A Social-Aware Framework for Efficient Information Dissemination in Wireless Ad Hoc Networks

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The authors present a social-aware framework for optimizing SPANs by exploiting two layers: users' relationships in the online social network layer and users' offline connections and interactions in the physical wireless network layer. The online content popularity distribution is also studied as a result of the users' online interaction profiles.

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ABSTRACT

In wireless ad hoc networks, each node participates in routing by forwarding data to other nodes without a pre-existing infrastructure. Particularly, with the wide adoption of smart devices, the concept of smartphone ad hoc networks (SPANs) has evolved to enable alternate means for information sharing. Using unlicensed frequency spectrum and short-range wireless technologies, a SPAN enables a new paradigm of applications and thus is seen as an attractive component in future wireless networks. In a SPAN, smartphones form local peer-to-peer networks to cooperate and share information efficiently. Recent studies have shown that if the users' social relations are considered while designing cooperation schemes and protocols in SPANs, the cooperation initialization and content dissemination can be notably improved to increase the overall network efficiency and communications reliability. In this article, we present a social-aware framework for optimizing SPANs by exploiting two layers: users' relationships in the online social network layer and users' offline connections and interactions in the physical wireless network layer. The online content popularity distribution is also studied as a result of the users' online interaction profiles. In the end, we integrate both online and offline layers, and discuss possible applications to further enhance the network performance.

INTRODUCTION

The concept of wireless ad hoc networks (WANETs) has been introduced as devices directly transmit data signals to each other while bypassing the wireless infrastructure, that is, the cellular network's base stations (BSs). In WANETs, communications usually happen over the unlicensed spectrum by using existing short-range wireless technologies such as Bluetooth and Wi-Fi-Direct, and thus the interference between cellular and WANETs can be avoided. This can significantly improve the performance of cellular networks by offloading traffic, extending coverage, increasing throughput, and enhancing reliability. Given these nice properties, WANETs are promising to serve as a good backup for the cellular network with a variety of applications, which include public and military areas. Furthermore, smartphone ad hoc networks (SPANs) particularly focus on smartphone users, which is a special case of WANETs that comes closest to our daily life. Given the wide adoption of smartphones all over the world, SPANs are thus regarded as a promising technology for introducing new applications such as proximity services and public safety applications.

In such an ad hoc network made up of mobile phones, movement and changes are constant factors, leading to the burden of maintaining reliable routing information. The existing literature on SPANs mainly focused on technical challenges such as communication issues, routing protocol, and resource allocation, while smartphone users' social connections are another major issue that can be further explored. To integrate the social networks and SPANs, it is necessary to study users not only as friends online, but also who would like to meet offline. Thus, we define the online social network (SN) as the online platform that reflects users' friendships and influence on one another. On the other hand, the offline social network refers to the physical wireless network in which users' mobility and proximity are considered, and where the contents data is transmitted.

The benefits of integrating SNs into SPANs are based on recent studies on information/content spreading behaviors. Researchers have realized that SN websites such as Facebook and Twitter are playing significant roles in the propagation of information over the Internet [1]. Observing these online SNs, people have found that in delay-tolerant networks (DTNs), with a small number of initial seeds in a local area, an efficient content dissemination mechanism through opportunistic sharing can guarantee content delivery while satisfying target delay requirements. Therefore, we see that if social awareness in both online SNs and offline SNs can be exploited to design efficient data forwarding mechanisms in SPANs, we can achieve efficient information dissemination with the lowest transmission cost. One brief illustration of content dissemination by integrating online SN and offline SN in SPANs is shown in Fig. 1.

