A Survey on Mobile Social Networks: Applications, Platforms, System Architectures, and Future Research Directions

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***Abstract*—Mobile social networks (MSNs) have become increasingly popular in supporting many novel applications since emerging in the recent years. Their applications and services are of great interest to service providers, application developers, and users. This paper distinguishes MSNs from conventional social networks and provides a comprehensive survey of MSNs with regard to platforms, solutions, and designs of the overall system architecture. We review the popular MSN platforms and experimental solutions for existing MSN applications and services and present the dominant mobile operating systems on which MSNs are implemented. We then analyze and propose the overall architectural designs of conventional and future MSN systems. In particular, we present the architectural designs from two perspectives: from the client side to the server side, and from the wireless data transmission level to the terminal utilization level. We further introduce and compare the unique features, services, and key technologies of two generations of architectural designs of MSN systems. Then, we classify the existing MSN applications and propose one special form of MSN, i.e., vehicular social network, and demonstrate its unique features and challenges compared with common MSNs. Finally, we summarize the major challenges for on-going MSN research and outline possible future research directions.**

***Index Terms*—Mobile social networking, application, service, platform, opportunistic networks, system architecture.**

I. INTRODUCTION

MOBILE social networking (MSN)[1] involves the interactions between participants with similar interests and/or objectives through their mobile devices within virtual social networks [1]. MSN leverages mobile communication networks and social networks, as mobile applications can use existing social networks to create native communities and promote service discovery and collaborations. Simultaneously, social networks can take advantage of mobile features and ubiquitous accessibility. For example, through social networks, knowledge about the social behaviors and relationships of the users can be used to define the structures and interactions among the users and their related organizations [2], so as to improve the efficiency of mobile communications [3] and the effectiveness of the services provided by mobile distributed systems on mobile networks. Moreover, a MSN can readily exploit mobile networks to support the concept of real-time web [4], which is at the forefront of the emerging trends in social networking.

Unlike traditional social networks that are centered on individual persons, MSNs can take advantage of the additional capabilities of contemporary mobile devices such as smartphones. These capabilities, such as global position system (GPS) receiver, sensing modules (cameras, accelerometer, gravity sensors, etc.), and multiple radios (second/third/fourth generation cellular, WiFi, Bluetooth, WiFi Direct, etc.), enable MSNs to enhance conventional social networks with additional features, such as location-awareness [5], the ability to interact asynchronously [6], the ability to capture and tag media [7], as well as the ability to automatically process sensing data [8], [9]. Different from conventional social networks in which people interact over the Internet, the multiple radios in mobile devices enable MSNs to also work over opportunistic networks, where each node can act as a host, a router, or a gateway, and connect with other nodes in an *ad-hoc* manner, without possessing or acquiring any knowledge about the network topology [10]. Thus, MSNs are potentially attractive for supporting interactions and collaborations between people in a number of mobile environments, as MSNs can take advantage of both infrastructure-based wireless networks (i.e., the mobile Internet) and opportunistic networks (i.e., wireless mobile *ad-hoc* networks, MANETs). Therefore, MSNs may be centered on the mobile devices that a person carries instead, and hence research on interactions between humans and mobile devices, i.e., human-computer interaction (HCI), may be crucial to the research on MSNs, in addition to the areas of computing for social networks and mobile networks.

From the aspect of computation, MSN can be considered as the integration of mobile computing and social computing in

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[1]Depending on the context, MSN also stands for mobile social network in this paper.

TABLE I
TAXONOMY OF THE CURRENT SURVEY WORKS OF MSNs

Subjects			**Survey works of MSNs**										
			[17]	[18]	[19]	[20]	[21]	[22]	[23]	[24]	[25]	[26]	[27]
MSN software system layer	MSN software system architecture												
	Applications and services	Applications	✓	✓			✓						
		Web-based services			✓					✓			
	Platforms	Mobile software platforms - commercial and based on Internet				✓							
		Mobile software platforms - based on hybrid network for distributed computing/application development				✓							✓
		Mobile operating systems						✓					
MSN network layer	MSN network architectures		✓	✓							✓	✓	
	Middleware designs for network services								✓	✓		✓	✓
	Protocol designs		✓	✓							✓		✓
	Wireless access infrastructures		✓										✓

various applications and services based on mobile distributed systems, which are eventually presented to users [11]. Thus, beyond conventional social networking applications and services (e.g., content sharing among the social communities [12]), many new applications may potentially be offered over MSNs. For example, location-based services and real-time social interactions in MSNs [13] can help mobile users collaborate with each other when they are driving, hence improving traffic safety and efficiency. Also, with the benefits of ubiquitous communications via mobile networks and low-cost methods to connect people via social networks, MSN can be very valuable for entrepreneurs looking to expand and reinforce their contacts anytime and anywhere [14]. Thus MSN has the potential to revolutionize many aspects of human life, as illustrated below:

Opportunistic Social Interaction: Taking advantage of opportunistic networking, MSNs can play a vital role in mobile virtual communities, by enabling people to have a real-time introduction of people nearby whom they might want to contact. People can use MSNs to meet new friends or locate old friends anywhere at any time; e.g., MSNs can help people find other people nearby who have the same problems or interests in a fast, reliable, and easy way, with little expenditure of money and time. Consequently, new relationships can be initiated and existing friendships can be reinforced through MSNs [15].

Science and Education: Scientific groups can use MSNs to share information and knowledge anytime and anywhere. Thus, MSNs can help the groups to expand both their knowledge base and their flexibility of organization in ways that would not be possible within a self-contained hierarchical organization. MSNs can also support educators by extending discussions with and among students beyond the classrooms.

Disaster Rescue: In a disaster, electricity and telecommunication networks may be damaged, so that reliable communications and Internet access may no longer be available. As a result, both people's ability to seek help and emergency management coordination processes may suffer considerable delays. One of the important requirements in such situations is to support people to communicate in an infrastructure-less way [16], as it may take too much time to install new communication equipment and restore damaged infrastructure. As MSNs can also work over opportunistic networks in an *ad-hoc* manner that does not rely on the Internet, they are attractive for supporting interactions and collaborations between people in disaster situations.

Government: Since various government agencies widely use MSNs, they can serve as a quick and convenient tool to enable governments to get up-to-date inputs from the public and to provide timely information to the public. This can help governments to improve their services and public policy making.

Currently, several surveys on MSNs can be found in the literature. As shown in Table I, corresponding to the media layers and host layers, we classify the survey works into two subjects—MSN network layer and MSN software system layer. The applications and network architectures of MSNs are summarized in [17], primarily from the perspective of communications and focusing on issues and approaches related to protocol designs in MSNs. The network architectures and social properties of MSNs are studied in [18]. Design mythologies of software services and software platform for MSN applications are summed up in [19] and [20], respectively. The features, commercial solutions and related architectures of MSNs are reviewed in [21]. A survey about the current dominant mobile operating systems (OSs) on which the MSN applications are running is presented in [22]. Also, the middleware techniques that could be used to improve the network performances of MSNs are reviewed and compared in [23] and [24]. Similarly,

[25] and [26] focus on the design of network services of MSNs and outline the corresponding future research directions. In addition, [27] presents a unified architectural model with a new taxonomy for context data distribution across different layers of mobile ubiquitous systems. However, from Table I, we can observe that a comprehensive survey on the overall design and development of applications, services and architectures of MSN systems in mobile networks, from the perspective of mobile software system and mobile computing, is still lacking. Such a survey not only can outline the positions of different software and mobile computing techniques in MSNs, but also can facilitate effective organizations and constructions of MSN software systems, and hence would be of interest to researchers, service providers, mobile application developers, and users of MSNs.

This paper fills the gap identified above by providing a comprehensive survey of MSNs, focusing on the applications, services, and architectural designs of MSN systems. The rest of this paper is organized as follows. Section II reviews the major platforms and solutions of MSNs, and introduces the popular mobile OSs that can support MSNs. Section III presents, analyzes, and compares different categories of MSNs according to their system architectures. Section IV classifies the existing MSN applications, and provides a case study on vehicular social networks (VSNs), which are emerging as MSNs for future transportation applications. Section V discusses the research challenges, emerging technologies, and potential research directions on MSNs. Section VI concludes this paper.

II. Current Platforms and Solutions

Many existing platforms and solutions already support MSNs. Commercial platforms such as Facebook and Twitter are very popular and widely used in smartphones and mobile devices. They mainly focus on the end users, but also provide some application programming interfaces (APIs), which can be used to develop new functions and applications based on these platforms. These platforms are reviewed in the first part of this section. Also, the research community is developing many experimental solutions for MSNs, such as for application development support, and opportunistic social connection ability which could enable MSN applications to run across decentralized and centralized mobile systems. The second part of this section investigates some experimental MSN solutions that could potentially be widely deployed in the future. Finally, in the third part of this section, the current dominant mobile operating systems (OSs), which provide the foundation supports to the MSN platforms and solutions are presented.

A. Popular Commercial MSN Platforms

Different from the conventional social networks, which are based on the use of web browsers as client to access the social websites via the Internet, the current commercial MSNs also provide specific mobile applications that run on the mobile devices. Such MSN applications usually have dedicated user interfaces that enable the users to access the respective social networks easily, while taking advantage of mobile distributed computing. For example, an MSN applications could allocate some computing tasks such as pre-storage and pre-processing of social context data in mobile devices. These schemes could help to decrease the networking overhead and time latency when MSN users access and/or post data from/to social networks through their mobile devices.

1) Facebook: Facebook is a social networking service. It is a rich site for researchers interested in the functions and services of social networks, as it contains diverse usage patterns and technological capacities that bridge online and offline connections [28]. In addition, previous studies have suggested that Facebook users tend to search for people with whom they have an offline connection rather than browsing for complete strangers to meet [29], and they are usually interested in what their friends are thinking about. The current mobile Facebook application supports most of the original services and functions provided by the Facebook social website. The mobile version of Facebook also provides an open platform with APIs, which can be used by third party providers to create applications that add more functionality to the original mobile Facebook application, hence enabling users to enjoy a richer experience. For instance, there are several new mobile Facebook applications that provide location-aware services by allowing users to update their geographic status, browse the current locations of their Facebook friends, and sort the friends by their distances from the users' current locations.

2) Twitter: Unlike most social networks, Twitter concentrates on micro-blogging services, and many extensions exist to support tweeting pictures and texts longer than 140 words. Any Twitter user can follow others or can be followed without reciprocation, and get the "what are you doing or thinking" information of their Twitter friends in real time [30]. In general, Facebook helps users to interact with friends and family in the real world, while Twitter helps users to communicate with people interested in similar things. Similar to Facebook, Twitter also provides a related mobile application, and associated APIs to application programmers, which enable them to develop new functions and services for Twitter. However, since Twitter is intended for micro-blogging of real-time news, it enables mobile phone users to update new messages to the Twitter website not only through the mobile Twitter application, but also by short messaging service (SMS). Furthermore, many of the micro-blogging systems that provide APIs are also compatible with Twitter. This means that if programmers have developed a new mobile application on another micro-blogging system like StatusNet, they can also easily and efficiently migrate the application to Twitter.

