Opportunistic IoT: Exploring the Harmonious Interaction between Human and the Internet of Things

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Abstract

The traditional view of Internet of Things (IoT) attempts to connect all the physical objects to build a global, infrastructure-based IoT. In this paper, however, we will present opportunistic IoT**,** which is formed based on the ad hoc, opportunistic networking of devices (e.g., mobile phones, smart vehicles) using short-range radio techniques (e.g., Bluetooth, Wi-Fi). The opportunistic IoT demonstrates inherently the close relationship between human and opportunistic connection of smart things. It enables information forwarding and dissemination within and among the opportunistic communities formed based on the movement and opportunistic contact nature of human. We characterize the bi-directional effects between human and opportunistic IoT, discuss the technical challenges faced by this new research field, and propose a reference architecture for developing opportunistic IoT systems. Some of our ongoing practices, including opportunistic mobile social networking, opportunistic marketing, and community service provision are further presented to demonstrate the potential application areas and technical solutions of opportunistic IoT.

Keywords: opportunistic IoT, opportunistic mobile social networking, heterogeneous community orchestration, information dissemination, human-centric sensing

1. Introduction

The Internet of Things (IoT) refers to the emerging trend of augmenting physical objects and devices with sensing, computing, and communication capabilities, connecting them to form a network and making use of the collective effect of the networked objects. Under the vision of IoT, the next-generation Internet will promote *the harmonious interaction between human, societies, and smart things* [1].

In the past few years, significant research efforts have been made on IoT, mainly from a *thing-oriented* perspective. A wide range of areas are covered, including object identification and tracking, object networking, sensing data visualization, privacy control, and so on [2]. Nevertheless, the “harmonious” interaction between human and IoT, or in other words — the social side of IoT, has yet little been explored.

In terms of its topology features, we can broadly category network connection into two types: *infrastructure-enabled* connection and *ad hoc* or *opportunistic* connection. The prior type uses pre-existing infrastructure (e.g., base stations, routers, access points) and manages the data in a centralized manner. The latter one, however, is founded on the development of opportunistic networks [3], which uses infrastructure-free, short-range radio techniques (Bluetooth, Wi-Fi, etc.) to build decentralized, ad hoc networks. Opportunistic networks are human-centric because they inherently follow the way that people opportunistically get into contact. For instance, customer *A* can connect with other customers that opportunistically meet in a coffee shop to build an ad-hoc mobile phone network. Information sharing and communication can be further conducted among the members of this “opportunistic, physical-proximity-triggered” community. When *A* leaves the coffee shop, the information she obtained from this **opportunistic community** (e.g., there will be an open-air concert in the *Central Park* tomorrow night) can be further disseminated to other newly-formed opportunistic communities (e.g., with his/her colleagues in the working place, with other passengers on the bus).

The traditional view of IoT attempts to connect all the physical objects to build a global, infrastructure-based IoT. In this paper, however, we will present **opportunistic IoT,** which addresses *information dissemination and sharing within and among opportunistic communities (with pairs of devices) that are formed based on the movement and opportunistic contact nature of human*. Various personal devices, such as mobile phones, wearable devices, vehicles, can form opportunistic IoT when they are equipped with the short-range communication and sensing modules. We illustrate the concept of opportunistic IoT through the following “opportunistic trading” use case.

Different from traditional market-based trading and online shopping, opportunistic trading is founded on the disseminating and matching of trading requests in opportunistic IoT environments. For example, Bob wants to buy a second-hand “Harry Potter” via the opportunistic trading agent (OTA) running on his mobile phone. While

Bob moves each day, his trading request is shared by people in the vicinity (forming an opportunistic community using mobile phones). Since the moving range and mobility pattern of Bob is roughly fixed (the number of people he can encounter is thus limited), to increase the number of trading request receivers and speed up the request dissemination process, OTA will employ other mobile nodes as "brokers" to help store and forward Bob's request. How to select brokers becomes a significant yet difficult problem, where we should consider the popularity of the node (in terms of its mobility patterns) and other social features (e.g., willingness to act as a broker). Two days later, Alice (the book seller), who lives in another district of the city, is found by OTA and the brokers.

The above scenario demonstrates the bi-directional relationship between human and opportunistic IoT. On one hand, opportunistic IoT becomes the primary media to sense and monitor human behaviours (e.g., mobility patterns can be learned from the GPS trajectories collected from user-carried mobile phones); on the other hand, the performance of IoT is also affected by human behaviours (e.g., social features are important for broker selection). In summary, opportunistic IoT presents a promising research domain to study the social side of the IoT. Further, according to the Oxford English Dictionary [4], *collaboration is the act of working with another person or group of people to create or produce something*. In technology, it encompasses a broad range of tools that enable groups of people to work together including social networking, instant messaging, web sharing, and so on. Wikipedia, Blogs, and Twitter are good examples of collaborative tools. By leveraging the opportunistic connection among people in the proximity, opportunistic IoT facilitates information dissemination and sharing, as well as spontaneous social networking (when the information exchanged is user profile [5]) among people in opportunistic communities, presenting a promising way to enhance instant human collaboration and data sharing.

In the following sections, we first describe the relations between our work and several closely-related research areas. The bi-directional effects between human and IoT will then be characterized. In Section 4, we discuss the research challenges on opportunistic IoT, followed by the description of a conceptual architecture in Section 5. Our ongoing efforts to opportunistic IoT are presented in Section 6. Finally, we conclude the paper and present the future work.

2. Research Background and Related Work

Research on opportunistic IoT can benefit from the ongoing and past research outcomes in *pervasive computing*, *opportunistic networking*, *social computing*, and *mobile social networking*.