The work in [2] has already shown that by grouping mobile nodes with similar mobility patterns into a cluster, the proposed cluster-based routing protocol can achieve higher delivery ratio,

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and lower overhead and delay. The authors in [3] also proposed the utilization of network-wide clustering to facilitate data propagation. The previous two works provided the original form of content sharing in SPANs. However, none of them focused on the social structure within each cluster, which can play a key role in further optimizing the efficiency of SPANs. To facilitate the design of social-aware SPANs, there are three keys that need to be fully exploited:

- *Offline SNs*: These constitute the physical layer where users locate within transmission distance and data is transmitted. Users' mobility patterns and encounter histories can be studied to derive the social structure in the physical wireless network, which can be utilized to establish reliable SPANs.
- *Online SNs*: These contain information such as virtual connections and friendships. Users' social online influence has a strong impact on the spreading breadth of the posted content. Studying the social connections among people in an online SN can assist in designing an efficient data dissemination mechanism in the offline SN.
- *Content popularity distribution*: If the popularity of online content can be accurately modeled, we can analyze the probability with which content will be requested, and thus design the content transmission mechanism more efficiently.

The future wireless technology needs to provide efficient means to bridge online and offline communities, that is, using online social structures and iterations to enhance data transmission in physical offline SNs. Therefore, we study both offline SNs and online SNs, and their combination in facilitating SPANs for data delivery. We first introduce existing models for user social connections in offline wireless networks. Then we talk about different structures of online SNs. In the end, we give examples of this emerging category of applications, and analyze the potential and benefits of combining offline and online SNs to facilitate data transmission.

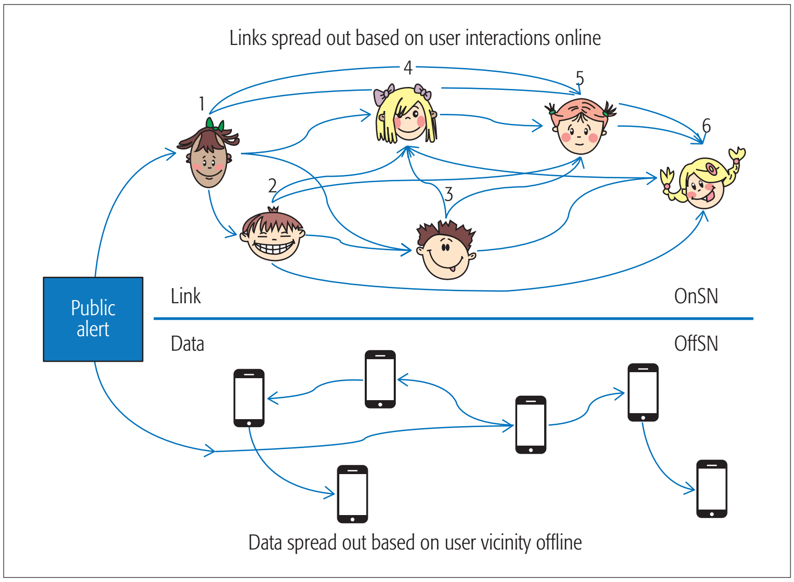

Figure 1. An integration of online and offline social networks in SPANs.

Offline Social Network

Similar to the content delivery in DTNs, due to the mobility of users, contents are shared among SPAN users through opportunistic encounters. Studying the social properties of SPAN users by considering their locations, mobility patterns, and interests will further improve the security and delivery delay. In the following subsections, we introduce three different aspects from which we can derive the offline social structures.

Local Community

Communities are the SNs that mirror our daily lives. People such as neighbors, co-workers, and classmates who we meet regularly are the perfect candidates for initialing a cooperative SPAN, since they are not only trustful content providers, but also easily meet the data transmission requirements of short-range communication such as Bluetooth. In those scenarios, slow mobility patterns and close transmission distances are critical factors to guarantee the high quality of short-range communication. Therefore, it is worthwhile to derive offline SNs from local communities. There are extensive studies that exploit these friendship-based SN characteristics to assist content delivery in DTNs. Furthermore, there are also algorithms that can be used to detect communities such as *k*-clique [4].