3) Foursquare: Foursquare is a location-based social network website for mobile devices. It encourages smartphone users to share their current geographic information with other Foursquare users by giving out rewards. Different from conventional social network websites, most of the Foursquare services are location-based. From the beginning, Foursquare has focused directly on mobile platforms. For example, the user interface of Foursquare is designed for smartphone screens, ensuring that it can be conveniently operated by smartphone users. Also, users can link their Foursquare accounts to other conventional social network accounts, such as Facebook and Twitter. This means that Foursquare users can share their information through

TABLE II
LIST OF THE SOLUTIONS FOR MSNS

Project	Description	Category	Ad-hoc network support	Mobile operating systems	Extensibility support
MobiSN [31]	Semantic based framework for mobile ad-hoc social network, which is implemented in Java 2 Micro Edition (J2ME)	Framework	Yes	Mobile operating systems which support J2ME	No
RoadSpeak [32]	For vehicular social networks, allows commuters to automatically join voice chat groups on roadways	Framework	No	None	Yes
AmbientTalk [33]	New event-driven based language for application development of mobile ad-hoc network	Language	Yes	Android, and J2ME under a CDC/Personal profile configuration	No
MobiSoC [34]	It provides a common platform which based on service-oriented architecture for rapid development and deployment of mobile social computing applications	Middleware	No	Windows Mobile	Yes
MobiClique [6]	Support mobile devices setting up mobile social ad-hoc communities through Bluetooth, focuses on opportunistic connections among mobile devices	Middleware	Yes	Windows Mobile	Yes
Haggle [35]	Data-centric networking framework, enables seamless network connectivity and application functionality, applications can adapt to different network conditions.	Framework	Yes	Android, iOS, Windows Mobile	Yes
Spiderweb [36]	Mobile application which enables the establishment of spontaneous collaborative social networks through Bluetooth	Application	No	Mobile operating systems which support J2ME	No
S-Aframe [37]	Agent-based multi-layer framework with context-aware semantic service, support efficiently developing context-aware applications for vehicular social network	Framework	Yes	Android, and J2ME under a CDC/Personal profile	Yes

Facebook or Twitter. Beyond location-aware services, Foursquare also provides tools for social sharing and online social games. Moreover, Foursquare also provides APIs that can be utilized by application developers to develop new services and add new functions to Foursquare. For example, developers can construct management tools, customize search engines, or even use the Foursquare APIs with other tools to develop novel geography-based games.

B. Solutions Supporting MSNs

Most of the popular MSN platforms discussed above are commercial MSNs offered by specific service providers through the Internet. Due to the mobility, dynamism, and opportunism of the distributed MSN users, in some situations, these platforms may not be able to meet the diverse service requirements of MSNs. Such situations include remote areas with poor wireless coverage and hence unreliable Internet access, vehicular networks in which network situations are highly dynamic and information transfers are sensitive to time latency, or disaster scenarios where the communication infrastructure has been damaged. Also, commercial MSN platforms often have some constraints that make them not very flexible or convenient for MSN research. Consequently, many researchers around the world are designing novel and open-source MSN solutions, using such approaches as new languages, new frameworks/ middleware, and so on. Most of these solutions are oriented towards mobile distributed networks that not only take advantage of commercial MSNs, but also complement commercial MSNs by supporting MANETs that function without connections to the Internet. Although these solutions are still in the experimental stage, potentially they will play important roles in the evolution of MSNs. Available solutions supporting MSNs, which result from different projects, are summarized in Table II.

1) MobiSN: MobiSN [31] is a semantics-based framework for mobile *ad-hoc* social networks. It is implemented in Java 2 Micro Edition (J2ME), and supports self-configured *ad-hoc* MSNs between users of mobile devices. MobiSN provides core functions and services for *ad-hoc* MSNs, such as friend matchmaking, automatic forming of groups, generation of ontology-based profiles through distributed indexes, and so on. Ontology-based computation of similarity between concepts is an important issue in semantic applications. The problem with the MobiSN approach is that it only considers the common ancestor and the root concept in calculating the similarity of two concepts. In addition, without any extensibility support, it is difficult for developers to create applications and services for *ad-hoc* MSNs based on MobiSN to fulfill the heterogeneous service requirements of different MSN users.

2) RoadSpeak: RoadSpeak [32] is the first framework proposed for VSNs, which allows commuters to automatically join voice chat groups on roadways. Unlike common MSNs, in addition to the interests of users, RoadSpeak considers the time interval and location in its definition of the VSN profile when user groups are formed. RoadSpeak partially supports extensibility. It provides a number of Java APIs to application developers, based on which developers can extend RoadSpeak clients to provide enhanced functionality. Nevertheless, RoadSpeak relies on client-server interactions. In a vehicular environment, it is difficult to provide a stable server among the vehicles all the time. In addition, RoadSpeak only provides a voice chat service. Its extension support is merely for the grouping of membership in this service, and not for application developers to extend it to provide other services and functions for VSNs. Thus, it can hardly fulfill the diverse service requirements of different users in a VSN.

3) AmbientTalk: AmbientTalk [33] is a high-level, object-oriented programming language for developing distributed mobile applications over MANETs. The basic idea of the AmbientTalk programming paradigm is that it can incorporate network failures in its programming model. AmbientTalk employs a purely event-driven concurrency framework based on actors. Actor executions can be concurrent with asynchronous actor method invocations; thus AmbientTalk is very suitable for highly dynamic networks. Also, the implementation of AmbientTalk combines the Java virtual machine (JVM) as a platform, which makes it easy for AmbientTalk programs to use Java libraries, and Java objects can easily use AmbientTalk as an embedded scripting language. However, AmbientTalk is a completely new language, which means that programmers have to spend time to climb the learning curve before using it to develop applications for MSN systems. Furthermore, AmbientTalk does not provide a library of existing application services, so it is not efficient for use in developing applications.

4) MobiSoC: MobiSoC [34] is a middleware that provides a common platform for the rapid development of mobile social computing applications (MSCA), and for distributing such applications on multiple servers in order to achieve scalable operations. Through capturing the social states of physical communities, and mining previously unknown patterns from emergent geo-social data with social states, a mechanism is designed to share the data on social states among the mobile devices to support real-time MSN applications. As the architecture of MobiSoC is based on the Service-Oriented Architecture (SOA), it supports evolution by providing modularity, extensibility, and language independence as well. Two prototype applications for smartphones, Tranzact and Clarissa, were designed and implemented based on MobiSoC. Experimental results involving these applications showed that MobiSoC can provide a reasonable performance in mobile devices. Nevertheless, a major shortcoming of MobiSoC is that mobile devices can only run the SOA client of MobiSoC, which uses the Simple Object Access Protocol (SOAP) to access a central server designed for enterprise-oriented applications. All services needed for interactions or message exchanges between mobile devices are hosted in the server. Thus, MobiSoC is not suitable for mobile devices interacting over MANETs.

5) MobiClique: MobiClique [6] is a middleware for MSNs. It integrates existing social networks and opportunistic contacts between smartphones to form *ad-hoc* communities that are based on opportunistic communications for social networks and social graphs. Different from previous solutions (e.g., RoadSpeak and MobiSoC) for MSNs, MobiClique does not depend on a central server or infrastructure connectivity, and it supports opportunistic connections directly between neighboring mobile devices. MobiClique enables mobile devices to set up an *ad-hoc* MSN through Bluetooth, using a store-carry-forward technique to disseminate contents around this network, which forms an overlay packet switched network capable of providing new network services. Moreover, MobiClique also provides an open API to encourage third parties to develop new services and applications based on it.

6) Haggle: Haggle [35] is a data-centric networking framework that separates application logic from network bindings. Haggle enables seamless network connectivity and application functionality so that applications can adapt to network conditions using the channel with the best connectivity. In other words, Haggle allows mobile applications to take advantage of both infrastructure and *ad-hoc* networks. When an infrastructure network is not available, Haggle can work in a distributed manner such that mobile devices are networked dynamically. For example, users can still send messages via *ad-hoc* connectivity over Bluetooth or search for information in contents cached in the neighborhood. Besides, with the use of a publish/subscribe model, users can declare their interests by keywords and receive data items that match the keywords from other users. Haggle supports many platforms, including Android, iOS, Windows Phone (WP), Linux, and Mac OS X.

C. Mobile Operating Systems

Mobile devices play a critical role in MSNs, and most MSN applications, platforms, and research on mobile networks are largely based on smartphones, in which the OSs are the essential software component that provides the services that make smartphones smart. For instance, OSs in mobile devices provide the basic libraries and drivers of hardware modules, which are the foundations of the software development kits (SDKs) of the popular MSNs (e.g., Facebook). They provide the distributed computing capabilities that enable easy implementation of various kinds of MSN applications/platforms. Moreover, the use of multiple sensor modules in smartphones to obtain sensing data is becoming important. Mobile OSs provide the necessary APIs for such modules, which enable the sensing data to be processed and linked to different MSN applications dynamically, thus improving the context-awareness and cyber-physical capacity of these MSN applications. Therefore, mobile OSs are crucial for MSNs. Android, iOS and WP are currently the dominant mobile OSs that are deployed widely in smartphones.

In general, each mobile OS has its specific advantages to MSNs. For example, since open source is an intrinsic feature of Android, many researchers are also conducting their studies on MSNs based on the Android system. Some researchers are focusing on designing middleware in Android, so as to support mobile social ecosystems [38], [39]. Haggle and AmbientTalk, which we reviewed in Section II-B, are also based on the Android OS. Since version 4.0, Android supports Wi-Fi Direct for peer-to-peer connections without a hotspot or Internet connection, which is essential for setting up opportunistic networks (one of the core capabilities of future MSNs). Unlike other mobile OSs, iOS is only licensed for use on Apple products. All applications can be built based on a precise configuration so that developers can test for one standard when developing iOS mobile applications. Thus, iOS is an ideal OS that supports developing various MSN applications with considerable stability. However, unlike Android, iOS is a closed-source mobile OS.

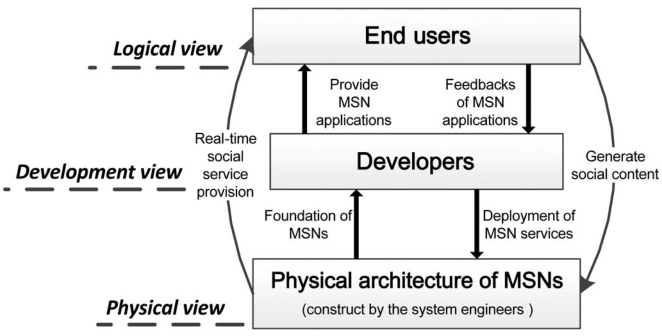

Fig. 1. Relation between the views of MSN architecture.

For example, stored user data cannot be exchanged among diffferent mobile applications, nor can interactions using that data take place. iOS is therefore not convenient for use in supporting MSN research. In addition, WP natively integrates.NET/XAML, DirectX/C++, and XBOX Live in it, to support mobile games. As social gaming is becoming popular, the WP OS potentially has a unique advantage to support social gaming within MSNs.