In his seminal paper [6], Mark Weiser prophesied that *pervasive computing* can learn and adapt to human needs in an unobtrusive, ubiquitous manner. Over the last decade, mainframe studies on pervasive computing are about ubiquitous tracking/sensing [7], context-aware computing [8], personalization [9], mainly relying on the wireless infrastructure support (e.g., cellular networks, WLAN). Opportunistic IoT, however, addresses the limitation of wireless infrastructures, such as lacking network coverage, high cost, etc. In addition, the core of pervasive computing is context-awareness. Opportunistic IoT takes pervasive computing further, to explore the learned human behavior and social connection to enhance opportunistic data sharing.

Opportunistic networking is based on spontaneous connectivity between users with wireless devices [3], facilitating inter-device data routing and forwarding. Opportunistic IoT extends the opportunistic networking concept from two aspects: 1) it is rooted from the Internet of Things vision, which inherits the nature of smart things on *ambient sensing*. Local-sensed information (traffic dynamics, noise levels) can thus be opportunistically shared by others, i.e., supporting the so-called *participatory sensing* [10]; 2) it particularly explores the co-existing of opportunistic communities in the physical world and online communities in the virtual world, and study the interaction and collaboration between heterogeneous communities. There are also several studies that try to introduce the opportunistic element into IoT systems. For instance, Blackstock et al. have developed Magic Broker 2 [11], a lightweight middleware that supports spontaneous interaction between smart devices (public displays, mobile phones). Rohokale et al. have proposed a novel cooperative approach for the analysis of receiver sensitivity to enhance relay-based communication in wireless sensor networks [12]. However, none of them explore human factors in IoT systems, especially the interaction and interplay between online and offline social communities.

Social computing refers to the computational facilitation of social studies and human interaction analysis as well as the design and use of technologies that consider social context [13]. Similar to opportunistic IoT, social computing takes human factors and social behaviour analysis as key dimensions. However, social computing emphasis mainly on the analysis of human interaction using Web data, it does not target at the study of physical communities.

Mobile social networking (MSN) refers to social networking where individuals with similar interests connect with one another through their mobile devices [14]. Similar to Web-based social networking, existing MSN services (e.g., Foursquare) occur in the virtual world, relying on full mobile access of the Internet. The opportunistic IoT, however, will drive a different form of MSN – the Opportunistic MSN [5], which aims to enhance spontaneous interaction/communication among people that opportunistically encounter in the physical world, without leveraging any infrastructure support.

In summary, opportunistic IoT shares many things in common with the aforementioned research areas, yet it goes beyond all those areas in terms of its focus and research challenges. Different from those areas that either focus on human behaviour/context analysis or opportunistic data sharing, the opportunistic IoT particularly addresses the interaction of the two research directions. Moreover, opportunistic IoT also studies the interlinking and collaboration between online communities and physical communities, as we present in the latter sections.

3. The Bi-directional Effects between Human and Opportunistic IoT

By analyzing the tight-coupled relationship between human and opportunistic connection of smart things, we present the bi-directional effects between human/societies and opportunistic IoT, as shown in Fig.1.

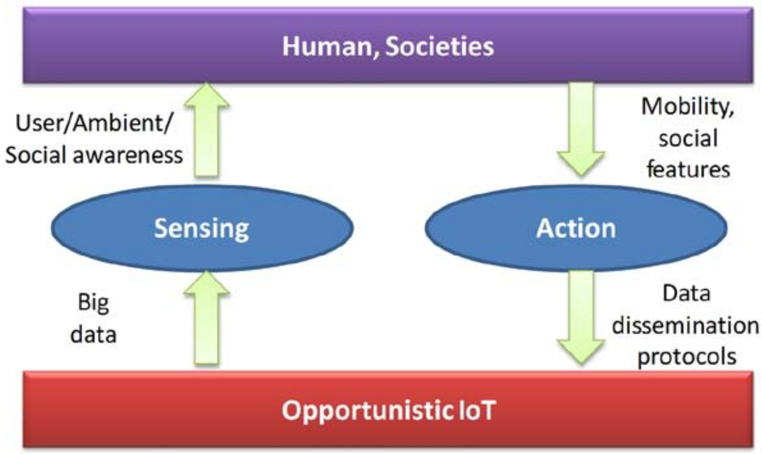

Figure 1: The bi-directional effects between human, societies and IoT.

3.1. Human-Centric Sensing with Opportunistic IoT

Various IoT devices (equipped with sensing and short-range communication capabilities) are weaved deeply into the fabric of everyday life. The diverse features of these devices present unprecedented opportunities to understand the aspects of interaction between humans and real-world entities. We characterize these human-centric interactions as *human-object*, *human-environment*, and *human-human* interactions. By analyzing the collected interaction data with advanced machine learning and data mining techniques, the opportunistic IoT is equipped with three sensing capabilities: *user awareness, ambient awareness,* and *social awareness* [15]. We characterize the attributes of them as follows.

- *User awareness* refers to the ability to understand personal contexts and behavioral patterns. Examples include human activity, human popularity, preferences, etc.
- *Ambient awareness* concerns status information on a particular space. Examples include space status and traffic dynamics (e.g., traffic jams).
- *Social awareness* goes beyond personal contexts and extends to group and community levels. The objective is to reveal the patterns of social interaction (e.g., group detection, friendship prediction, situation reasoning), human mobility, etc.

