Cyber-Physical-Social-Mediated Communication

Zhiyong Yu, Leye Wang, Wenzhong Guo, Bin Guo, Daqing Zhang

Column: General Interest

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Zhiyong Yu
Fuzhou University

Wenzhong Guo
Fuzhou University

Daqing Zhang
Institut Mines-Télécom

Leye Wang
Peking University

Bin Guo
Northwestern Polytechnical University

***Abstract*—We introduce the concept of cyber-physical-social-mediated communication (CPS-C) and analyze why CPS-C is better than pure cyber-mediated communication for two popular applications: mobile social networks and mobile crowd sensing. CPS-C utilizes its unique characteristics (i.e., cyber-physical synchronization, human intelligence, and physical displacement) to bring benefits, including natural boundary of information exposure, tangible interaction, targeting receivers on the fly, decentralization, and piggybacking. As a result, energy efficiency and user experience are improved. We highlight the existence of human-machine intelligence in the communication process, which has rarely been addressed.**

NOWADAYS, UBIQUITOUS/PERVASIVE COMPUTING,[1] as well as cyber-physical-social systems,[2] are widely recognized as the new computing paradigm, which will bring promising solutions for many emerging fantastic applications, such as the smart home, intelligent traffic, and fine-grained environmental monitoring. Three spaces, i.e., cyber, physical, and social spaces, interact via intelligent technologies of sensing, communication, computation, and cognition. Each type of technology can be enhanced by fusing artificial intelligence and human intelligence, e.g., human as a sensor[3] and human computation.[4] However, existing works rarely consider the enhanced communication mediated by the fusion of cyber, physical, and social entities. Thus, in this article, we provide the vision of cyber-physical-social-mediated communication (CPS-C).

To facilitate discussion, in this article, communication refers to the process of sending *digital data* from one location to another distant location, and it occurs not only within the social space (i.e., between humans), but also in intra- or inter-spaces. Therefore, CPS-C is an umbrella concept that covers various communication morphologies. In cyber-mediated communication, signals are transmitted in the form of electronic, optical, or magnetic waves through computer network infrastructures, without macromovements of humans

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or objects (i.e., physical displacement). In contract, physical-mediated communication leverages the movements of physical entities to carry information, such as storage devices, repeaters, or terminals, and move through traditional transportation systems, such as postal parcels, animals, and vehicles (e.g., sneakernets). Similarly, social-mediated communication transmits information through a self-sentient human. Although the majority of physical entities' movements involve human intention, the difference lies in the fact that in the social-mediated communication, mediations understand the information and accordingly provide a field control of the communication.

Although most digital data today use cyber-mediated communication, we claim that physical- or social-mediated communication continues to play a complementary but important role. Current pure cyber-mediated communication is not energy efficient when the carried data are with a large amount and/or a low refresh rate, and pure cyber-mediated communication suppresses the motivation of face-to-face communication between humans, which harms the user experience in some situations. To go beyond these limitations, mediations from two or three spaces should be fused to enhance communication in terms of energy efficiency, user experience, etc.

Near-field communication, mobile *ad hoc* networks, delay-tolerant networks, and opportunistic networks[5] can be regarded as early morphologies of CPS-C. Although these related concepts are already proposed, no one recognized their common characteristics or summarized them into one communication paradigm. In this article, we summarize and analyze why CPS-C is better than pure cyber-mediated communication for two popular applications: mobile social networks[6,7] and mobile crowd sensing.[8,9] CPS-C utilizes its unique characteristics (i.e., cyber-physical synchronization, human intelligence, and physical displacement) to bring benefits, including natural boundary of information exposure, tangible interaction, targeting receivers on the fly, decentralization, and piggybacking. As a result, energy efficiency and user experience are improved.

