D2D Big Data: Content Deliveries over Wireless Device-to-Device Sharing in Large-Scale Mobile Networks

Xiaofei Wang, Yuhua Zhang, Victor C. M. Leung, Nadra Guizani, and Tianpeng Jiang

Abstract

Recently the topic of how to effectively offload cellular traffic onto device-to-device sharing among users in proximity has been gaining more and more attention from global researchers and engineers. Users utilize wireless short-range device-to-device communications for sharing contents locally, due to not only the rapid sharing experience and free cost, but also high accuracy on deliveries of interesting and popular contents, as well as strong social impact among friends. Nevertheless, the existing related studies are mostly confined to small-scale datasets, limited dimensions of user features, or unrealistic assumptions and hypotheses on user behaviors. In this article, driven by the emerging big data techniques, we propose to design a big data platform, named D2D big data, in order to encourage wireless device-to-device communications among users effectively, to promote contents for providers accurately, and to carry out offloading intelligence for operators efficiently. We deploy a big data platform and further utilize a large-scale dataset (3.56 TB) from a popular device-to-device sharing application that contains 866 million device-to-device sharing activities on 4.5 million files disseminated via nearly 850 million users in 13 weeks. By abstracting and analyzing multi-dimensional features, including online behaviors, content properties, location relations, structural characteristics, meeting dynamics, social arborescence, privacy preservation policies, and so on, we verify and evaluate the D2D big data platform regarding predictive content propagating coverage. Finally, we discuss challenges and opportunities regarding D2D big data and unveil the promising upcoming future of wireless device-to-device communications.

Introduction

With the increasing quantity and quality of multimedia services over mobile networks, there has been a huge increase in traffic over recent years [1]. This has caused major hardships in effectively handling such traffic. This is mainly due to the lack of scalable mobile network operators' (MNOs') infrastructure and the congested wireless network.

A recent new trend is to encourage users to obtain interesting content files from the devices of other users around them. This can be carried out by caching and sharing files with the help of advanced device-to-device (D2D) communications, which is an effective method to largely offload the duplicate cellular downloads [2]. D2D can thus significantly break the "bottleneck" of the MNOs' infrastructured networks. Note that in this article, we consider various types of wireless D2D communication techniques between devices directly, even including the Third Generation Partnership Project (3GPP) D2D communication underlaid LTE networks.

Many studies, like [3, 4], have shown that by mining the social and mobile behaviors of users, they are inclined to share popular content files via frequent offline encounters over D2D communications [5]. However, all of the previous studies in the literature have focused only on one particular group of users (on a scale of hundreds or thousands), based on small-scale data analysis and algorithms design, which cannot exploit D2D for mainstream high-quality services rather than just as a tool. The promising D2D framework for now should be significantly enhanced to be able to elaborate the huge potential of D2D deliveries over a large number of mobile users (on the scale of millions), in a wide area (cities or even countries), which motivates us to integrate state-of-the-art big data techniques to encourage smart D2D deliveries among users effectively, to promote contents for providers accurately, and to carry out offloading intelligence for operators efficiently. This is because there is an increasingly vast amount of different types of data (activity logs, traffic logs, profiles of users and contents, etc.) not yet discovered and fully utilized.

The emerging big data techniques pose many new unprecedented opportunities and challenges to conventional data analytics over groups of mobile users for exploiting the capacity of D2D sharing because of the significant dimensionality, heterogeneity, and complexity therein, for example, *volume*, *variety*, *velocity*, *value*, and *veracity* [6, 7]. Hence, it is crucial to shift our attention from single-group-based research studies to a big-data-based framework for D2D, as illustrated in Fig. 1. First, the D2D platform can easily provide support to adopt general statistical measurement algorithms on the large-scale user base (e.g., millions of people) in order to grasp a common understanding over the analysis results. In fact, the utilization of D2D big

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data highly depends on the exploration of multi-dimensional features extracted from complex mobile user behaviors (e.g., geographical homophily of clustered users, social relationships, interest similarity, and mobility models) and the complicated content properties (e.g., content size, categories, and time-varying popularity). In particular, the sharing activities among mobile users can formulate a connected graph so that the D2D big data framework can apply advanced theories and algorithms based on complex network theory. However, the integration of D2D and big data has not been discussed and analyzed toward a significant volume of real data collected from practical D2D sharing applications in mobile networks. Although the online virtual communities of social network services, in which people with a shared interest (e.g., a specific hobby or activity) can interact and socialize with each other, have been researched thoroughly, offline realistic people-to-people (i.e., D2D) content-based interactions can be further socialized and opportunistically connected toward a promising future with the assistance of big data techniques.