3.2. The Impact of Human Behaviors on the Opportunistic IoT

Data sharing is the major application area of opportunistic IoT, which exploits humans' mobility and their gregarious nature to transmit information. Since the source node and destination nodes might be unaware of each other (e.g., in the opportunistic trading use case, *Bob* and *Alice* are unaware of each other) and may never meet in opportunistic networks, forwarding a message (e.g., selling a book called "*Harry Potter*") from its sender to the nodes of interest (e.g., from *Bob* to *Alice*) becomes a big challenge. A trivial solution would be to flood the whole network with the message [16], but this would clearly saturate both network resources (in terms of available bandwidth) and device resources (e.g., in terms of energy, storage, and so on).

A better solution is to replicate the content to only selected nodes that have more chances to contact and influence others, and thus the *broker-based* solution is proposed (as demonstrated in the opportunistic trading use case). With this solution, each node (e.g., node *Bob*) carrying a message evaluates the suitability of any other node it makes contacts with as the broker (many social features are measured, as depicted later).

Messages are thus *opportunistically* disseminated by exploiting both the source node (e.g., node *Bob*) and the brokers selected, until they reach a node of interest (i.e., node *Alice* who lives in another district of the city wants to buy the book).

In opportunistic IoT, contacts between nodes are inherently tied with users' social behaviors (e.g., two mobile phones contact when user *A* and *B* meet in a coffee shop). We thus need to exploit various social behaviors in designing broker-based data dissemination protocols. For example, when selecting brokers, the social features such as user popularity (does the broker meet many different people each day), social willingness (is the broker willing to carry and forward the message), social network structure (Bob's friends are more likely to act as his brokers), preferences (the broker may filter dissemination it tasks according to his/her preferences), and so on, will affect the performance of the protocol designed. Therefore, we state that the application of opportunistic IoT is also driven by exploring human behaviors and social features. One use case is illustrated in Fig. 2, where a broker is selected to carry and forward a message in the school campus, by measuring her social features such as social popularity and willingness.

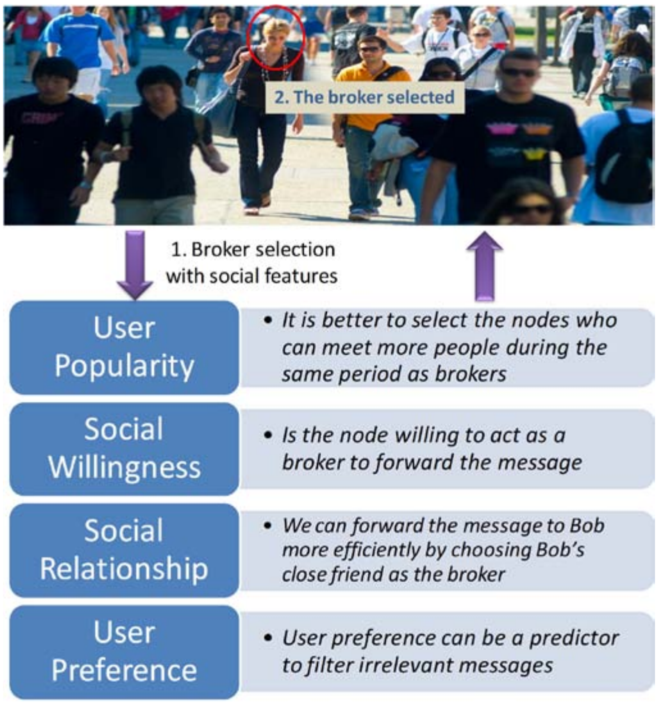

Figure 2: The impact of human behaviors on the opportunistic IoT

Besides data routing, there are several other human factors that may affect the formation and performance of opportunistic IoT. For example, human usually carry different kinds of mobile devices (mobile phones, PDAs, etc.), with distinct capabilities (some are more powerful with respect to the other nodes). We thus should consider device heterogeneity when designing the networking protocols for opportunistic IoT. In decentralized environments such as opportunistic IoT, trust relationship among peers also plays an important role. As mentioned earlier, the development of services in opportunistic IoT (e.g., sharing local-sensed information; formation of opportunistic communities for common-goal achieving) relies on the collaboration among opportunistically-encountered people. Mechanisms for establishing trust are thus crucial to maintain information security and data privacy in opportunistic communities. We discuss about this in detail in Section 4.3.

Overall, the bi-directional effects between human and IoT reflect the basic nature of opportunistic IoT. It also reveals the social side (while not technical side) of IoT and presents the human-centric (while not thing-oriented) view of IoT, which has been little concerned in previous studies of IoT.

4. Challenges and Research Opportunities

Developing the potential benefits offered by opportunistic IoT poses a number of challenges and concerns. In facilitating the development of opportunistic IoT systems, a fundamental issue is the design of data dissemination protocols. Other important issues include heterogeneous community orchestration, security and incentive mechanisms for user collaboration, and so on.

4.1. Human Behavior and Data Dissemination

Data dissemination in opportunistic IoT is a difficult problem. The heuristic behind the dissemination policy is that, since content providers and content consumers might be completely unaware of each other in a dynamic network, and never be connected at the same time to the same part of the network [3]. Therefore, data objects should be moved and replicated in the network in order to carry them to interested users despite disconnections and partitions.

As presented in Section 3.2, to facilitate data dissemination and reduce its cost, the broker-based solution is often used. To this end, researchers start to explore mobility models [17, 18], co-location patterns [19, 20], and social network structure [21] as key pieces of human behavior/context information to predict nodes' activeness and estimate their "social popularity" to serve as brokers in the near future. This seems to be promising because contacts between nodes are fundamentally tied with human behaviors. Two basic assumptions are leveraged here: (1) The higher a node's popularity, the higher the chances of it meet more devices; and (2) all users are willing to act as brokers (the so-called "selflessness brokers"). However, the latter assumption does not always hold, since brokers have to contribute computational resources during the data carrying and forwarding process. According to the social theories, socially selfish is a basic attribute of human beings [22, 23], which will affect human behaviors. Besides, preferences will also affect the behaviors of a broker. Therefore, we should measure the affects of various social features and taking consideration of them when designing data dissemination protocols for opportunistic IoT systems.