EXAMPLES AND OUR EFFORTS ON CPS-C

CPS-C mediations fused from cyber, physical, and social entities could be in varied forms, such as storage devices in the post, terminals in vehicles or human hands, network devices on elevators, and tags carried by animals. For example, Amazon Snowball,[10] a 50 TB device, can be mailed back and forth so that digital transfers can be performed locally at considerably high speeds. This device can be as low as one fifth of the cost of backing up over the Internet. DakNet[5] can supply Internet connectivity to underdeveloped regions where traditional networks do not subsist. Mobile access points periodically mounted on motorcycles or buses pass through and exchange information with village kiosks equipped with digital storage and short-range wireless communication. Sensor networks can be used in building structural health monitoring, but collecting data from the sensor nodes is a challenge in these systems. Zhang *et al.*[11] proposed a method that utilizes elevators to address this challenge. When an elevator passes by each floor, a representative node on this floor transmits the collected data to a base station on the elevator through short-range communication. As a result, communication cost can be minimized, even without *a priori* knowledge of the elevator's movement. CarTel[12] nodes are designed to gather and deliver data from sensors embedded on automobiles. They can rely primarily on other CarTel nodes, mobile phones, USB drives, Wi-Fi, or Bluetooth to communicate with the server. In the MIT Reality Mining project,[13] participants' trajectories were collected to determine their interests, activity patterns, etc. Some participants stored their data on mobile phones locally and returned the phones at the end of the project. ZebraNet[14] let animals carry special tags with sensing abilities and deployed base stations to gather data from tags and deliver them to the server. ZebraNet utilizes the encounters between animals to help them exchange the gathered data. As a result, each animal holds the data sensed by itself and eventually from other animals that it has encountered. In these examples, human intelligence is evident during communication because we should decide when to send what to whom, explicitly or implicitly.

To facilitate further analysis, our efforts on CPS-C in the applications of mobile social networks and mobile crowd sensing are described in detail as follows.

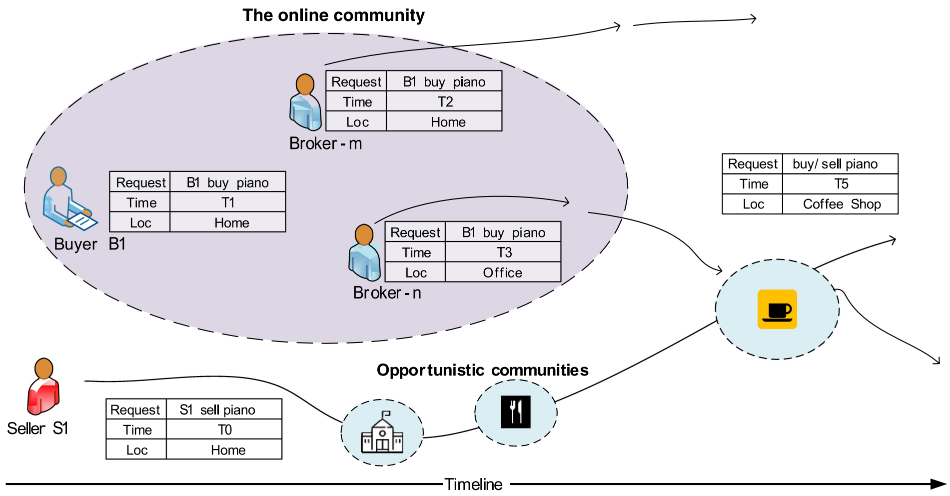

Figure 1. HybridSN for cross-space opportunistic advertising.

HybridSN

Hybrid social networks (HybridSN)[15,16] combine online and opportunistic mobile social networks to enhance them both. Figure 1 shows an example: Seller *S1* posts a selling request at time *T0*, and buyer *B1* posts a buying request at *T1*. *B1*'s friends (*Broker-m* and *Broker-n*) are appointed as brokers (i.e., popular persons in the physical space to carry and forward messages), and the tasks are assigned to them via pure cyber-mediated communication at *T2* and *T3*. As *S1* moves, selling requests are shared with the people he encounters. At time *T5*, *Broker-n* and *S1* meet in a coffee shop; thereupon, the buying and selling requests are matched. Then, *B1* is notified of the matching, and the transaction can be performed. In HybridSN, the advertisement messages are spread cross-space (i.e., cyber and physical spaces), and the time efficiency and audience coverage are outperforming the advertising in a single space.