III. System Architecture of MSNs

Architectural design plays a crucial role in MSN systems, as all the applications, services, and platforms of MSNs discussed above eventually need to be orchestrated in an architecture that forms a seamless MSN system over mobile networks. We present the architecture of MSNs through three architectural views from different stakeholders' perspectives [40], [41]: physical view from the aspects of system engineers of MSNs, development view from the aspects of MSN application developers, and logical view from the aspects of end users of MSNs. The three views and their relations are as illustrated in Fig. 1. In this section, we first review these three architectural views for conventional MSN system architectures, which mostly employ client-server interactions and are widely used by existing MSNs like Facebook, Google+, and others. Second, based on the same three views, we introduce and analyze a novel architecture for MSNs, which could very well be part of the future evolution of MSNs, as well as its related services, features, and key technologies. In addition, we compare these two kinds of architectures for MSNs.

A. Conventional Architecture of MSNs

1) Physical Architecture View—System Engineers: As shown in Fig. 2, the physical architecture of the conventional MSN systems is a client-server architecture in which the clients are connected to the server via the Internet. Most widely used MSN platforms, such as Facebook and Twitter, are based on such an architecture, which consists mainly of three parts: i) server side—contents/service provider; ii) a wireless network to access the Internet; and iii) client side—mobile devices.

The server side provides the central coordination and diverse service provision of MSNs. It normally has three basic components: networking server, central process, and database. The main benefits of using the servers to provide most MSN services through the Internet are the simplification of service implementation, reduction in the hardware requirements of the users' mobile devices, and the high efficiency of centralized control and coordination of the communications of mobile devices. The shortcomings are in common to those of most client-server architectures, i.e., the servers have high stability and reliability requirements since the MSN services rely on them, and in some special situations (e.g., the density of mobile nodes is too high in some specific places and/or time periods, or many servers have been damaged in a disasters situation), the operational servers may suffer from traffic overloads, and result in considerable time latency of MSN applications running on users' mobile devices.

Fig. 2. The physical architecture of the conventional MSNs.

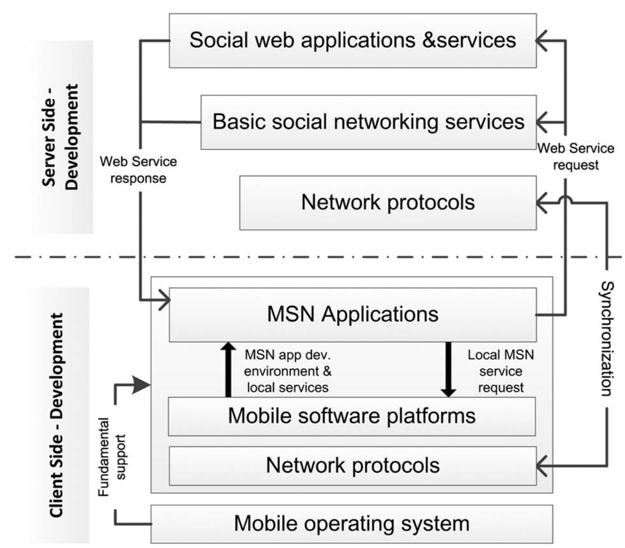

Fig. 3. The development view of the conventional MSNs.

In contrast, the client side is distributed over different mobile devices. With advanced developments of mobile devices, the client side of MSNs is able to play more important roles in three aspects: i) ubiquitous MSN services access, e.g., through

TABLE III
SUMMARY OF EXISTING STANDARD INTERFACES

API	Features
Facebook Graph APIs	- Retrieve and post data to Facebook - Facebook-based feedback system
Twitter Embedded Tweets	- Tweet into the content of website, - Display tweet with expanded media (e.g. photo, video, etc.)
Google+ APIs	- Connect with other for better engagement - Use Google+ features
Foursquare APIs	- Check in from other apps - Collect data from similar locations to identify target audiences
Bitly APIs	- Offer access to the best available content directly
YouTube APIs	- Search and view videos - Retrieve standard feeds - Authenticate users to upload videos
Amazon AWS APIs	- APIs are visualized in a web console for managers and analysts - Covers a vast of elastics resources at infrastructure layer, e.g., computing and data services - Sufficient SDKs for Android, iOS, Java, .NET, PHP, Python, Ruby, etc
Google APP Engine APIs	- Based on Python and Java - Allow limited operations, e.g., storing and retrieving data from a non-relational database

4G Long Term Evolution (LTE), WiFi, etc.; ii) distributed computing ability, e.g., taking advantage of the storage and computing capacities of smartphones to pre-store and process the frequently-used social contents and services, and perform real-time compression of photos (before uploading) on mobile devices, hence decreasing the latency and network overhead of MSNs; iii) multi-dimensional sensing capacities such as GPS, accelerometer, camera, which enable real-time positioning and future context-aware services.

2) Development View—Developers: In the client-server architecture, the developers of MSNs also focus on the two sides accordingly as shown in Fig. 3, so as to provide attractive and personalized MSN applications and services to end users.

For the development of mobile clients, the current dominant mobile OSs already integrate sufficient network protocols and libraries (e.g., for multiple sensing models), and provide the related APIs. Also, as shown in Table III, based on the OSs, most of the popular MSN platforms provide SDKs with standard APIs to support the development of different MSN applications. Moreover, with the development of mobile cloud computing [42], functions such as the Amazon Web Services (AWS) APIs are exposed to mobile clients in various ways for different developers to develop customized MSN applications. For example, AWS provides application language specific libraries for developers who prefer certain programming language in developing clients of MSN applications, including SDKs for Android, iOS, Java, .NET, PHP, Python, Ruby, etc. Meanwhile, the APIs of AWS are exposed as web services in order to integrate with existing heterogeneous systems. Finally, such APIs are visualized in a web console for managers and analysts. The functions provided by AWS APIs cover a vast set of elastic resources at the infrastructure layer, e.g., computing and data services.

Thus, the major development of the mobile client for MSNs is the user interface. Different from conventional web browser based social networks, considering the limited screen size of mobile devices, a specific user interface that is fit for operations of mobile devices is very important. One key requirement is developing suitable user interfaces for specific MSN applications, which could simultaneously support user-friendly operations on mobile devices, and provide a consistent user experience like the conventional Internet-based social websites that MSN users are accustomed to.

On the server side, the architecture mainly consists of three parts [43], [44]: i) network protocols, e.g., TCP/IP, UDP/IP, which enable connections to mobile devices that access the Internet through various wireless networks; ii) basic social networking services, such as profile repository, matching logic, authentication control, etc., which are used to update, exchange, share, and deliver contents and services to mobile clients; and iii) social web applications and services, so as to provide real-time social services to the clients of MSNs running on mobile devices, e.g., map services, multimedia services, and social games.

Currently, with smartphones, users can access the Internet either through local wireless networks (i.e., WiFi) or cellular networks (e.g., 4G LTE). In normal situations, client-server based MSNs are available via some wireless access networks. Therefore, to achieve a user-oriented design of MSN applications [45], the major requirements of the application developers are to provide desirable and appropriate MSN applications and services to different mobile users of MSNs efficiently and effectively, so as to fulfill their diverse service requirements anytime and anywhere. In order to support these, current MSN research mainly focusses on two types of approaches: social behavior analysis and context-awareness. In addition, for service-oriented MSNs, security and privacy are always a concern for the existing and future MSN applications [46]. These challenges are discussed in more detail in Section V-A.

Social Behavior Analysis: Using information on the social behavior of MSN users distilled through MSN activities, we can analyze human interactions and social trends, and help governments to improve the efficiency of their operations, businesses to improve their marketing efforts, and so on. For instance, through the information on location and activity of MSNs, we can analyse the periodicity of human movements and people's

TABLE IV
SOCIAL BEHAVIOR ANALYSIS

Approach	Examples	Description	Features
User activity and history based	Socioscope [47] Friendship linking [48] Goose [49]	Using multiple probability and statistical methods and index to measure the level of reciprocity between MSN users and communication partners	- Detect changes in human behavior at any time - Encounters of mobile users in MSNs follow a heavy-tailed distribution
Online social network based	Flink system [50] [51]	Employs multiple techniques such as semantic and graph model for reasoning with social information and for extraction and visualization of online social networks, and classification of social behaviors	- Multiple web based techniques are adopted simultaneously - User experience oriented
Social relationship based	Multi-layered friendship modeling [52] Strength of weak ties [53]	Multiple models and techniques are adopted to distinguish the impacts of different social behaviors to MSN friends	- The speed of content dissemination can be improved - Network overhead can be decreased
Algorithm based	Community-based greedy algorithm [54]	Adopts algorithm for detecting communities, and uses dynamic programming algorithm for selecting communities to find influential nodes	- Improve network performance of MSNs, such as faster finding high influence node

TABLE V
CONTEXT-AWARENESS

Approach	Examples	Description	Features
Recommendation system based	Contextualized recommendation [55] SocialFusion [56]	Evaluates a set of social conditions and context-aware actions, and to prove whether or not the conditions have been logically verified for both individual and groups of MSN users	- Focus on analyzing and discovering the social relationships between users - Fuse the data streams from mobile users, social networks, and sensors
Social identity based	WhozThatFor [57]	Supports increasingly complex MSN applications	- Online social identities with environment adaptive ecosystem
Proximity based	G2G [58]	Provides a location-awareness MSN platform for personalized recommender systems and gaming	- Detect preferences of nearby friends - Collection of geographic-proximity information about GSM cells
Architectural system based	Agent-based system architecture [59] Multidimensional social network architecture [60]	Provides system level approaches to effectively collect, process and utilize contextual data from different source; and facilitate development and deployment of context-aware MSN applications	- Based on open interfaces between social networking platforms - Generic models to deploy and evaluate different specific context-aware schemes

social relationships. In turn, understanding the behaviors of mobile users can help improve the experience of users and enhance the services provided by content/service providers of MSNs. One important requirement of social behavior analysis is the diversified sources of the social data; thus the APIs (i.e., call, message and location record) provided by the mobile OSs need to be used to develop tools to record and gather such data from numerous of MSN users. The current research about social behavior analysis over MSNs is summarized in Table IV.

Context-Awareness: Context-aware services [61] have emerged as an exciting new area of research in the mobile and ubiquitous computing communities, which has the potential to create many new revenue streams for content/service providers of MSNs. Due to the mobility of users in MSNs, it is very difficult for content/service providers to be aware of the personal status of users at a specific time and specific place in an efficient manner, since each user's activities, interests, and objectives are very diverse and depend on many unknown parameters. Therefore, one key application of context-awareness for MSNs is to ensure that the server side of MSNs can provide appropriate, useful, and relevant contents and services to mobile subscribers anytime and anywhere.

Currently, a smartphone may utilize its components such as camera, GPS, microphone, and Bluetooth radio to collect sensing data. As well, the APIs of mobile OSs may provide access to contact lists and calendars that can reveal some basic information about the smartphone users. These data can provide context information, such as a user's current location and activity, to the MSN platform that runs on the mobile OS of the smartphone. Then, based on such information, the MSN platform can gather and process the information, determine its value, interact with the MSN application on top of it, and upload such information to the server side, hence extending the services and functions of the MSN application by making the application context-aware. Some research work in this area found in the literature is summarized in Table V.

3) Logical View—End Users: The end users are at the terminal ends of MSNs. They are only concerned with the functionalities of MSNs. Through their mobile devices, end users could use a number of MSN applications that employ the client-server paradigm supported by the backside MSN services in real-time. Meanwhile, the end users could provide feedbacks on the MSN applications to the developers, and update specific social contents to the social website via their mobile devices. As discussed above, because of the features of mobile networks and mobile devices, the client-server based MSNs have several additional functions beyond the common functions of social websites.