4.2. Heterogeneous Community Orchestration

With the development and prevalence of opportunistic communities, people will live in heterogeneous social communities within cyber-physical spaces - both online communities and social networks where digital content is exchanged, and in the physical world, which exploits opportunistic contacting (i.e., face-to-face) between pairs of networked devices (e.g., smart phones) to exchange each other's content.

Different social networks have distinct features in terms of geographical coverage, infrastructure support, function time, and so on. This also leads to distinct human interaction patterns (e.g., comment/like in online communities, co-location in ad hoc communities) and implicit social knowledge (e.g., friendship/trustworthy/ influence in online communities, social popularity/movement patterns in ad hoc communities) that can be extracted from them. Study of the interaction between opportunistic and online social networks (e.g., how does online social network data mirror physical events), as well as merging their complementary features and fully combining their merits (e.g., connecting the two forms of social networks to enhance data dissemination/sharing), however, become an important yet challenging research area. We use the term "*heterogeneous community orchestration*" to represent the potential interaction/collaboration issues raised in multiple, heterogeneous, virtual/physical community environments.

So far, research on online and opportunistic communities follow two separate research lines. The interaction/collaboration of the two forms of communities has yet little been explored. There have been studies about social network analysis across heterogeneous networks. For example, Tang *et al.* [24] developed a framework for classifying the type of social relationships by learning across different networks (e.g., email network, mobile communication network). Researchers from CMU study the relationship between the users' mobility patterns and structural properties of the online social network, to identify the implicit social link between physical interaction and online connection [25]. Lee *et al.* proposed a geo-social event detection method by mining unusually crowed places (e.g., reporting social events such as festivals or protests) from geo-tagged Twitter posts [26]. However, numerous open issues remain unexplored, such as the aggregated/collaborative effects of distinct social networks, data dissemination over heterogeneous social networks, and so on.

4.3. Security and Incentive Mechanisms for User Collaboration

The sharing of data in opportunistic IoT applications can raise significant security concerns, with information being sensitive and vulnerable to privacy attacks. For example, in the opportunistic trading scenario, sensitive personal information such as user location, mobility patterns, preferences may be used by data dissemination protocols. The new security challenge introduced here is the *protection of the privacy of participants while allowing their devices to reliably share/forward data in opportunistic IoTs*. Data anonymization techniques [9], which conceal the identity of users when they contribute/forward data, can be one way to deal with this problem, but there are still many issues to be addressed in the future.

In opportunistic IoT, anonymous contributors are often used as brokers to carry and forward data. If there lacks the control over ensuring source validity and information accuracy, data credibility issues may arise. For example, the source node may send incorrect data; malicious nodes may modify the data it received and forward it to other nodes. Therefore, trust maintenance and abnormal detection methods should be built into opportunistic IoT systems to determine the trustworthiness and quality of the data being transmitted. However, traditional strategies often rely on online authentication from centric servers, which cannot meet the opportunistic connection and decentralized nature of opportunistic IoT systems. There are two possible ways to address this. First, we should follow a basic rule that *the attack to a network is largely dependent on what kind of routing mechanism the opportunistic network uses*. For instance, Uddin *et al.* have proposed the protection mechanisms for address spoofing in opportunistic networks under the Spray-and-Wait protocol [27]. Second, it is beneficial to leverage the close tie between online and opportunistic communities in opportunistic IoT. For instance, the trust relationship established among people in online social networks can be leveraged to strengthen security protection in opportunistic communities.

Opportunistic IoT offers immense potential to consumers and service providers. However, for these innovations to evolve from ideas to tangible products for the mass market, many commercial issues also require resolution. For example, in broker-based data dissemination protocols, brokers need to contribute their computational resources to other nodes. However, the fact is that most opportunistic IoT devices (e.g., mobile phones, wearable sensors) have limited resources, such as energy and storage capacity. Therefore, the development of a solid economic model is highly important, and additional strategies for incentives and reputation for data contributors are needed (references are those explored in peer-to-peer systems [28] and ad-hoc networks [22]).

5. A Conceptual Framework

To facilitate the development of opportunistic IoT, a generic system framework is essential. The framework should provide a set of mechanisms for dynamic network management, human behavior analysis, and information sharing among mobile nodes. It should address most of the issues mentioned in the previous subsections and provide a uniform interface for information distribution/access by various applications. We have proposed a conceptual framework for opportunistic IoT systems, as shown in Fig. 3. It can be a starting point to build opportunistic IoT applications with framework support.

The framework is maintained on IoT devices, where the following basic components are involved: the opportunistic network management (dynamic, intermittent connectivity), trust/security/privacy maintenance (e.g., data anonymization, malicious node detection, data access control, data quality enhancement), resource management (e.g., bandwidth, storage, computing, energy), social feature extraction (e.g., social network analysis, user preference learning, mobility pattern mining), incentive mechanisms for user collaboration, and the library of various data dissemination protocols (flooding, popularity-based broker selection, and so on). It should be noted that to enhance the linkage and interaction with other forms of networks, especially online social networks, the infrastructure also has a component for heterogeneous community/network orchestration (HCO). The HCO component is responsible for exchanging useful information and handling data floating among distinct networks.