Buy4Me

Buy4Me[17,18] is a delivery system that utilizes the "social piggyback" phenomenon. When a user needs to deliver information or objects from a location/person to another location/person, Buy4Me can recommend a friend of the user to complete the task without (if not, minimal) extra effort, because this friend also has to move in the same way even without this task. Figure 2 presents that user *A* wants to buy a bag, but the specialty store is far from her present location. With Buy4Me, she merely needs to input her request, including the store's location and the task completion deadline. Buy4Me *predicts*[19] based on the historical trajectories that one of her friends (user *B*) will visit the store soon, and afterward, *A* and *B* will meet in a cafe. If user *B* is willing, then he can help buy the bag for user *A*. In this manner, Buy4Me can save time, energy, and environmental costs and supply opportunities to promote friendship via serendipitous social interactions.

effSense

We have conducted a pioneer study that quantitatively examines the energy efficiency of CPS-C. For the crowd-sensing task that does not require uploading data in real-time, effSense[20] enables users to save cost by locally aggregating data and uploading them along with a voice call or Bluetooth gateway that mobile phones encounter (instead of directly uploading through a 3G/4G network). Figure 3 shows a simple example. u_1, u_2, u_3 are users with a data plan, whereas u_1^*, u_2^*, u_3^* represent users without a data plan. Additionally, a location-fixed Bluetooth gateway (*D*) and server (*S*) are available. effSense supplies the following routes to reduce bandwidth and energy cost: route $u_3^* > D > S$, wherein a nondata-plan user transmits data through the Bluetooth gateway; route $u_1^* > u_3 > D > S$, wherein a nondata-plan user initially transmits data to a data-plan user (u_3) and then u_3 uploads data through the Bluetooth gateway; and route $u_2^* > u_2 > u_1 > S$, wherein a data-plan user aggregates data from other users and completes the data uploading

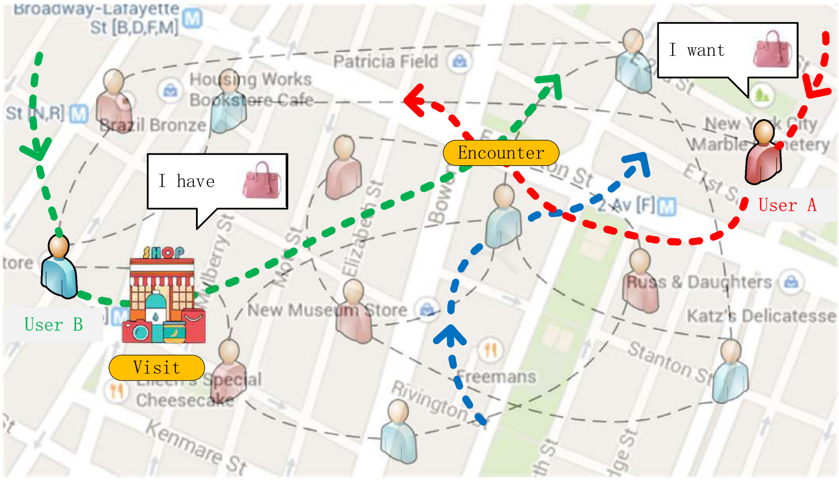

Figure 2. Buy4Me as a piggybacking delivery system.

task *parallelly with a voice call*. Experiments show that effSense can conserve 55% energy for users with a data plan and 48% data traffic for users without a data plan.

CHARACTERISTICS AND ADVANTAGES OF CPS-C

The communication process is roughly composed of three phases: encoding, transferring, and decoding. The encoding/decoding phase involves information comprehension, encryption, etc., and the transferring phase includes targeting and controlling, aside from data carrying. This process reveals why CPS-C is a preferred approach in terms of energy efficiency and user experience in mobile social networks and mobile crowd sensing, since improvements occur within these phases. We summarize that CPS-C has three unique characteristics compared with pure cyber-mediated communication, namely, *cyber-physical synchronization, human intelligence, and physical displacement*. In comparison with the pure cyber-mediated communication that "nobody knows you are a dog," when a message is received, CPS-C often notifies with a messenger or the sender himself standing before you. We name this characteristic cyber-physical synchronization. Humans, as a part of CPS-C mediations, can understand the carried information and accordingly provide a field control of the communication. We name this characteristic human intelligence. CPS-C transmits information not only via computer network infrastructures, but also via the movements of physical or social entities through the transportation system. We name this characteristic physical displacement. These three characteristics will bring the following five advantages, which consequently improve energy efficiency and user experience.