Interactive Communications: This service supports the interaction of MSN messaging with other communication capabilities of a mobile phone, such as SMS and email. It enables MSN users to send social messages to their friends either by connecting to the Internet or through cellular services.

Updating Personal Status: This service allows MSN users to automatically or manually upload or share context information generated by the sensing devices or gathered from other mobile applications to MSN through the Internet. Examples of such information include a mobile user's location, activities the user is currently participating in (e.g., revealed through newly uploaded photos), and so on. The user's friends can then quickly get the information though the social network. In addition, such information can be made available to MSN applications.

Advertisements: Unlike conventional advertisements, the advertisements provided by social networks are usually pushed to users instead of the users pulling information from some websites [62], [63]. Based on a user's activity, the content and service providers of MSNs can distribute personalized and customized advertisements to the MSN user through the Internet. As an enormous number of people are using MSN applications on their mobile devices every day and everywhere, advertisements in MSNs can potentially be a big source of revenues for MSN content and service providers.

Location Service: Different from conventional social websites, mobile users can obtain location information from their smartphones in several ways, such as through GPS, the Internet, or cellular networks. This service not only enables mobile users to get their current location information, and to inform their friends of this information, but can also enable many additional functions by collaborating with other MSN services. For instance, a location service can help mobile users to find friends who are currently in their vicinity when they are visiting some specific area, e.g., a shopping mall. Also, a location service can work with the tagging social media service to automatically tag a user's friends in a photo taken by the user's smartphone and locate them in a digital map. Based on this service, MSN users can share their current locations by checking in on websites like Foursquare, introduced in Section II-A, find places of common interest with those of their friends, arrange to meet with them, and so on. Furthermore, studies [64]–[67] have verified that location-based social network services provide an important new dimension in understanding human mobility. For example, it is shown in [64] that social relationships can explain about 10% to 30% of all human movements, based on an analysis of different kinds of location datasets (social network check-in data and location data from smartphones).

B. Future Architecture of MSNs

Recent technological advances have given mobile devices such as smartphones the capability to generate, store, and share contents directly without central servers. Spatial sensing data (e.g., on location, temperature, movement speed) are also available by multiple sensing models and contextual computing capabilities [68] embedded in a mobile device. Such contents may be of interest to specific groups of people in a specific time or geographic area. Many opportunistic contacts may also be available to form opportunistic networks [69] for sharing or collecting data between mobile devices when people move around in their daily lives. Apart from using smartphones to get social contents and services from social networks through the traditional communication network (i.e., the Internet), opportunistic networks formed with smartphones allow social messages to be forwarded in an *ad-hoc* manner using opportunistic channels between people. Opportunistic network is especially suitable for data sharing between people in the same geographical vicinity. Mobile users can exchange data through short-range communications by Bluetooth or WiFi Direct using their smartphones. Since opportunistic data sharing does not rely on any network infrastructure, it reduces data traffic through the Internet. It can also support data sharing in remote areas or disaster scenarios (e.g., earthquake, tsunami) where infrastructure might be unavailable or damaged. The overall comparisons of conventional and future MSNs are summarized in Table VI.

1) Physical Architecture View—System Engineers: As shown in Fig. 4, future MSNs will likely have a hybrid architecture (client-server and peer-to-peer), which is an integration of the traditional Internet and opportunistic networks. Mobile devices can communicate with each other with or without infrastructure. In addition to data such as news, weather forecasts, traffic alerts, and social media that can be retrieved from the Internet, user-generated data such as messages, photos, and micro-blogs can also be collected and shared through opportunistic contacts between mobile devices. Thus, comparing to the conventional client-server architecture of MSNs, the future MSNs have three additional capabilities: i) opportunistic data exchange, ii) multi-hop communications, and iii) mobile opportunistic computing.

The traditional Internet architecture assumes a connected path from source to destination with a low propagation delay and packet loss rate [70], but it cannot take advantage of the benefits arising from opportunistic contacts. In contrast, opportunistic networks do not assume that a connected path exists over the Internet. Instead, opportunistic interactions between mobile devices take place when data is sent from a source node to one or more destination nodes via either direct communications between devices using Wi-Fi Direct or Bluetooth, or other mobile devices as relay nodes using a store, carry and forward approach. Opportunistic data exchange is particularly suitable for people located physically close to each other. One good example is to share news among passengers on a train by opportunistic networks. As 3G connectivity on a train may not be stable due to the train's fast-moving speed and being occasionally inside tunnels, through opportunistic data sharing, passengers who have already downloaded some news on their smartphones can share them with other passengers. This mechanism can provide alternate sources of data and significantly reduce the traffic load of the 3G networks.

Apart from data sharing between direct neighbors, multi-hop communications have also been explored in opportunistic networks. Due to the mobility of users, it is challenging to provide end-to-end communications between two specific users who are not direct neighbors. This is usually done via multiple intermediate users to relay the messages. Since the exchange of data between nodes consumes resources such as energy and storage, only encountered nodes that have a higher probability

TABLE VI
COMPARISONS OF CONVENTIONAL AND FUTURE MSNS

	Conventional MSNs	**Future MSNs**
Architecture	client-server	hybrid (client-server + peer to peer)
Network	Internet	hybrid (Internet + opportunistic networks)
Data Flow	end-to-end	end-to-end + opportunistic contacts
Connectivity	rely on 2G,3G,4G & Wi-Fi Hotspot	make use of any connectivity available
Data Delivery	Ensure quality of service	Ensure quality of service in Internet and provide best effort services for delivery in opportunistic networks
Data Storage	mainly on server side	on both client and server sides
Features & Services	1. communication interacting 2. updating personal status 3. advertisement 4. location service	Include all features and services in conventional MSNs and 1. message/file transfer 2. media streaming 3. content dissemination 4. neighbor discovery
Key technologies	1. social behavior analysis 2. context-aware	Include all key technologies in conventional MSNs and 1. ad-hoc connectivity 2. data forwarding & data dissemination 3. simulation of human mobility pattern
Application Domains	1. social networking services 2. game 3. travel 4. business 5. education 6. healthcare 7. dating 8. road traffic	Provide a more comprehensive coverage in the application domains of conventional MSNs and include new application domains such as 1. social networking in developing/ rural regions 2. disaster relief 3. vehicular networks

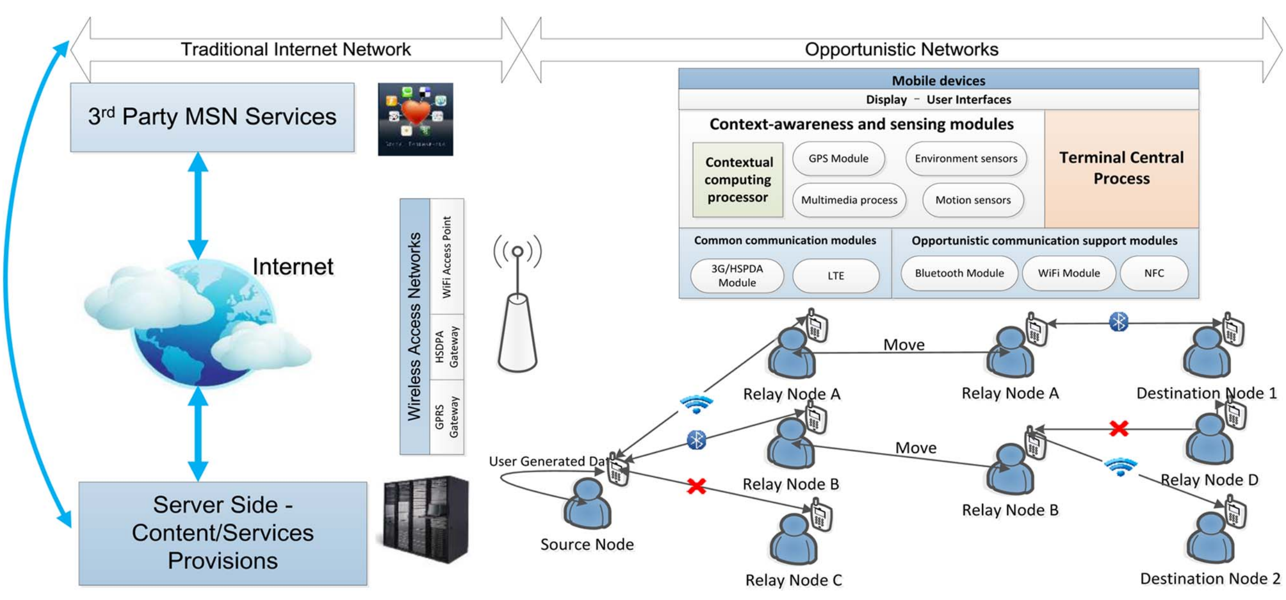

Fig. 4. The physical architecture of future MSNs.

of delivering the data to the destination node(s) should be selected as relay nodes. The delivery probability is estimated based on contact history, mobility pattern, social relationships, or common interests between users.

In addition, from computing aspects, mobile opportunistic computing can be considered to be an evolution of mobile computing, in which multiple autonomous mobile computing devices interact with each other to cooperate and achieve a common goal in an *ad-hoc* and opportunistic manner, such as solving a big computation problem through distributed task executions [71]. Similarly, in opportunistic networks, many autonomous mobile devices communicate with each other in order to execute a task, such as mobile crowdsourcing. However, applications or systems in opportunistic networks may need to contend with intermittent connectivity and potentially long delays [72].

2) Development View—Developers: As shown in Fig. 5, different from the conventional client-server MSN architecture, data exchange between users over opportunistic network will be used for future MSNs. Mobile users who are in the same vicinity can exchange data directly through short-range communication capabilities equipped on their mobile devices.

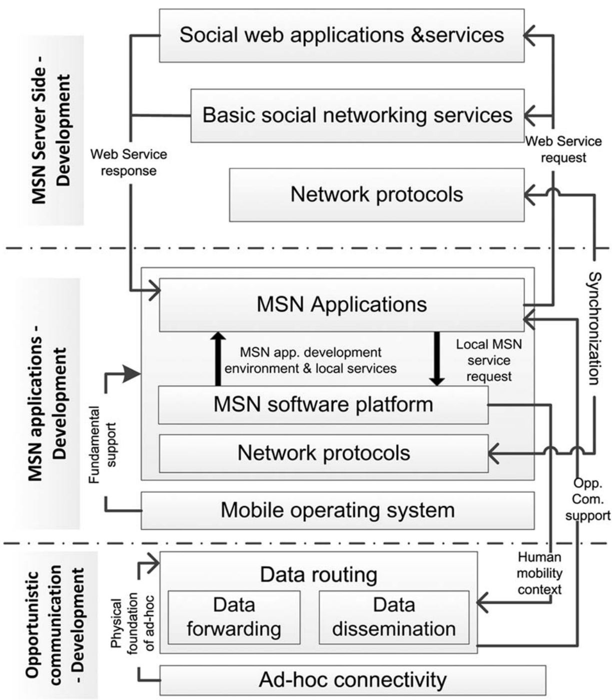

Fig. 5. The development view of future MSNs.