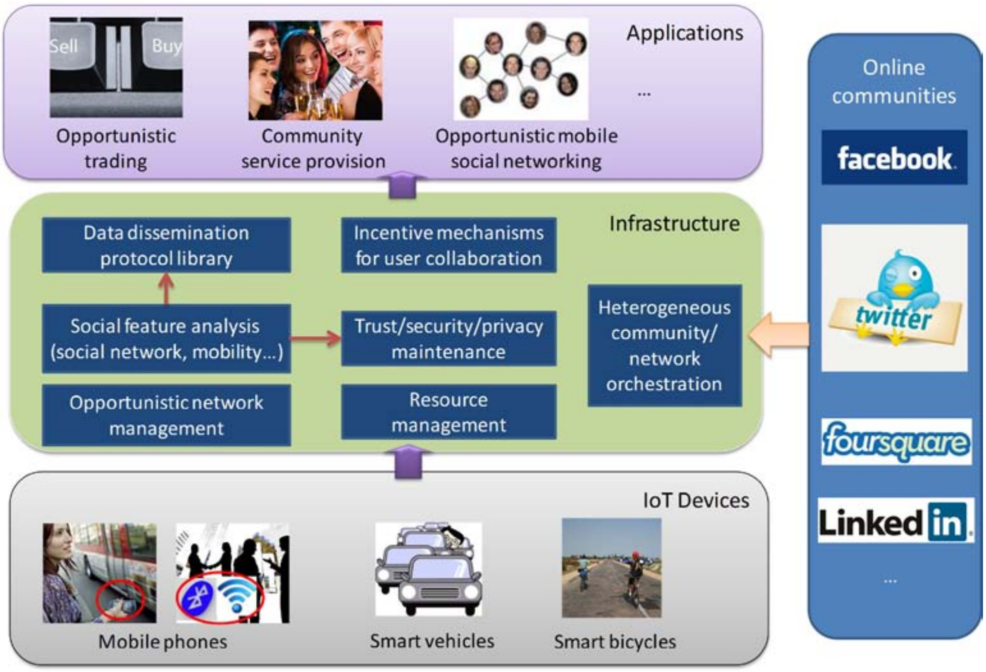

Figure 3: A conceptual framework for opportunistic IoT.

6. Our Practice to Opportunistic IoT

The human-centric nature of opportunistic IoT brings new potentials in many application areas. We make a summary of our ongoing work in the following and present our insights on how to address the challenges faced by opportunistic IoT.

6.1. Opportunistic Mobile Social Networking

Forging social connections with others is the core of what makes us human. Opportunistic social networking aims to improve social connectivity in physical communities by leveraging the information detected by smart devices. The SOCKER application we developed is such an example, which can build ad-hoc communities of like-minded people [29]. For instance, if Harry wants to organize a basketball game at weekend in the university campus, he can post a request to SOCKER and recruit participants who are basketball fans and who live nearby. A broker-based mechanism is used by SOCKER to facilitate the dissemination of community-formation requests in the campus-wide environment. Finally, people who are socially- and physically-close to each other are opportunistically recruited to participate this activity. The concept of broker-based community creation is illustrated in Fig. 4. For each opportunistic community OC_i in the figure, users in solid and dash circles represent present brokers and previous brokers, respectively, while users in solid rectangles are the matched community members (e.g., basketball fans).

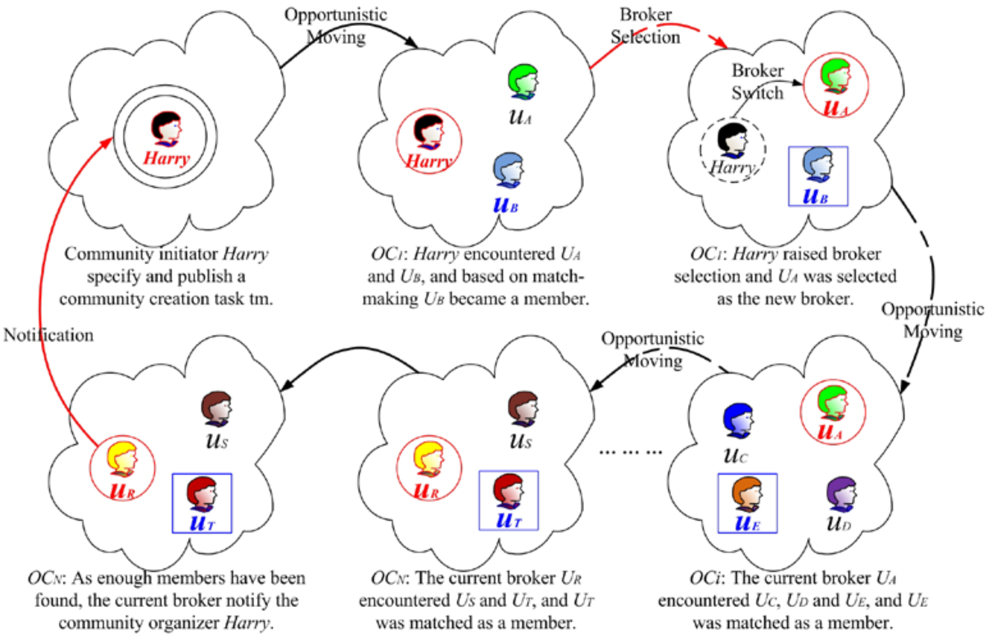

Fig. 4. Community creation in SOCKER

In Fig. 4, Harry initiates a community creation task t_m and serves as the first broker. Once Harry moves into a new opportunistic community, he will disseminate t_m to the users encountered for match-making (each user keeps a list of her interests), and the matched users will be added to the community member list (e.g., u_B is added in OC_1). Afterwards, broker election is carried out in this opportunistic community based on a specific broker selection strategy, and the "broker-switch" action will be performed once there is a more effective broker (e.g., u_A is selected as the new broker for t_m in OC_1). The dissemination process terminates when *i*) the required number of participants is found (e.g., at least five matched users should be found to organize a basketball game), or *ii*) the pre-specified request dissemination time is expired. For instance, Harry hopes that the community can be created within three days. We define it as the *community creation expiry time*.