Opportunistic Encounter

In the SNs of local communities, users are known to each other as families, friends, co-workers, classmates, and so on. However, there are many people who work or study in the same building but are strangers to each other. Users who are stably within proximity of each other are also ideal candidates for SPANs to transfer or relay data. Achieving cooperative communication from nearby users or strangers will be feasible if users are well motivated and secured, and it is a mutually beneficial action to expand the SPAN coverage for multicast [5]. This kind of SN can be developed from peer-to-peer encounter histories. Metrics such as frequency and length of the encounters are the key parameters that determine the social connections of users. One way is to find the probability of two users having an effective encounter. An effective encounter means that the two users are within the maximum transmission distance, and their encounter duration is long enough to finish the data transmission. Based on the Bayesian parameter estimation method, deciding the distribution that fits the data best is essential; known works include Beta distribution [6].

Common Interest Groups

Despite the locality and mobility of users, interest is another critical social aspect of users. Common interest groups differ from local communities in the sense that people may live, work, and study in various locations and do not necessarily go to the same place every day. However, they love to access similar contents, and may like to go to activities and events arranged by themselves or others related to games, movies, books, pets, careers, or hobbies. Forming the offline SN through users' interests can improve the effectiveness of SPANs in the following three aspects.

In recent years there has been a dramatic rise in the number of mobile users who are connected to social network websites, such as Facebook and Twitter. In particular, social network websites have been playing a significant role in the propagation of information online, and content data has become the main source of traffic in wireless networks offline.

First, users with common interests are more likely to have opportunistic encounters than others. For example, people who are interested in comic books will possibly attend a comics show. The mobile app Meetup brings people the convenience of arranging group meetings offline for people who share the same interests. Indeed, SPANs have drawn lots of attention for assisting temporary large-scale events where a huge scale of communication is needed for a short period of time. Second, within such an SN, the probability of successfully acquiring desirable content will be much higher than that in a local community opportunistic encounter, since people with the same interests are more likely to have mutually interesting contents. Third, it has been shown in [7] that there is a high locality of interest for data within a certain region (i.e., certain contents are usually popular within a certain local region). For example, users who want to stream a live football game are mostly to come from regions of the home and guest teams.

Online Social Networks

In recent years there has been a dramatic rise in the number of mobile users who are connected to SN websites, such as Facebook and Twitter. In particular, SN websites have been playing a significant role in the propagation of information online, and content data has become the main source of traffic in wireless networks offline. Given that users actively exchange information over those SNs, it will be helpful to extract the social structure among mobile users by exploring the interacting patterns online. This social structure derived from user online iterations can be regarded as the online SN, corresponding to the offline SN extracted from users' wireless connections offline. Next, we discuss online SN structures from three aspects.

Bidirectional

The SN applications such as Facebook and Wechat belong to the bidirectional online SNs, since in those online SNs, connections are confirmed by both sides of users, and contents posted by either side are viewable by the other. Thus, a user's activity will influence anyone in a bidirection online SN. A bidirectional online SN is similar to the local community in the offline SN, where the connection is formed between mutually known users. A bidirectional online SN can be utilized to assist a cooperative SPAN, since users are trustworthy friends to each other.

Unidirectional

In popular SN websites such as Twitter and Weibo, users can follow anyone they are interested in, such as movie stars, singers, and celebrities in other areas. It is unnecessary for two users to know each other, and a social connection can be established. An online SN extracted from a unidirectional social connection shows great potential in designing efficient data forwarding mechanisms. For example, daily posts, news, and advertisements from accounts with huge followers are able to make more people see them than other accounts. Thus, the information achieves the maximum propagation within the shortest time.

Centralized Content

The centralized content social structure can be found in the popular SN website called Douban, where users can create contents related to film, books, music, and recent events and activities. Users are also allowed to form groups based on the topics in which they are interested. Inside the groups, users do not have to know each other, but they can access the same contents inside the group, and may contribute to enrich the content if they are willing to do so. This online SN is similar to offline common interest groups.