Short-range communications can significantly reduce power consumption and avoid unnecessary communications over the wide-area network infrastructures. The developers of future MSNs need to focus on three layers from the bottom to the top: opportunistic communications, MSN applications on top of the mobile OSs, and MSN server side. In this part, we first review and analyze the two key technologies: *ad-hoc* connectivity and opportunistic data routing, which could support the development of opportunistic communications; and then summarize the technology about simulation of human mobility patterns, which may play an important role to facilitate collaborations across the upper MSN application layers and opportunistic communications over future MSNs.

Ad-Hoc Connectivity: In addition to wide-area wireless networking interfaces such as 2G, 3G, and 4G, recent mobile devices are also equipped with short-range radio interfaces such as WiFi Direct and Bluetooth, which enable local peer-to-peer communications at a low-cost. Such technologies enable future MSNs to operate even without infrastructure. Currently, Wi-Fi Direct has peer-to-peer transfer speeds of up to 250 Mbps with a maximum distance of 656 feet, while Bluetooth 4.0 has lower power consumption and operates with speeds up to 25 Mbps over a distance of at least 200 feet.

Opportunistic Data Routing—Forwarding and Dissemination: Due to their dynamic and volatile nature, opportunistic networks operate under a completely new networking paradigm such that traditional routing protocols cannot be applied to them. In fact, they introduce new technical challenges and problems. There has been much research on data routing approaches in opportunistic networks, which store, carry and forward messages from source to destination nodes via intermediate nodes in a decentralized and distributed environment. The simplest approach is epidemic routing [73]. When a node encounters another node, they exchange messages that the other node does not possess. The protocol obviously incurs the highest transmission and storage costs. However, in practice the number of messages exchanged during each contact between two mobile nodes is limited by the duration of the contact. To improve the message delivery success ratio, nodes coming into contact should exchange only those messages that have a higher probability of being delivered to their destinations when processed by the receiving nodes. Many different approaches exist to optimize epidemic routing by reducing the number of copies of messages sent over the network. Some of these approaches are summarized in Table VII. The basic idea of the existing work is to spread the message to a small set of nodes that have a high probability to deliver the message to the destination [73]. Much of the existing work made predictions based on the mobility pattern [68] and the contact history [76], [90] of users. Recently, social relationships have also been explored to divide users into different social groups to better predict their meeting probability [6], [76]–[78]. The intuition is that people meet more often if they are friends, family, or colleagues. By exploring the social relationships, we can understand and predict the meeting pattern of people more accurately.

Some research has also been conducted on data dissemination approaches that disseminate a type of message to as many interested nodes as possible. These approaches are summarized in Table VIII.

Simulation of Human Mobility Patterns: Simulating human mobility plays an important role in evaluating the above data routing approaches in opportunistic networks. The simulators in [91], [92] can simulate human mobility based on real-world traces or mobility patterns. Real-world traces of communications between Bluetooth devices have been captured by various projects [93]–[95], enabling useful data such as contact frequency, contact durations, and locations. These traces can help researchers design better data routing approaches by exploring the real-world interactions between mobile devices. However, they are limited by the small size of the data sets due to the high costs of experimentation, and by the large Bluetooth scanning intervals due to energy constraints. For example, in the MIT Reality Mining project [93], the population size was limited to 100 students and the Bluetooth scanning interval was limited to every 5 minutes. In addition, CAMEO [96] is designed to collect and reason upon multidimensional context information derived by mobile devices and their users.

The use of mobility models is another option to model human mobility. These approaches are summarized in Table IX. In traditional simulations, the random walk [83] and random waypoint [84] models are commonly used and already built-in some simulators (e.g., ns-2). Nevertheless, they are often criticized as not capturing the moving pattern of people realistically. One reason is that human beings seldom walk according to the random waypoint model. On the contrary, people move following other kinds of patterns that are related to their daily activities, such as home, work, or school [83], [88]. In addition, many of these activities are closely related to our social relationships and behaviors [86], [87].

3) Logical View—End Users: Similar to Section III-A3), the end users are at the terminal ends of future MSNs. Beyond the features and functions of conventional client-server based

TABLE VII
DATA FORWARDING APPROACHES

Approach	Example(s)	Description	Characteristic
Message reduction based	Spray and Wait [73]	The number of message copies entering the network is limited.	Low delivery ratio and high network overhead
Mobility pattern based	Message Duplication Reduction [74]	When nodes carrying the same message meet, the node predicted to have the earliest encounter with the destination node keeps the message while the other nodes discard the message.	Low delivery ratio and low network overhead
Contact history based	PROPHET [75] SimBet [76]	Uses the history of past encounters between nodes to predict whether or not an encountered node can deliver a message to a destination.	High delivery ratio and high network overhead
Predefined Interest based	Dynamic Groups based [77]	Messages are sent via relay nodes in the same group with same declared interest in the network.	High delivery ratio and low network overhead
Social relationship based	MobiClique [6] SimBet [76] Bubble Rap [78]	Messages are forwarded based on the social relationship declared/found in the network.	High delivery ratio but a long warm up time is required

TABLE VIII
DATA DISSEMINATION APPROACHES

Approach	Supported by	Description
Dynamic groups based [76]	Predefined interests	Group messages are flooded within that interest group.
Cooperative user-centric information based [79]	Predefined interests	When nodes meet, they exchange summaries of stored data items and request all interested data items.
Cognitive heuristics based [80]	Predefined interests	Each node associates a utility function with each data item. The utility function is determined based on the number of encountered nodes that are interested and the number of times that the data item has already been disseminated.
Contentplace [81]	Estimated social relationships	The utility function used in this approach is the sum of a data item's access probability for its community divided by the size of the data item and the social weight of a user's association with a community.
Publish/subscribe based [82]	Estimated social relationships	A socially aware overlay network is built between nodes that have a higher closeness centrality within their communities. Data are disseminated using publish and subscribe operations via these nodes.

TABLE IX
MOBILITY MODEL

Approach	Example(s)	Description	Characteristic
Random based	Random Walk [83] Random Waypoint [84] Random Map-based [85]	Node movements are based on random directions, speeds, location.	Low accuracy (The simplest approach)
Map based	Random Map-based [85] Shortest Path Map-based [86]	Nodes move to randomly selected locations following shortest path/defined roads on a specific map.	Low accuracy (Better than random based approach)
Social relationships based	CMM[86] HCMM[87]	Node movements are determined by the social relationships of nodes.	High accuracy
Human activities based	Random Walk [83]	Major activities of people during a work week are simulated. When nodes are doing the same activity in the same location, groups are formed. Nodes in the same group use the same movement parameters.	High accuracy (Better than social relationships based approach)
Statistical features based	SLAW[88]	Statistical features, including heavy-tail flights and pause-time, are captured by both empirical and analytical study based on real mobility traces.	High accuracy and high resource consumption

MSNs, with the integration of the traditional Internet communication and opportunistic network architectures, many new features and services can be extended to end users in future MSNs.

Messaging/File Transfer: Internet connectivity is sometimes expensive and slow. It may not even be available at some locations, e.g., in rural regions and disaster areas. Future MSNs will enable users without Internet connectivity to access the Internet via the connectivity of peers who are willing to provide relaying services by receiving, storing and forwarding messages [97] or files [95] through their mobile devices.

Media Streaming: Cooperative media streaming services are proposed in [98] for future MSNs. All mobile devices send their location information to a centralized server via the Internet. The centralized server sends commands to mobile devices so that all of the mobile devices can connect together via *ad-hoc* connectivity such as WiFi Direct by moving to a specific location. Some of the mobile devices are further connected to the centralized server via the Internet. Media streaming services can then be shared among these mobile devices with the advantage of the high speed *ad-hoc* connectivity.

Social Contents Dissemination: With the integration of the traditional communication and opportunistic network architectures, social contents such as news, weather forecasts, traffic alerts, and social media can be retrieved from the traditional communication network by any node initially and then shared with all others over opportunistic networks. Even if the traditional communication network becomes unavailable, future MSNs may still be able to provide some services over opportunistic networks. In addition, whereas conventional MSNs rely on traditional communication networks to support interactions between users (e.g., when user A sends a message to user B, the message is first passed to the server side and then retrieved by user B, over the traditional communication network in both cases), in future MSNs, peer-to-peer data exchanges will be used to support direct short-range communications between users in the same vicinity. For example, exchange of business cards with colleagues and photos with friends will be carried out through short-range communications between the mobile devices. Users can exchange data with each other opportunistically, which gives more flexibility in communications without relying on the traditional network infrastructures.

Besides, mobile users can access a great deal of useful local contents such as news, weather forecast, traffic alerts, and social media via the Internet. The contents are often of interest to nearby users. Future MSNs enable users to get such contents from other mobile users without accessing the Internet. Opportunistic data exchange in future MSNs facilitates context-aware and social-oriented information sharing considering the locations, environmental context, and social interaction of the mobile users.

For example, in [82], contents are disseminated among mobile devices using a publish-and-subscribe model. In addition, micro-blogging services such as Twitter enable users to send short messages that are followed by a public audience as in conventional MSNs. Future MSNs will allow users to share micro-blogs directly over opportunistic networks [99]. The localized social structures may help to deliver micro-blogs to interested recipients in an effective manner.

It will also be possible to search for information locally in future MSNs. A query can initially be propagated to a mobile device in a specific geographic area via a centralized server, and then further propagated between neighboring nodes over opportunistic networks [100].

Neighbor Discovery: Neighbor discovery will be a vital service in future MSNs. Interactions between physically proximate people were facilitated in [101] by using Bluetooth discovery to find nearby devices and a centralized server to match the profiles of users. With this service, conference participants can find the right people to meet, large companies can facilitate internal collaboration between employees, and individuals can find people with common interests in various social environments.

Another neighbor discovery service was proposed in [102]. Mobile devices disseminate the results of local device scanning to alert each other to the presence of parties of interest in a larger area that is beyond local scanning range. Users may then send messages to others to arrange for meetings.

IV. Applications of MSNs

A. Classification of the Existing MSN Applications

As discussed above, supported by the emerging techniques of MSNs, many MSN applications have been widely used in our daily lives, and many more MSN applications will appear in the near future. Inspired by the classifications of MSN applications presented in [7] and the poem *six honest serving men*,[2] we classify the existing MSN applications into three classes: *where*, *who*, and *what*, as shown in Table X.

Where: The MSN applications make responses based on the changes of locations. Examples of such applications are Foursquare and Facebook Places introduced in Section II-A, and location service presented in Section III-A3). Also, in [103], based on the geo-community structure of MSNs, the authors explore and model both geographic and social properties of users' mobility via a semi-Markov process to facilitate data dissemination of MSN applications.

Who: The MSN applications make responses based on the changes of objects' proximities. For example, similar to the client-server architecture of MSNs discussed in Section III-A, a central server can be adopted to collect and compute information collected from individual users, so as to disseminate proximity results to the users' social groups on demand. The current research works about this type of MSN applications mainly focus on efficient group initialization. For instance, based on an online survey that involved 342 people from Europe, the authors in [104] propose a contact recommendation mechanism. This mechanism can efficiently select contacts in order to address them as a social group, so as to ease the initialization of group interactions.