The single-broker approach. The crucial issue for SOCKER is to design an appropriate broker-selection approach to facilitate data dissemination. We have proposed the single-broker approach, where brokers are selected based on their social features. Two social features or metrics are used to measure the usefulness of candidate brokers, namely *user popularity* and *user effectiveness*. As a basic broker selection metric (i.e., benchmark), *user popularity* chooses a new broker simply based on the predicted number of contacts the user may encounter in a given period, which is learned from historical contact data. As an improved broker selection metric, *user effectiveness* additionally leverages the contextual data obtained during the community creation process (using the list of already encountered users to refine user popularity) [29]. Specifically, each user maintains a list of users that she is likely to meet (learned from user contact history), and the current broker maintains a list of already encountered users (i.e., the context information) since the dissemination process starts. We then calculate the difference-set (*DS*) of the two user lists, the size of which is used to measure the effectiveness of a user in the broker election process. If the *DS* of a new encounter is higher than the current broker, *broker switch* will happen.

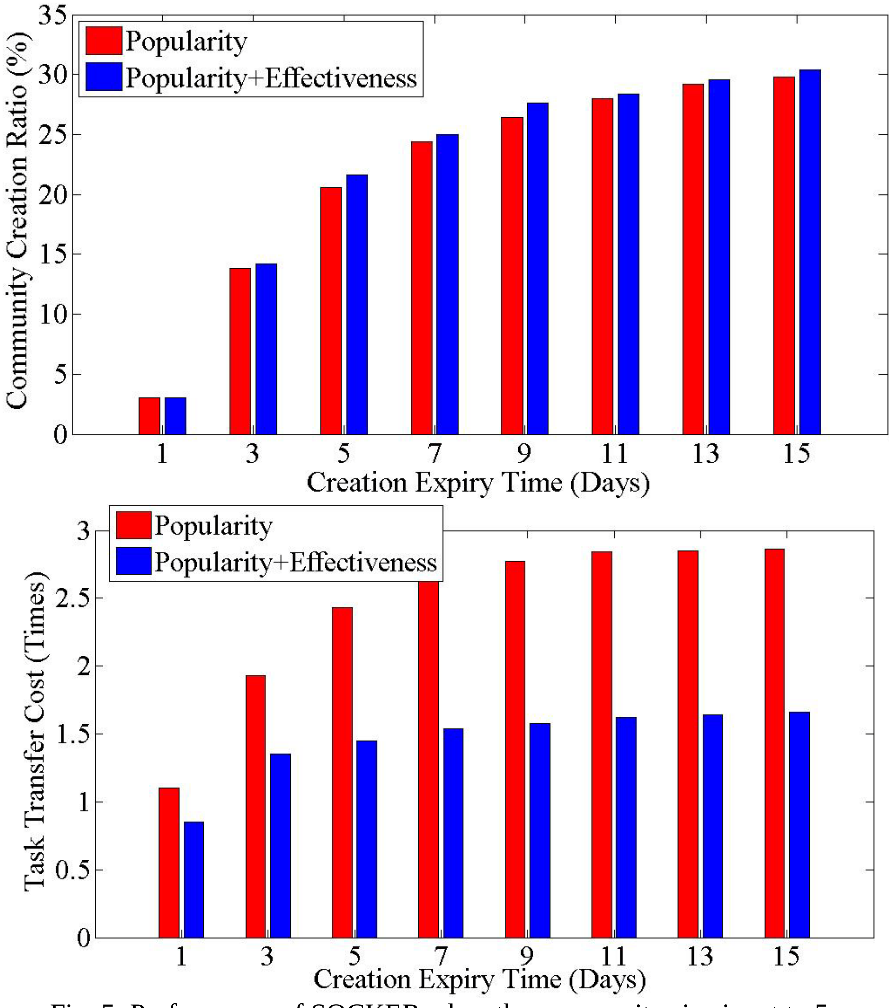

Fig. 5: Performance of SOCKER when the community size is set to 5.

We used the MIT Reality Mining (RM) [30] dataset to evaluate the performance of two different community-creation metrics. The RM dataset contains the co-location information of 106 subjects (staffs and students) at the MIT campus over more than one year. These subjects were equipped with Bluetooth-equipped mobile phones, and their co-location information was collected via frequent (every 5 minutes) Bluetooth device discoveries. To make the dataset more manageable, we have extracted twelve-week of collocation data, corresponding to Sep. 14th to Dec. 7th, 2004. Specifically, the first eight weeks were used as the training dataset while the last four weeks were used as the testing dataset. Meanwhile, while real-world human mobility traces are available, social activity related information (e.g., user preferences/interests) does not exist in the RM dataset. Thereby, we design the experiment as follows: (1) we assume that there are 20 different preferences; (2) each user u_i has p_i preferences, where p_i is a randomly-generated integer ($0 < p_i \leq 20$), and each user has five preferences on average; (3) in the experiment, we randomly generate 100 community-creation tasks, where the task initiators and the start time of these tasks are selected randomly.