Online Content Popularity

Users' online requests for content can be influenced by both internal (users' own interests) and external (influence from outside) reasons. While a user's internal factors are difficult to predict a priori, the external influence that comes from users' interactions in an online SN can be estimated. Such an analysis of network externality (external influence from media, friends, etc.) constitutes one of the major topics studied in online SNs, but it focuses more on social influences than on the structures discussed in the previous sections.

With the information circulating over the online SN and the data transmitted over the offline SN, the popularity distribution of online content is worthwhile studying to assist in the design of a content propagation mechanism, such as different forwarding schemes for popular and regular contents, and thus enhances the efficiency of SPANs. Fortunately, based on practical measurement, spreading impact modeling, and user profiling, it has been proven that it is not difficult to predict popular trends and access patterns [8].

Parametric Method

One simple way is the parametric method by assuming that the popularity of online content follows a certain distribution. Then the problem becomes among those known distributions, which of them will fit the online content popularity? There have been many studies in this area, and we select Zipf's law, Pareto's law, and power-law distributions for a brief introduction.

Zipf's Law: Zipf's law was first introduced in language study to model the frequency of used words, where the frequency of any word is inversely proportional to its rank in the frequency table. Later, people found that a similar relation occurs in many other areas, including the population ranks of cities' corporation sizes, ranks of the number of people watching the same TV channel, and so on. Based on numerous studies, Zipf's law has been established as a good model of the measured popularity of online videos. In [4], the authors adopted Zipf's law to model video resources online for BS-assisted device-to-device (D2D) communication, which is similar to data transmission in SPANs but over licensed spectrum.

Pareto's Law: Pareto's law was first used to describe the distribution of income. Different from Zipf's law, instead of asking what the largest income in a specific rank is, Pareto's law asks how many people have an income greater than a given number. Indeed, there is a tricky connection between Zipf's law and Pareto's law in the way the cumulative distribution is plotted. While the Zipf rank distribution is plotted with ranking on the horizontal x axis and number on the vertical y axis, in the Pareto distribution, the x and y axes are flipped. Therefore, we can see that Pareto's law is also able to fit the online content popularity as Zipf's law does. In [1], the authors did a test on whether Pareto's law applies to user generated content video popularity, and the simulation results based on real data show a good fit on the Pareto's law.

Power Law Distribution: A power law distribution does not tell us how many people have an income greater than a specific number as in Pareto's Law, but the number of people whose income is exactly the given number. Indeed, the power-law distribution is a direct derivative of Pareto's law, which covers a wide range of varieties including the frequencies of words in most languages, frequencies of family names, and so on. The authors in [9] used power law distribution to fit the online content popularity, and compared the power law fit against other alternative distributions such as exponential distribution and log-normal distribution The results indicated that the power-law is a better fit than the alternative distributions.

Non-Parametric Method

Finding a closed-form expression of online contents' popularity distribution can be challenging. In addition, the distribution of online contents is highly time-varying as users continue to access them. Therefore, many studies argue that assuming content is drawn from a given probability distribution may not be appropriate. Fortunately, the nonparametric method provides another way of estimating popularity instead of fitting any parameterized distributions. The use of this model can automatically derive a distribution model from the observed data and learn the network structure.

Non-Parametric Regression: As one form of regression analysis, non-parametric regression does not refer to a pre-specified functional form but a flexible functional form constructed by information extracted from the observed data. The authors of [10] used a Cox proportional hazard regression model to infer the popularity of content with publicly observable metrics, such as the threads lifetime, views, and comments number. The Cox proportional hazard regression does not assume any parametric structure for the baseline hazard.

Stochastic Process: In probability theory, there are some discrete-time stochastic processes that are similar to the users' content selection process online. One example is the Bayesian non-parametric methods' extension, Indian Buffet Process (IBP), which models an Indian buffet where each diner chooses several samples from infinite dishes. The first customer selects its preferred dishes according to a Poisson distribution without any external influence, whereas the following customers make their selection with the prior information based on the first customer's feedback. Therefore, the decisions of subsequent customers are influenced by previous customers. One simple illustration of IBP is shown in Fig. 2.

