterloo awarded in 2019.

Christian Timmerer (M'08–SM'16) is currently an Associate Professor with Alpen-Adria-Universität Klagenfurt, Klagenfurt, Austria. He is a Co-Founder of Bitmovin Inc., San Francsico, CA, USA, as well as the Chief Innovation Officer (CIO) and the Head of Research and Standardization. He holds seven patents and has coauthored more than 200 publications in workshops, conferences, journals, and book chapters. He participated in several EC-funded projects, notably DANAE, ENTHRONE, P2P-Next, ALICANTE, SocialSensor, ICoSOLE, and the COST Action IC1003 QUALINET. He is also the Principal Investigator in national-funded projects, such as AdvUHD-DASH, PROMETHEUS, and ATHENA. He also participated in ISO/MPEG work for several years, notably in the areas of MPEG-21, MPEG-M, MPEG-V, and MPEG-DASH. His research interests include immersive multimedia communications, streaming, adaptation, and quality of experience. He was the General Chair of WIAMIS 2008, QoMEX 2013, ACM MMSys 2016, and Packet Video 2018. Further information can be found at http://blog.timmerer.com.

Wenwu Zhu (S'91–M'96–SM'01–F'10) received the Ph.D. degree from New York University, New York, NY, USA, in 1996.

He was with Bell Labs, Murray Hill, NJ, USA, as a Member of Technical Staff, from 1996 to 1999. He was the Chief Scientist and the Director of Intel Research China, Beijing, China, from 2004 to 2008. He was a Research Manager and a Principal Architect with Microsoft Research Asia, Beijing, China. He is currently the Vice Chair of the Department of Computer Science and Technology, Tsinghua University, the Vice Dean of the National Research Center for Information Science and Technology, the Co-Director of the Data Science and Information Technology Research Center, Tsinghua–UC Berkeley Shenzhen Institute, and the Vice Director of the Tsinghua Center for Big Data. His current research interests include the areas of multimedia communications and networking, social-aware multimedia computing, and cross-media AI. He is an AAAS Fellow, an SPIE Fellow, and a member of the Academy of Europe. He was a recipient of six Best Paper Awards, including T-CSVT 2001 and ACM Multimedia 2012. He served on the Steering Committee for the IEEE TRANSACTIONS ON MOBILE COMPUTING (T-MC) from 2007 to 2010. He served or serves as the General Co-Chair for ACM Multimedia 2018 and ACM CIKM 2019. He has been Editor-in-Chief of the IEEE TRANSACTIONS ON MULTIMEDIA (T-MM) since 2017.