We tested SOCKER under different community creation expiry time. Figure 5 illustrates the experiment results of the two community-creation methods (i.e., *user popularity* and *popularity+effectiveness*). We measure them by calculating the community completion ratio (*CCR*, i.e., the average ratio of successfully completed tasks) and task transfer cost (*TTC*, i.e., the average broker-switch times of successfully completed tasks). Both *CCR* and *TTC* are calculated within the specified expiry time. The results indicate that better performance can be achieved when both social features are leveraged in the broker-selection approach.

6.2. Opportunistic Marketing Service

When people contact and connect, they influence and exchange the information they own. In opportunistic IoT, peer influence/contact becomes more important than ever, which offers a wealth of new marketing opportunities. For example, we are now developing *Opportunistic Trading* (as the use case described in the introduction) [31]. The aim of it is to build a virtual flea market service that works in mobile phone-based opportunistic networks to facilitate request dissemination and match-making among co-located buyers and sellers of goods. An example that illustrates the opportunistic trading process is shown in Fig. 6.

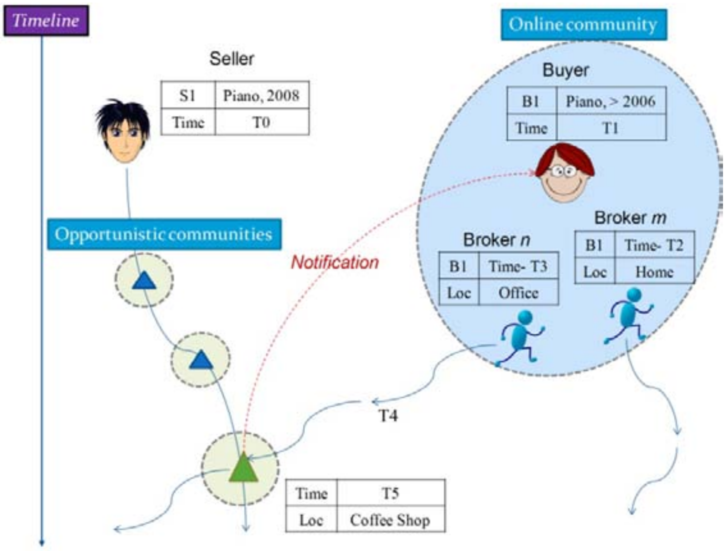

Fig. 6: Opportunistic marketing: an example.

The multi-broker approach. To reduce network cost on data flooding, only sell requests are disseminated, the buyer (while not the seller) is notified when her request is matched. Different from SOCKER, a multi-broker mechanism is proposed, where the buyer can select *k* brokers and replicate her request to them. At time *T5* in the example, *S1* and *Broker n* meets in a coffee shop, and the buyer/seller requests are matched. *B1* is then informed of the matched result.

6.3. Community Integration and Orchestration

As a promising research direction, we have studied the aggregated effects of heterogeneous community orchestration through two projects: *Social Contact Manager* and *Hybrid Social Networking*.

(1) Social Contact Manager: integration of data from heterogeneous networks. The ability to use the power of a network of social contacts is important to get things done. However, as the number of contacts increases, people often find it difficult to maintain their contact network using human memory alone. People are frequently beset with questions like "*Who is that person? I think I met him in Tokyo last year*." Existing contact tools make up for the unreliability of human memory by storing contact information in digital format; however, manually inputting contact data can burden the users. To address this issue, we develop SCM (Social Contact Manager), an intelligent social contact management system [32]. It supports the auto-collection of rich contact data (e.g., profile, face-to-face meeting contexts) from online and opportunistic networks, leveraging the aggregated power of pervasive sensing and Web intelligence techniques.

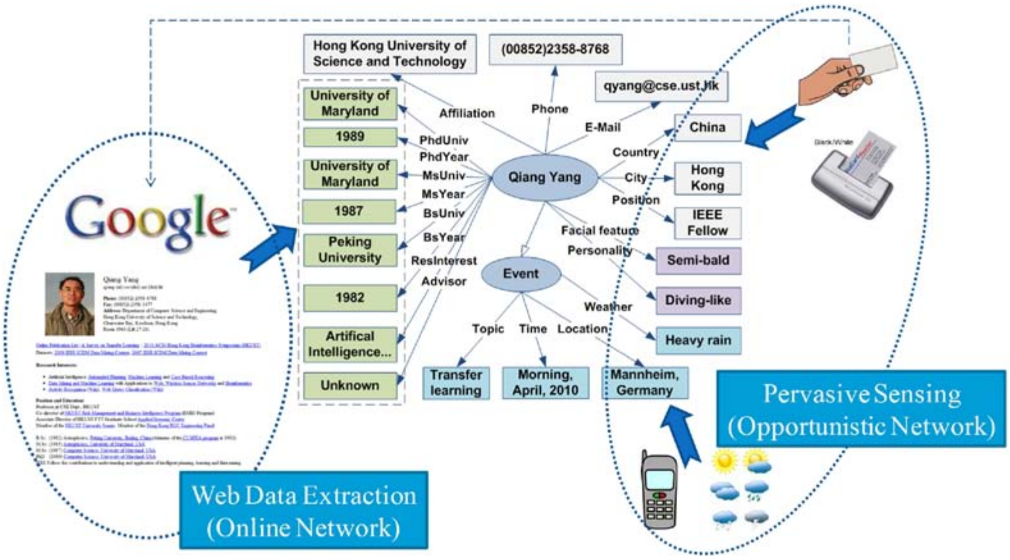

Fig. 7: Social contact manager: data integration from heterogeneous networks.