The online content popularity spreading process in an online SN is analogous to the stochastic processes of IBP if regarding the online SN as an Indian buffet, the online content as dishes, and

Dish

Customer	1	2	3	4	5	6	7	8	9	10	...
1	1	1	1	1	0	0	0	0	0	0	
2	1	0	0	1	0	1	0	0	0	0	
3	0	1	0	1	1	1	0	0	0	0	
4	1	0	1	0	0	1	1	1	0	0	...
5	1	0	0	1	0	1	1	1	0	0	
6	1	1	0	0	1	1	0	0	0	1	
...					...						...

Figure 2. One realization of the Indian buffet process.

the users as customers. Users enter the online SN sequentially to request their desired content, which changes the popularity distribution of content, and thus affects the probability of this content being requested by others. Popular content is requested more frequently, whereas content that is only favored by a few people or newly produced content is requested less frequently. For comparison, there are three real datasets of YouTube video viewing count, which are sampled from top ranked videos, random videos, and copyrighted videos. We observe the effectiveness of using the IBP to describe the online content popularity in Fig. 3.

Integration of Online and Offline Social Networks

From the previous discussions, we learn the characteristics of online and offline SNs. Future wireless technologies need to provide efficient means to bridge online and offline communities, that is, using online social structures and iterations to enhance data transmission in physical offline SNs. In this section, we give examples of this emerging class of applications, and analyze the potential and benefits of combining offline and online SNs to facilitate efficient data transmission in WANETs.

Content Sharing Between Friends

Given a local-community-based offline SN and a bidirectional online SN, one application is the pre-loading of content from social networking applications, which has been shown to consume a significant portion of the overall wireless network traffic. Real trace experiments conducted by the CRAWDAD team at the University of St. Andrews [11] demonstrated the effectiveness of online SN and offline SN integration. The researchers first explored the online SN and offline SN from participants' Facebook friendships and sensor mote encounter records on campus. Then they used the detected communities and cliques to see whether they helped determine routing paths. Their results show that when the content dissemination uses the information from either an online SN or an offline SN, the delivery ratios do not show significant difference between the two. However, integrating the two leads to a higher delivery ratio and significantly lower communication cost.

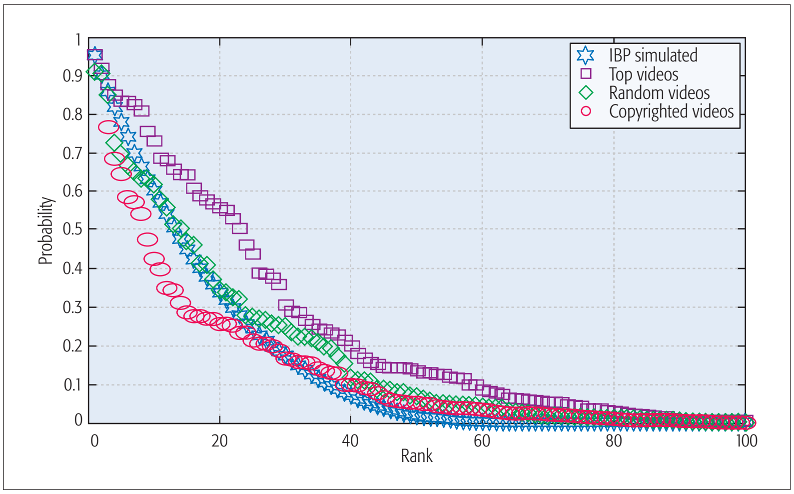

Figure 3. Video rank and selection probability by real trace and IBP.

This result is not surprising, since the social structures obtained from online and offline SNs help better targeting of content data, relays, and destinations. We can elaborate on this idea by the following example. User A and user B frequently interact online. If A posts or shares content online, it is highly likely that B will access it. Thus, the content should be pre-loaded and forwarded to B to avoid increasing traffic during peak hours. While A is located far away from B, the content shared by A is accessible by B's two other offline SN friends C and D. Then the data can be forwarded to B from C during the day since they work in the same office building. D can forward the data to B at night since they are neighbors.