What: The MSN applications make responses based on the purposes of the specific applications. Such applications are usually designed for specific application areas, e.g., healthcare [105], entertainment [106] and so on. In particular, pervasive collaboration is an emerging trend of MSN applications. Taking advantages of mobile phone sensing [107], the MSN applications can contribute sensing data from the crowd [108] and accomplish specific tasks collaboratively in different application scenarios. Examples of the collaborative MSN applications currently available in the research community are Joinus [109] and CarTel [110].

Furthermore, as discussed in Section III-B, taking advantage of opportunistic networks, it is anticipated that the future MSN applications could be widely used in new areas beyond existing application areas, e.g., disaster relief and transportation. A future MSN application for disaster relief has been proposed in our previous work [16]. In the rest of this section, we use

[2]Six questions What, Where, Who, When, Why and How, called 5W1H, from "Six Honest Men" poem of R. Kipling, Just So Stories. Penguin Books, London, 1902.

TABLE X
CLASSIFICATION OF MSN APPLICATIONS

Class	Sub-Class	Features	Examples
Where - MSN applications make responses based on the changes of locations	Location-based/Check in-based	- Mobile advertising - Nearby friends connection - Frequent customer identification	Foursquare, Facebook Places, Yelp, [103]
Who - MSN applications make responses based on the changes of objects	Proximity-based	- Connect people around users - Information sharing between nearby people	Linkility Nextdoor, Cluster[104]
What - MSN applications make responses based on the specific application purposes	Healthcare-based	- Information sharing between medical professionals, patients and patients' family - User life Information logging	Sermo, PatientsLikeMe, MyFamilyHealth, Core, Mobilehealthnet[105]
	Entertainment	- Multimedia and content sharing - Social activity sharing and organization - Social gaming	Facebook, Twitter, Google+, MobiSNA[106]
	Pervasive collaboration	- Make use of the sensing models of different mobile phones in a social context [107] - Integrate multiple sensing data from crowd sources to accomplish specific tasks [108]	Joinus[109], CarTel[110]
	Profession and education	- Users' build connections based on real-world professional relationships	Linkedin, iTeach

TABLE XI
DIFFERENCE BETWEEN NORMAL MSNS AND VSNS

	Normal MSNs	VSNs
Types of social relationships	Between human and human	• Between human and human • Between human and machine • Between machine and machine
Network architecture	Internet and opportunistic networks	Internet and VANETs
Dynamic rate of network topology	Random, depends on the specific scenarios	Usually very high due to the movement speed of vehicles
Energy constrains	High constrains and sensitive for most mobile devices	It may not sensitive, as mobile devices could be charged in vehicles
Real-time requirements	Normal, limited time-latency is acceptable	High, especially for safety applications

a case study to introduce and explore how MSN applications could be effectively used in transportation in the future.

B. Case Study—Vehicular Social Networks

In many parts of the world, people spend a considerable amount of time on their daily commute to and from work. Commuters often follow the same routes at about the same time. Since their travel patterns are highly predicable and regular, it is possible to form recurring virtual mobile communication networks and communities between these travelers and/or their vehicles [32]. VSN involves social networking that occurs in a virtual community of vehicles, their drivers, and passengers, where one or more individuals in such an environment have similar interests, objectives, or other characteristics, and have the capability to interact with each other [111]. Research has shown that knowledge of the social interactions of nodes can help to improve the performance of mobile systems [112]; therefore it is anticipated that VSN applications can be widely used in many fields. The three most common types of applications over VSNs are: a) Safety improvements: applications that improve the safety of people on the roads by notifying the occupants of vehicles about any dangerous situation in their neighborhoods [113]; b) Traffic management: applications that provide users with up-to-date traffic information enabling them to improve route selection, traffic efficiency and driving behavior; c) Infotainment: applications that enable the dissemination, streaming, downloading, or sharing of location-dependent information such as advertisement, and multimedia files such as audio and video over the VSN [114].

Different from normal MSNs, where the participants are human beings who interact with one another using smartphones and mobile devices, the participants of VSNs are heterogeneous, and include vehicles, devices onboard vehicles, as well as drivers and passengers. Thus, three types of relationships are found in VSNs: i) between humans, ii) between humans and machines, and iii) between machines and machines. Also, due to the features of vehicles and the special application environments, the VSN systems have unique characteristics that distinguish them from normal MSN systems, as summarized in Table XI.

The architecture of a VSN system is shown in Fig. 6, in which the "embedded system in vehicles", "pedestrian", and "roadside infrastructures" can be mapped to the common mobile nodes of future MSNs shown in Fig. 4. VSN systems are built on top of vehicular networks that provide connectivity between users and devices participating in the VSN as well as the Internet at-large. While cellular networks can provide such connectivity, the cost

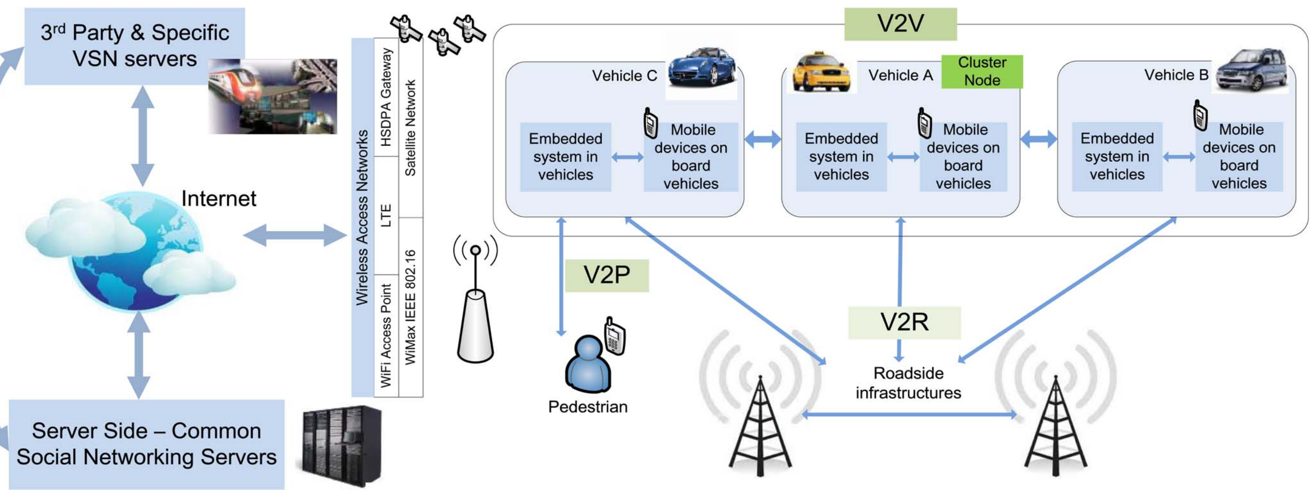

Fig. 6. The physical architecture of VSNs.

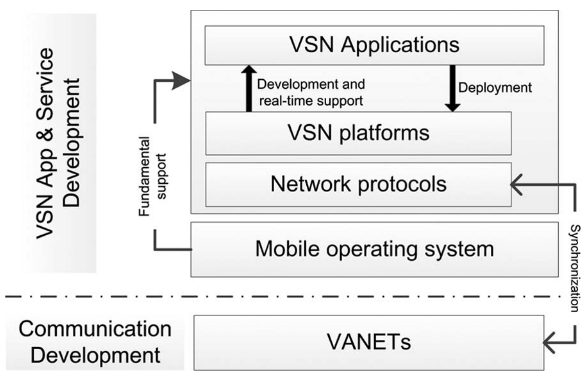

Fig. 7. The development view of VSNs.

may be too high and the latency too large. Instead, a vehicular *ad-hoc* network (VANET) may be established to connect the users and devices onboard vehicles that are physically close to each other [115], [116]. For example, drivers or passengers may carry smartphones with various forms of wireless communication capabilities (e.g., 3G cellular, WiFi Direct), or vehicles may be equipped with embedded computing and networking systems, which support the use of Dedicated Short Range Communications (DSRC) for vehicle-to-pedestrian (V2P) [117], vehicle-to-vehicle (V2V), and vehicle-to-roadside (V2R) communications, with deployed roadside infrastructures in the latter case.

To realize this architecture, as shown in Fig. 7, we should first establish a vehicular network, such as a VANET, which enables spontaneous communications among the devices onboard vehicles and users' mobile devices, and determine its communication specifications. The second step is to develop a software platform (e.g., a middleware) based upon mobile OSs on which to develop and install different applications that function in the VSNs. A number of research projects about VANETs had been conducted, such as investigating stable routing protocols [118], and adopting distribution-adaptive distance with channel quality for multi-hop wireless broadcast [119]. Considering the theme of this paper, in this section, we focus on a suitable mobile software platform for VSNs.

Existing research works on designing VANET applications fall mainly into two categories: language approach and middleware approach [120]. Language approaches are usually language extensions or libraries, which provide new language constructs for developing applications for VANETs. Using a high-level programming language, application developers can flexibly develop diverse types of services, applications, and platforms for VSNs. Nevertheless, such language approaches usually do not provide any implemented application services and mechanisms for VSNs, which may result in a low efficiency in application development. Thus, such approaches could neither provide a set of desirable services to different applications nor manage communications among mobile nodes (e.g., vehicles) [121]. Middleware is a layer of software that manages the interactions between applications and the underlying network by providing various services to the applications. Using a middleware to provide a common set of services for VSNs can simplify the application development process. However, existing middleware for mobile networks are tightly coupled with the applications and thus can hardly meet the highly heterogeneous and ubiquitous service requirements of the diverse users of VSNs [122]. Consequently, it is of interest to investigate and develop a software platform that uses the high-level application programming approach to support the efficient development and deployment of a diverse range of VSN applications.

Furthermore, due to the dynamism of VANETs and the opportunism of user connections in a VSN, dynamic network connectivity (e.g., as vehicles move at high speeds, the wireless links may become unreliable and have short lifetimes) and diverse service requirements of different users in VSNs, which may vary with user locations, time periods, and/or traffic situations, are unique and important challenges of the VSN applications [123]. Thus, effective solutions which can improve the autonomy and self-adaptivity of applications to dynamic service requirements of users in VSNs are needed. Context information in a VSN refers to the information related to the characteristics and specific situations of users, such as their locations, identities, roles, activities, the time at which they engage in the activities, their preferences in interactions with others, local environmental conditions, the current network status, and so on. Also, semantic techniques can be used to formally represent the context information of users and service properties at a high level of abstraction, thus enabling automated reasoning on the represented context information. Such reasoning could facilitate the interactions between entities even if their statuses are unknown to each other [124]. Therefore, the integration of context information and semantic techniques in VSNs can potentially provide a systematic approach to improve the capabilities of applications to fulfill the diverse service requirements of VSN users in highly dynamic vehicular environments [125].

V. Technical Challenges and Future Research Directions

With the development of mobile networks and social network services, many key technologies and research achievements enabling the functionality of MSNs have appeared, and more and more mature MSN applications and services are being successfully used in daily life. However, many technical issues and challenges involving MSNs remain to be addressed. There are also many opportunities to improve the efficiency, functionality, intelligence, and ubiquity of the applications and services for MSNs in the future. In this section, we present and discuss these challenges, some novel techniques, and future research directions for MSNs.