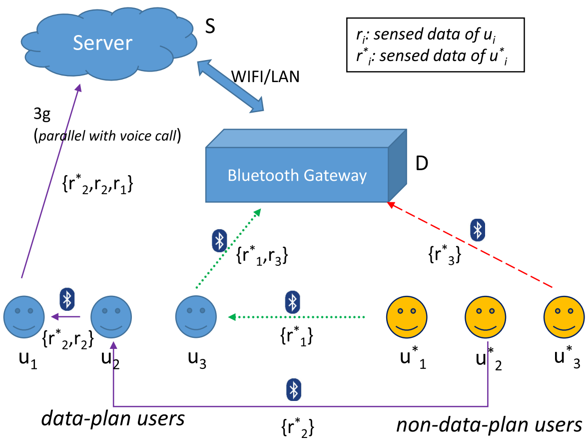

Figure 3. effSense for mobile crowd sensing.

Natural Boundary of Information Exposure

The information carried by CPS-C mediations is easy to keep safe and private. For example, when a passenger pays the bus fee through a smart card sweeping over the reader, she does not need to worry about her card being misappropriated by other passengers. For people outside the CPS-C channel, they are likely not disturbed by information from CPS-C. In many situations, the information to be shared is only of interest to people in a certain local region. Thus, CPS-C can help shield unrelated people without extra guards, such as firewalls.

Tangible Interaction

Nowadays, attention becomes scarce with the information explosion. CPS-C can appropriately attract the receivers' attention because "it never rains but it pours." It never *rains* because of its natural boundary of information exposure, and it *pours* because it supplies tangible interaction. Tangible interaction means a person interacts with digital data through the physical environment by utilizing the human abilities to grasp and manipulate physical objects. Object displacement and information delivery are intertwined in CPS-C. The receiver can learn the information context from tangible features. Moreover, the social or physical entities can generate additional information, which results in high fault tolerance. For example, in Buy4Me scenario, the friend can touch the bag to feel its texture. Tangible interaction can also confirm the credibility of the information source (e.g., iris scanning to register attendance at an office, transferring a physical token to prove that the information in the same CPS-C channel is truly from the sender). As we do not need to explain the context of the information through the channel and do not need to waste resources to ensure information credibility, the energy can be reduced.

Targeting Receivers on the Fly

As all terminals are reachable in a fleeting moment in the cyber space, the possible receivers of a message seem to be too many. Although we can utilize our online relationship, most of the links belong to two classes: created by physical contact or by online searching and stayed inactive thereafter. Therefore, physical contact is important before pure cyber-mediated communication. CPS-C is a means of physical contact and needs no prepaved channel. For example, CPS-C, in an opportunistic mobile social network, can supply serendipitous social interactions. The messenger or sender can inspect the features of a potential target before leaving a message, including mobility, social status, social popularity, and willingness, which are hints of whether this candidate is a proper receiver or not. The messenger can even target a receiver with no storage or display device for digital data. In this sense, CPS-C can serve as the capillaries of information flow to solve "the last mile problem."

Decentralization

Most CPS-C morphologies can work in a decentralization style, such as near-field communication, mobile ad hoc networks, delay-tolerant networks, and opportunistic networks. Decentralized network architecture indicates that the information can be routed from the sender to the receiver through the shortest path (physical and logical) rather than detouring through an information center. This type of local peer-to-peer communication can satisfy a significant part of communication demands. As CPS-C could work without relying on a center, the load of network infrastructures for remote communication can be relieved. Furthermore, decentralization is favorable for the self-managing and healing of a network, because a centralized network may easily have a single point of failure. These advantages can lower the cost of energy and other resources. For example, in effSense scenario, sending data via 3G/4G will cost considerably more energy than sending via Bluetooth (the latter even has the chance to avoid sending). Another merit of decentralization is that the terminals have further decision-making power and capability. Therefore, the communication demand for local information fusion can be satisfied.