In summary, integration of online and offline SNs increases delivery ratio and reduces communication cost in the following ways. First, with the users' friendship structures and content popularity in online SNs, one can decide which data to forward and to which user to forward. Second, the transit communities that are formed by users' mobility patterns in offline SNs determine when to forward the data, and which user to forward it to as an ad hoc relay [12].

Information Propagation

In the case of pure information broadcasting, friendship is not necessary as in the previous application. In online SNs such as Twitter and Instagram, tweets and pictures are pushed to all followers once posted. In offline SNs, data can be broadcast among strangers as long as they are within a certain transmission range. The TOSS algorithm proposed by [13] integrates online and offline SNs together to assist information broadcasting. TOSS first models the content access probability online using a Weibull distribution to decide which content has the higher priority to be forwarded. Then it exploits users' spreading impact and user-dependent access delay between the content generation time and each user's access time from the SN; it also extracts users' mobility impact from the offline SN. The authors use these inputs to derive the probability of accessing content. The objective function is to maximize the access probability without infrastructure-assisted communication and subject to the access delay constraint. Finally, TOSS can decide which seed users are responsible for pushing the content to other users they opportunistically meet. The trace-driven evaluation demonstrates that TOSS can reduce up to 86.5 percent of the cellular traffic while satisfying the access delay requirements of all users.

When the objective is to maximize information propagation, it is critical to target certain initial seeds who have large influence on the others [14]. Most works on offline SNs select seeds with high mobility patterns in or between communities, which makes them have larger probability to encounter the others and thus increase delivery ratio. However, as we all know, a celebrity on Twitter can have his/her tweets pushed to millions of followers, which is far more influential than any active nodes offline. Thus, taking one's online influence into consideration when disseminating information offline will have great potential to facilitate data dissemination and reduce communication cost. This system model is promising in areas such as local advertisement pushing and public emergency alarm systems.

Interest Groups

People grouped in small networks, such as by regions and interests, are more likely to access the same content and meet in certain places. The work done in [15] implies that to achieve better diffusion performance, each node should diffuse data similar to their common interests when it meets a friend, and diffuse data different from their common interests when it meets a stranger. This work tried to take strangers as bridges and relays to forward one's disinterested data to interested communities. Such an algorithm reaches a high delivery ratio; however, a limited amount of communication cost can be reduced, since many disinterested nodes are also infected.

The social patterns of interest groups online include useful information such as users' interests and the groups to which they belong. In addition, people tend to have multiple interests, and some of them are active members in different groups. Thus, if each node can access that information before they forward data in an encounter, they can better target the bridge and relay nodes in different interest groups. On one hand, with the information extracted from the online SN, we know which interests groups the users belong to, and thus which data should be forwarded to them, to ensure that most of the infected users are those who are interested in the content. On the other hand, with the information extracted from the offline SN, we know which users do actively move among the different groups. Therefore, one can design algorithms to better target the carrier nodes to achieve minimal delay and reduce communication cost.

Conclusions

In this article, we study how to use a social-aware framework to optimize information dissemination in SPANs. We exploit users' social connections in two layers: the online SN and offline wireless network. We also provide further discussion on online content popularity, which is another representative of user interactions online. In the end, we propose three applications to integrate offline SNs and online SNs to enhance content delivery in SPANs from three different aspects: bidirectional friendship-based content sharing, unidirectional information broadcasting, and interests-oriented content sharing. Overall, there is great potential to combine offline and online SNs to facilitate content spreading SPANs.

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Biographies

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We proposed three applications to integrate the offline SN and online SN to enhance content delivery in SPANs from three different aspects: bi-directional friendship based content sharing, uni-directional information broadcasting, and interests oriented content sharing. Overall, there exists great potential to combine the offline SN and online SN in facilitating content spreading SPANs.