A. Privacy and Security

In MSN systems, the privacy of social network sites could be undermined by many factors, and users are becoming increasingly concerned about the dangers of compromising their personal information. For example, mobile users may disclose personal information when they are exchanging their social network identifiers between devices that use short-range wireless technology such as WiFi/Bluetooth for opportunistic networking as introduced in Section III-B. Further, a mobile device in a client-server MSN architecture presented in Section III-A may notify a centralized server about the current location of the device. By querying the server, mobile devices in these client-server systems can find nearby mobile users, and information about them, such as their identities, interests, and so on. Because most of the social network sites are relatively easy to access, posted contents can be reviewed by anyone with an interest in the users' personal information. The problem is that many social network sites are not taking adequate steps to protect user privacy, and some third parties may access such information posted on the social networks for malicious purposes [126].

Security and privacy of MSNs is closely related to online social networks [127], mobile *ad hoc* networks [128], [129], and mobile sensing [130]. One important challenge in dealing with the issue of privacy in MSNs is that of supporting heterogeneous MSN applications with personal information without compromising the anonymity of the users who provide such information [131]. For instance, it often happens that even if the users do not directly provide information about their identities, the users may provide some social information (i.e., their email addresses, interests, etc.), which could be mapped back to the users' identities through social network sites, or through information cached within the mobile and stationary devices in the surrounding environment. In FindU [132], privacy-preserving personal profile matching schemes have been proposed for MSNs. An initiating user can find from a group of users whose profiles best match with his/her, so as to limit the risk of privacy exposure by exchanging only necessary and minimal information about the private attributes of the participating users. Narayanan and Shmatikov [133] also proposed a framework for analyzing privacy and anonymity in social networks and developed a new re-identification algorithm targeting anonymized social- network graphs.

Location privacy is one of the major privacy concerns in MSNs [134]. Knowing the locations of a user makes it possible to trace him or follow his daily routines. Chang *et al.* [135] showed that simply omitting location updates does not provide adequate privacy protection, especially in situations where the friendship relationships between users are known. They proposed a fake location update algorithm that allows a user to protect his privacy without the use of any third party services. Similarly, Puttaswamy and Zhao [136] adapted an approach where untrusted third-party servers are treated simply as encrypted data stores, and the application functionalities are moved to the client devices. The location coordinates are encrypted when shared, and can be decrypted only by the users that the data are intended for.

Other than privacy, trust is another important aspect for online social networks. It enables entities to cope with uncertainty and uncontrollability caused by the free will of others. Trust computations and management are highly challenging issues in mobile networks due to computational complexity constraints, and the independent movements of component nodes [137]. Trust also becomes an essential and important element of a successful social network. Sherchan *et al.* [138] provided a comprehensive review of social and computer science literature on trust in social networks. It reviewed the existing definitions of trust and defined social trust in the context of social networks. It further discussed recent works addressing three aspects of social trust: trust information collection, trust evaluation, and trust dissemination.

The indirect anonymity problem exists when a piece of information indirectly compromises a user's identity [139]. In addition, once a user's social network identity has been intercepted in a MSN, it can be used to mount a replay and spoofing attack. In a spoofing attack, a malicious user can masquerade as another user whose identity has been intercepted by simply sending or replaying the intercepted identity to mobile or stationary devices that request the user's social network identity [140]. Thus, mitigating the replay attack is another crucial challenge to privacy and security in MSNs.

Furthermore, authentication and access control are vital for security and privacy in MSNs with the presence of various internal/external threats, since adversaries will monitor and expose sensitive data of other participants. To address these challenges in MSNs, there are several authentication, authorization and access control mechanisms that focus on the following aspects: Privacy preserving in collaborative environments [141], flexibility to access authorization dynamics, adaption to network mobility [142], anonymity guarantee of mobile social services provided by mobile device, minimizing protocol and storage overheads [143], [144], etc. As a matter of fact, trade-offs exist between the security strength and the communications/storage efficiency of authentication, authorization and access control mechanisms, which require careful considerations in the design process.

B. Resource Management and User Behaviors

Since users of mobile devices have their own needs of local resources in their devices, such as bandwidth, processing power, and energy, participation in MSNs will inevitably lead to a decrease in resources available to the users. To solve this problem in MSNs, resource management techniques used in distributed computing may be applied to MSNs, e.g., renting in advance resources offered by other mobile devices [145]. Bandwidth allocation is important for radio resource management to achieve the best performance in MSNs [17]. Ioannidis *et al.* [10] studied the dissemination of dynamic content, such as news or traffic information, over a MSN. They formulated an optimization problem and proposed a distributed method to determine how the service provider can allocate its bandwidth to make the content at users as fresh as possible. Similarly, how the content providers and the network operator can interact to minimize the cost for content distribution in MSNs was investigated in [146]. It introduced a novel coalitional game model to investigate the decision-making process of the content providers and the network operator. Although different approaches have been proposed for optimizing resource management, the impact of user behavior and their social relation remain to be further explored in MSNs.

Human altruism has been investigated deeply in [147], [148], where it was shown that human cooperation relies on rewards or punishments. Similar reward-based and punishment-based approaches are also applicable in MSNs. The basic idea is to encourage nodes to store and forward messages for the benefit of others, such as the approaches of data forwarding and data dissemination introduced in Section III-B-2). In reward-based approaches [149]–[151], credits are paid by source nodes that send messages to others and given to intermediate nodes that carry and deliver messages. Another credit-based approach [152] uses the concept of message trading. A node can download a message from another if it can provide a message in return. A similar approach is used in PlanetLab [153], a globally distributed platform used for developing and evaluating network services. In punishment-based approaches [154], selfish nodes are detected by other nodes, which propagate announcements of the identity of the selfish nodes over the network. The announcements eventually result in the selfish nodes becoming unable to receive any messages. Most existing *ad-hoc* based MSN protocols are designed based on the assumption of altruistic cooperation among nodes. However, the exchange of messages between nodes consumes resources such as energy and storage. Some nodes may download interested data items but refuse to store and forward data items to others. Taking into consideration the behavior of nodes is therefore important in designing MSN systems. A routing approach that considers the willingness of nodes when selecting relay nodes was proposed in [155]. Based on the assumption that users are partially altruistic, [156] showed that if all users have an altruistic coefficient $\beta > 0$, then the price of the anarchy of traffic routing is bounded by $1/\beta$. The impacts of different distributions of altruism on the throughput and delay of MSN systems are studied in [157], which shows that MSNs are robust to the distributions of altruism because of the existence of multiple paths. Future research directions may include exploring the user interests in different application contexts to enhance data sharing. It is also interesting to exploit the social relationships between users to understand the user behavior, social and activity patterns. The behavior and activity patterns can form the basis of personalized resource allocation in the mobile devices and enhance data sharing between mobile users.

C. Data Mining

As presented in Section III-A, MSN services and applications can benefit greatly from the context information generated or collected at mobile devices. Data mining techniques may be utilized to provide high quality, useful and real-time context information to MSNs, hence improving the quality and efficiency of MSN applications and services. There are two main approaches to using data mining to support MSNs: one is through the Internet; and the other is through distributed mobile devices and their surrounding environments.

With the advent of cloud computing, a recent strategy is to use "network analysis software" [158] on the Internet to automatically extract social information from the online social networking sites, including the users' identities, interests, and relationships with others. The computation power and the rich resources on the cloud servers enable fast processing of large amount of data. However, it often happens that a user may have different account names; hence, it could be difficult to map all of the information to one particular user. Similarly, using non-unique data fields to map data can easily result in inaccurate data sets. Another problem is that most of the data on websites are not available to the browsers, but are hidden in forms, databases, and interactive interfaces [159]. Although many web servers provide APIs that enable easy access to the hidden data, they normally require some form of authentication in order to be used. Thus, the challenge is for data mining software to maintain the credentials to process different online social websites in parallel without simultaneously endangering the security of the users.

Data mining can also be performed on the distributed mobile devices, which focuses on the context and interaction of users with their environments and surrounding people. Data mining software should be able to access and analyze the data stored on the mobile devices of users, such as contact lists, location history, and so on, which reflect the closest social contacts or real friends of the users. The local data on mobile devices can also be combined with the online social data on the Internet, e.g., using a crawler to access such data. Similarly, the software running on the local mobile devices can collect information and then publish the relevant information to the external websites. Nevertheless, it is a challenge to preserve the user's privacy while minimizing battery consumption in the mobile device, since such devices usually have limited energy supplies [160]. In addition, it is possible for the mobile devices to collect data from their surroundings, in order to detect social interaction patterns by getting information from sensors deployed in vehicles or other mobile devices [161]. Such information could be aggregated and processed with other information obtained from the social websites mentioned above, so as to generate more comprehensive information and further optimize the mining of context information and data quality for MSNs.

D. Optimization for Cross-Layer Design and Resource Allocation

The concept of cross-layer design is based on an architecture where different layers (i.e., physical, network, and application layers) can exchange information in order to improve overall network performance [162]. As discussed Section III-B2), analyzing social behaviors can improve the opportunistic communication for applications/services of MSNs. In fact, we can also utilize such information to optimize the design of protocols in different layers, and many good results have been achieved in significant studies on cross layer optimizations for MSNs [163]. Furthermore, through cross layer optimization, we can extract related context information about data dissemination in the network layer, so as to enrich the information that has been obtained about social behavior and to improve the applications/services in the application layer. For example, we can use middleware as a bridge to enable the upper layer (i.e., the application layer) and lower layers (i.e., network and physical layers) to support each other simultaneously at mobile devices' run-time, hence forming a dynamic and optimum partnership. In addition, different from conventional social networks, MSNs are not only centered on the individual person, but also on mobile devices. Thus, information (i.e., sensing data, unique IDs in mobile devices, etc.) about mobile devices and the relationships with their owners may also be crucial in optimizing communications.

Optimization is very helpful for data dissemination and resource allocation in MSNs. Ning *et al.* [164] proposed a Self-Interest-Driven (SID) incentive scheme to stimulate cooperation among selfish nodes for disseminations of advertisements in autonomous MSNs. It introduced "virtual checks" to eliminate the needs of accurate knowledge about whom and how many credits an advertisement provider should pay. It formulated the nodal interaction as a two-player cooperative game, whose solution is obtained by the Nash Bargaining Theorem to maximize the benefits of nodes in data disseminations. Similarly, Niyato *et al.* [146] investigated how the content providers and the network operator can interact to distribute content in a MSN. The objective of each content provider is to minimize the cost that pertains to the time used to distribute the content to the subscribed mobile users and the cost due to the price paid to the network operator for transferring the content over a wireless connection through a base station. It introduced a novel coalitional game model to investigate the decision-making process of the content providers and the network operator. Chen *et al.* [165] further developed a coalitional game theoretic framework to devise social-tie based cooperation strategies for device-to-device communications. They developed a network assisted relay selection mechanism to implement the coalitional game solution, and showed that the mechanism is immune to group deviations, individually rational, and truthful. Recently, Ashraf *et al.* [166] explored social networks for optimized user association in wireless small cell networks with device-to-device communications.