Our solution is inspired by the general contact acquaintance process. In social occasions, our connection with a new contact usually starts from exchanging *business cards*. After obtaining basic information from *business cards*, people gather more information about the contact from the Web. An interesting phenomenon is revealed, in which the "business card" plays a key role, triggering and leading the contact data gathering process. SCM explores techniques to automate this process, as illustrated in Fig. 7. We employ a mobile card-scanner to extract basic information from the collected business cards (forming an opportunistic network). The scanned basic information is then used to obtain other contact information from the Web (i.e., the online network) using an information extraction method based on a hybrid of heuristic rules and Conditional Random Field (CRF) [33]. The collected information can be leveraged to manage their contacts better, especially for efficient contact retrieval in name-slipping situations [32].

(2) Hybrid Social Networking: interlinking heterogeneous social networks to facilitate data dissemination. People now connect, interact and transit in heterogeneous social communities (e.g., online, physical, interest/professional groups) within cyber-physical spaces. In the past few years, significant research efforts have been made on facilitating information sharing in online and opportunistic communities. However, they follow separate research lines, and the interlinking of the two forms of communities has little been explored. We have thus proposed the *hybrid social networking* (HSN) infrastructure [31], which is inspired by the multi-community involvement and cross-community traversing nature of modern people. For example, at one moment, *Bob* is staying at a place with Internet connection and he can communicate with his online friends (in the *online community*); later, he may travel by train with merely ad hoc connection with nearby passengers (forming an *opportunistic community*). Here we use HSN to indicate the smooth switch and collaboration between online and opportunistic communities.

One of the key features enabled by HSN is the popularity-based online broker selection protocol. Different from existing protocols, the online broker selection approach we proposed allows users to choose brokers *online* from his social connections, while not requiring direct contacts with others in the real world. Users advertise their predicted popularity in the online community, and a publisher can choose the ones with highest-popularity among them. Online broker selection also decreases the time cost on task allocation: the selected nodes can be allocated the dissemination task with no delay if they are online, while offline brokers can be informed of the allocated task once they are within an environment with Internet connection (hotspots, wired network, etc.)

We compared the performance of HSN with single-community dependent methods (e.g., the pure ad hoc method), which was also evaluated based on the MIT RM dataset. We used Opportunistic Trading (depicted in the Introduction) as the background application. As shown in Fig. 6, when using HSN in opportunistic trading, brokers will be chosen from the online connection (or friends) of the buyer. As shown in Fig. 8, for the experiment results of two typical users, great performance improvement (in terms of success rate) is obtained when using HSN. For example, the improvement is about 15% for node 69 and almost 40% for node 79. This is because that the integration of an online community shortens the broker selection process, and increases the opportunity to select brokers with high popularity (in *ad hoc* or *direct contact-based* broker selection method, brokers with high popularity may not be encountered and chosen). In summary, the interlinking of distinct social networks can enhance data dissemination among people.

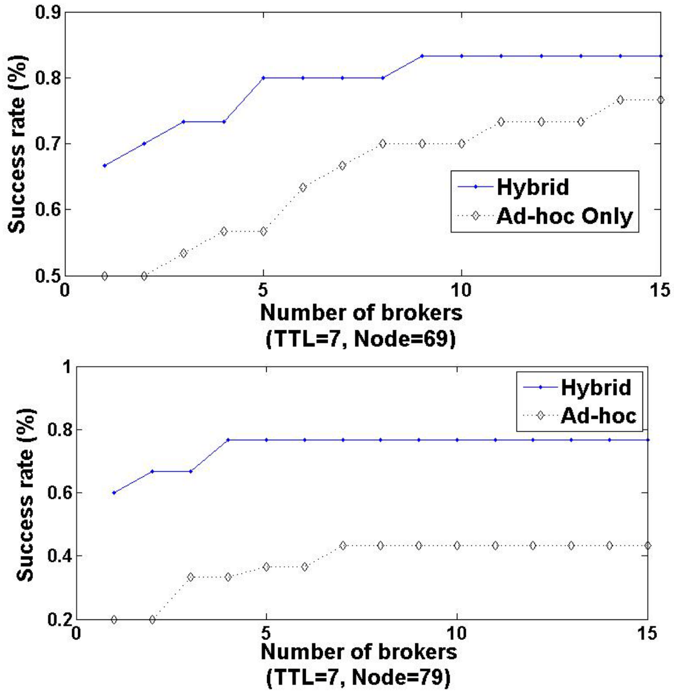

Fig. 8: The effects of hybrid social networking to data dissemination.

7. Conclusion

This paper has presented opportunistic IoT, a new research area that addresses information dissemination and sharing within and among opportunistic communities that are formed based on the opportunistic contact nature of human. The bi-directional effects between human behaviors and opportunistic IoT, the co-existing of online and opportunistic communities, as well as the interaction between heterogeneous communities, raise numerous research challenges to opportunistic IoT. Some of them have been discussed in this paper, such as the design of effective protocols on data dissemination considering the impact of human behaviors and mobility patterns, the orchestrating and collaboration of heterogeneous communities in terms of their distinct features, and so on. All these challenges present substantial research opportunities for academic researchers, industrial technologists, and business strategists. We further present four of our ongoing projects/applications on opportunistic IoT, ranging from opportunistic social networking and community service provision, and demonstrate our experience to address the challenges.

In addition to information dissemination, we will explore resource (e.g., built-in sensor resources can be different among users) and service sharing (e.g., different users may keep different services in their device) [34] within and among opportunistic communities in the future work. We believe that the convergence of anthropology, social science, and pervasive sensing and computing techniques, will greatly propel the development of IoT to its new stage, i.e., stepping into the era of the Social IoT.

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