Piggybacking

The transportation system may cost more energy than pure cyber-mediated communication. However, in most cases, social or physical entities have their own movement incentives. For example, people go to work and go home, animals migrate for food, vehicles transport passengers or goods, and planets revolve around the sun. They are not designed to deliver information. However, CPS-C leverages these physical displacements for information delivery while adding minimal or even no extra burden to these objects. We call this phenomenon piggybacking. Although carrying information by piggybacking must wait for an opportunity, it deserves to wait because it can save energy, and sometimes, it is the only feasible solution, e.g., in HybridSN scenario, the seller goes to a cafe to have lunch, and the shortening of the distance between the seller and buyer is a side effect.

CONCLUSION AND OPEN ISSUES

To overcome limitations of pure cyber-mediated communication on energy efficiency and user experience in mobile social networks and mobile crowd sensing, we propose CPS-C by fusing artificial intelligence and human intelligence in communication, because CPS-C can benefit from natural boundary of information exposure, tangible interaction, targeting receivers on the fly, decentralization, and piggybacking. Although they are not the focus of this paper, the following open issues are quite important for future exploration.

1) *Conceptual framework and research approach for CPS-C*. Given the diversity of CPS-C morphologies, a unified conceptual framework is necessary but challenging to present. A research approach of CPS-C should be outlined dedicatedly since currently, only a few separate examples are studied.
2) *Routing or forwarding strategy for CPS-C*. The study of efficient routing or forwarding strategies for CPS-C is complicated because of the scarcity of knowledge about the topology and mobility of CPS-C. A compromise must be achieved between knowledge requirement and communication performance. Human intelligence must be considered when targeting and controlling at the transferring phase.
3) *Security and privacy in CPS-C*. The identity of the sender and receiver should be protected from intermediate users, and the integrity and security of the carried data should be guaranteed, i.e., data on the go should not be lost, changed, or eavesdropped.

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Zhiyong Yu is an associate professor in the College of Mathematics and Computer Science, Fuzhou University, Fuzhou, China. He was also a visiting student with Kyoto University, Kyoto, Japan, from 2007 to 2009 and a visiting researcher with the Institut Mines-Telecom, TELECOM SudParis, Evry, France, from 2012 to 2013. His current research interests include pervasive computing, mobile social networks, and mobile crowdsensing. He received the M.E. and Ph.D. degrees in computer science and technology from Northwestern Polytechnical University, Xi’an, China, in 2007 and 2011, respectively. Contact him at: yuzhiyong@fzu.edu.cn.

Wenzhong Guo is a professor and director of Fujian Provincial Key Laboratory of Network Computing and Intelligent Information Processing. He was a postdoctoral research scholar with the Department of Computer Science, National University of Defense and Technology, Changsha, China, from 2011 to 2014, a visiting professor with the Faculty of Engineering, Information and System, University of Tsukuba, Japan, in 2013, and a visiting professor with the Department of Computer Science and Engineering, State University of New York at Buffalo, Buffalo, NY, USA, in 2016. His research interests include the fields of wireless sensor networks, network computing, and mobile crowdsensing. He received the Ph.D. degree from the Department of Physics and Information Engineering, Fuzhou University, Fuzhou, China, in 2010. Contact him at: guowenzhong@fzu.edu.cn.

Daqing Zhang is a professor with TELECOM SudParis and SAMOVAR, CNRS, France. His research interests include context-aware computing, urban computing, mobile computing, etc. He was the general or program chair for more than ten international conferences. He received the Ph.D. degree from the University of Rome La Sapienza, Italy, in 1996. He is the associate editor for ACM *Transactions on Intelligent Systems and Technology*, IEEE Transactions on Big Data, etc. Contact him at: daqing.zhang@telecom-sudparis.eu.

Leye Wang is an assistant professor with the Key Lab of High Confidence Software Technologies, Peking University, China. His research interests include ubiquitous computing, mobile crowdsensing, and urban computing. He received the Ph.D. degree in computer science from the Institut Telecom SudParis and University Paris 6, France, in 2016 and was a postdoc researcher with the Hong Kong University of Science and Technology. Contact him at: leyewang@pku.edu.cn.

Bin Guo is currently a professor with Northwestern Polytechnical University, China. His research interest includes ubiquitous computing and mobile crowd sensing. He is a senior member of IEEE. He received the Ph.D. degree from Keio University, Japan, in 2009. Contact him at: guob@nwpu.edu.cn.