E. RESTful Web Service and Cloud Computing

Web services have paved the way for new types of mobile software systems like MSNs. The best-practice of SOA will help to make web services initiatives a success [167], [168]. However, currently most of the mobile applications based on SOA, such as MobiSoC introduced in Section II-B4), can only run as SOA clients in mobile devices, while all service requests and interactions are completely reliant on conventional centralized SOA servers that exchange SOAP messages with the clients. The high network overhead of SOAP messages results in a low efficiency in the use of wide-area wireless networking resources, while the centralized architecture makes it difficult to apply SOA to opportunistic networks. The Representational State Transfer (REST)-ful Web Service [169] is an approach to using REST purely as a communication technology to build SOA, where services are defined using SOA style decomposition and REST-based Web Services are leveraged as a transport. Different from conventional SOA based solutions, the RESTful Web Service is well suited for basic, *ad-hoc* integration scenarios with a low resource overhead (e.g., network overhead) as it is based on a light-weight design principle [170]. Thus, it is of interest to investigate the development of mobile applications and services for MSNs based on RESTful Web Service.

Cloud computing is evolving as a key computing environment to enable the sharing of resources such as infrastructures, platforms, and value-added services and applications [171]. Cloud computing consists of three levels from the bottom to the top: infrastructure as a service (IaaS), platform as a service (PaaS), and software as a service (SaaS). Today, linking traditional social contents and web services to the cloud is becoming increasingly important, as doing so can scale up information processing capabilities and achieve striking results with high efficiency through parallel and distributed computing techniques [172]. Thus, MSNs could leverage the computational advantages of a cloud computing platform to manage and coordinate the synchronization, dissemination, and deployment of the diverse social contents, applications, and services of MSNs. In addition, since SaaS based applications are eventually presented to users as online services, SOA should potentially be the most suitable software architecture for developing SaaS-specific MSN applications on cloud platforms.

F. Dynamic Service Collaboration and Human Computer Interaction

As discussed in Section III-B1), services such as Instant Messaging (IM), video conferencing, and shared presentations could be developed into important tools for business and private life [173]. Since social networks have developed into widely used platforms for interconnecting people with intrinsic collaboration features such as the sharing of contents and services, and today's smartphones are equipped with a range of sensors, powerful processors, and high-bandwidth wireless networking capabilities, the collaboration of services with respect to MSNs is anticipated to become widespread in the near future. As discussed above, SOA could provide a unified specification for service interactions, and support the composition and collaboration of services across different MSN platforms and mobile OSs in a flexible manner, by providing a general and unified strategy that makes software service collaboration possible. The interactions between humans and mobile devices cannot be neglected, as humans could also contribute intelligence and human-based services in MSNs. However, as the application purposes and specialties of individuals are various and the capacities of their mobile devices are heterogeneous, an optimization mechanism that could simultaneously support efficiently and effectively allocating the computing tasks and human based tasks among individuals is still lacking [174]. Thus, investigating the applications of HCI theories and related techniques for MSNs may potentially yield useful findings in this area.

G. Mobile Crowdsourcing

Crowdsourcing [175] has evolved to cover a variety of activities engaged by online societies involving networks, incentives, and the aggregate behavior of large groups. It helps people to exploit the collective intelligence from a large number of individuals to solve complex problems, and provides an effective and economical mechanism to carry out initiatives with members of the public [176]. For example, Amazon Mechanical Turk (AMT) has created a marketplace for carrying out work that is difficult for computers but relatively simple for humans. There is a remarkable trend to approach mobile crowdsourcing through the use of mobile devices [177], as this can help with the handling of a diverse range of problems involving real-time data gathering and processing, and collaborations among a large number of participants in mobile environments. It can also shorten the distance between people around the globe, and therefore enable them to work together and contribute knowledge in an effective and economical manner [178]. MSNs could potentially take advantage of mobile crowdsourcing to investigate the effectiveness of mobile social collaborative applications. MSNs also provide an ideal platform to encourage mobile users to participate in crowdsourcing. One key challenge is that, as the availability of an individual's mobile device may be unreliable (particularly in opportunistic networks), such as due to the crash of mobile operating systems, battery exhaustion, and intermittent networking disconnection, this may result in service failures and impede the pervasive use of crowdsourcing applications [179]. However, most of the existing solutions [180] for mobile service failure handling rely on specific protocols, and could not support different crowdsourcing applications of MSNs widely, thus a novel mechanism that could handle possible service failures and to ensure a high level of reliability of mobile crowdsourcing applications needs to be investigated.

H. Energy Constraints and Wireless Electric Energy Transmissions

Since smartphones play an important role in MSNs, while the battery life of a smartphone is very limited, power conservation is an important driver for designers of applications for MSNs. Usually, the power consumption of a smartphone arises from: (i) the processor and display/touch screen, (ii) radio interfaces such as WiFi, Bluetooth, 3G, and (iii) sensing devices such as GPS, accelerometer, proximity sensor, camera, and so on [160].

Designing efficient duty cycles for the use of power-hungry radios is necessary to extend a smartphone's battery life [181]. In order to find an appropriate strategy to save energy, knowledge of the amount of energy spent in every single action performed by the smartphone is needed [12]. Fortunately, some mobile OSs, such as Android, have already provided such functions. Also, the authors in [182], [183] proposed a context-aware platform and mechanism to efficiently balance energy consumption and the acquisition of sensing data, e.g., to reduce the acquisition of satellite signals for location coordinates while maintaining accurate localization. Furthermore, a middleware architecture called My-Direct was proposed in [184]. Inside this architecture, the authors designed an intelligent mechanism that adopts the multi-agent approach to automatically detect events occurring in the environment, so as to reduce energy consumption of MSN applications. In addition, data dissemination of MSN applications may also result in much battery consumption on mobile devices. To address this, the geographic regularity of human mobility in MSNs was exploited in [185] to design a semi-Markov analytical model that describes such mobility patterns, which was used to optimize the route design in data dissemination of MSNs. In addition, a simulation platform for MSNs was proposed in [186] that could potentially help researchers to evaluate different energy optimization schemes for MSN applications. Nevertheless, there is still a tradeoff between the quality of user experience and power consumption, as users are more concerned about the effectiveness of MSN applications, which tends to increase with power consumption in some situations. Thus, it is challenging to develop applications for MSNs that provide a favorable user experience without significantly reducing the battery life of smartphones.

WiTricity is a recently released technology. It supports highly efficient wireless electric energy transfers by using mid-range resonant coupling [187]. Different from radio waves, resonant coupling uses a closed magnetic field; thus no energy is wasted when the energy receiving device is out of the range of a WiTricity transmitter. Also, the radiation levels of WiTricity are significantly below the applicable health and safety limits, even though a large amount of power is being transmitted. Investigating the WiTricity technique applied in mobile devices is meaningful and very useful for MSN applications and services in the future; e.g., the strategy of relaying transmissions to extend the power transfer range of WiTricity [188], and the optimization of WiTricity transmitters and receivers for mobile devices [189].

I. Mobile Internet of Things

The Internet has enabled an explosive growth of information sharing, but it has also escalated the problem of information overload. By 2020, the number of Internet users will reach almost five billions. The increasing number of people connected to the Internet is resulting in a massive amount of data uploads and downloads. With the advent of mobile and sensing technology, the number of smart objects connecting to the Internet is also growing rapidly. Future network design should be prepared to handle at least 10^{15} smart objects such as sensors, smartphones, radio frequency identification (RFID) tags, and smart grid terminals and control points through the Internet, which is much larger than the current size of the web [190]. Anticipating the vast volumes of data, it is a challenge to identify valuable information as judged by the individuals and share with the users the right information at the right time and right place.

Internet of Things (IoT) has been envisioned to comprise an integral part of the future Internet that extends into the cyber-physical world [191], [192]. IoT involves a worldwide network of interconnected objects that are uniquely addressable, based on standard communication protocols. Increasing research is taking place to explore the technical requirements and business models to address today's societal challenges by deploying IoT technology, e.g., for health monitoring, traffic congestion avoidance, pollution monitoring, security and safety, and industrial process optimization. The advancement of mobile devices enables physical interaction with smart objects to facilitate information sharing and services [193], [191]. Mobile devices can collect data and interact with smart objects simply by reading the RFID or NFC tags, or taking pictures of visual markers [194]. For example, the Pervasive Service Interaction (Perci) project has examined different aspects of Pervasive Mobile Interaction (PMI). It has investigated basic mechanisms for integrating PMI with mobile services, improving interoperability between them, and improving the usability of physical user interfaces and interaction techniques [195].

Apart from RFID and NFC tags, mobile users can collect sensing data from sensors in their vicinity through short-range communications with their smartphones, e.g., using Bluetooth or WiFi. The concept is similar to "Data Mules", which allow moving entities to collect data from the wireless sensors in their surroundings [196]. Evolving from stationary sensor networks, mobile sinks or data mules have been suggested for data collection particularly in sparsely deployed sensor networks [197], [198]. Ubiquitous data sharing is highly valuable for mobile users to obtain sensing data that cannot be collected directly on their own. Mobile users can share the collected sensing data with each other through short range communication opportunistically or via the Internet [199], [200]. This can create a community of MSNs that collect sensing data from heterogeneous smart objects and distribute relevant and accurate sensing information. Given the fact that location-based services are increasingly popular, MSNs may emerge as a common platform to host and share a large amount of valuable information. For example, context- and social-aware data dissemination has been explored for opportunistic networks. Boldrini *et al.* [201] proposed a middleware that automatically learns context and social information of the users in order to predict their future movements. Yoneki *et al.* [82] proposed a socio-aware overlay over detected communities for publish/subscribe communications. Jaho *et al.* [202] divided users into different interest induced social groups and locality-induced social groups to improve information dissemination in social networks. IoT is foreseen to be integrated seamlessly with MSNs to provide valuable information and services ubiquitously for mobile users.

VI. Conclusion

Interest in MSNs as a bridge between mobile technology and social science has been growing rapidly in the past few years. More and more MSN applications, services, and systems are being deployed and widely use in daily life. Through ubiquitous services, MSNs have not only changed the way people communicate with each other, but also promoted human collaborations. This has led to revolutions in many domains of human life, such as education, science, health-care, government, and so on. In this paper, we have presented the basic concept, unique features, and application domains of MSNs that distinguish them from conventional social networks. With the emphasis on the applications, services, and system architectural design of MSNs, we have introduced some mature commercial MSN platforms as well as experimental MSN solutions, presented the dominant mobile OSs on which MSN applications and services are developed and deployed, and discussed the overall architectural designs of MSN systems over mobile networks and their related services and key technologies. A special form of MSNs—VSN has been described in our case study to illustrate emerging applications with MSN technology.

In the future, many issues still need to be further explored to improve the efficiency, functionality, intelligence, and ubiquity of the applications and services for MSNs. Some of the directions are to consider the contextual information, user behavior, and available resources to improve the data quality and efficiency of MSN applications and services using data mining and optimization techniques. Another important direction is privacy and security, which is essential to protect the personal information of users and provide authentication, authorization and access control of data. RESTful Web Service and cloud computing for MSNs are important directions for service providers and developers to provide ubiquitous MSN services. Investigations of HCI and crowdsourcing in MSNs could help to promote intelligence and collaboration of MSN applications. Other emerging applications such as mobile IoT is of interests to explore to further extend MSNs for future health monitoring, traffic control, and pollution monitoring.

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