Therefore, the integration of wireless D2D communications with big data techniques can extend the limited applications in practice, leading to a new paradigm of offline user-to-user sharing. Thus, it is necessary to deploy a platform based on big data techniques (e.g., Hadoop, Spark, MLlib) for carrying out comprehensive measurement and analytics based on *large-scale* real-world D2D sharing activities in order to enhance the functionality and capability of D2D big data and to improve the quality of D2D services.

To the best of our knowledge, we are the first group to study big-data-based large-scale offline D2D content dissemination service in mobile networks. Our contributions can be summarized as follows:
- We propose an advanced framework of a D2D big data platform over cloud-based systems.
- We discuss a potential system and modules for a D2D big data framework to strongly encourage D2D sharing.
- We provide valuable measurement, analytics, learning, prediction, and recommendation results.
- We discuss useful implications and guidelines for exploiting D2D big data for enriching offline services.

In addition, we also discuss opportunities and challenges to hopefully unveil the upcoming future of wireless D2D communications.

D2D Big Data Framework

The original objective of utilizing D2D was just to query neighboring peers for obtaining desired content files, and also to broadcast interesting or urgent information among mobile users. Extending the scope of existing D2D studies in delay-tolerant networks (DTNs), opportunistic networks (ONs), and mobile social networks (MSNs), which are mostly designed for offloading and sharing based on a small number of users, we propose to design a D2D big data framework for a large-scale user base.

It is useful in facilitating the functionality of D2D sharing tools to level up toward an enhanced offline content dissemination service and a mobile interest exploitation platform, which can serve a

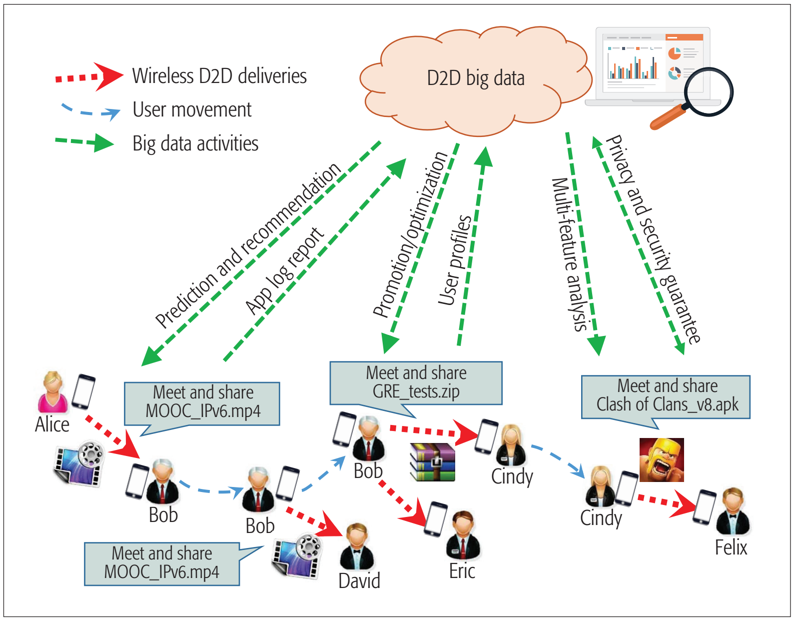

FIGURE 1. Illustration of wireless D2D deliveries integrated and supported with D2D big data.

significant amount of mobile users over a large area (even a nation).

From the perspectives of mobile users, operators, and content providers, as shown in Fig. 2, D2D big data consists of three parts.

Content Promotion Big Data (*Cloud of Promoting*): It is a platform open to customers who want to promote content effectively and rapidly. The main functions are content uploading, budgeting, promotion supervision, and strategy visualization. The target is to help the content providers devise better promotion strategies and popularize content by making D2D deliveries in a short time. Additionally, multi-dimensional features involving users' interests, relationships, user impacts, and social groups will be analyzed to generate a proper strategy for content providers to make their promotion decisions.

Interest Exploitation Big Data (*Cloud of Interests*): This is an interest mining and analyzing platform that focuses on mining users' preferences to realize the functions of interest recommendation, discovering the interests of nearby users, establishing groups, and obtaining interesting contents. The interest exploitation functions are realized by extracting features of users' interactive traces, preferences, sharing habits, and content popularity to perform customized and accurate recommendations.

D2D Analysis Big Data (*Cloud of Analysis*): As the core of the scheme, the D2D big data analysis platform is built to process and analyze any data sets and to gain meaningful results that the content providers need. The main part is a series of algorithms and frameworks of measuring and extracting multi-features from the traces, including time-varying online behaviors, location relations and similarity, content properties and users' preference entropy, characteristics of social groups, meeting dynamics, friendship tree analysis, and so on. In addition, they are implemented by the Spark-based big data framework to ensure high performance and accurate prediction.

While users move and share content files, the system carries out streaming-based and batch-based processing. Prediction and recommendation are made by learning-based tools involving machine learning, unsupervised learning and collaborative group recommendation algorithms to realize content promotion and friendship recommendation.

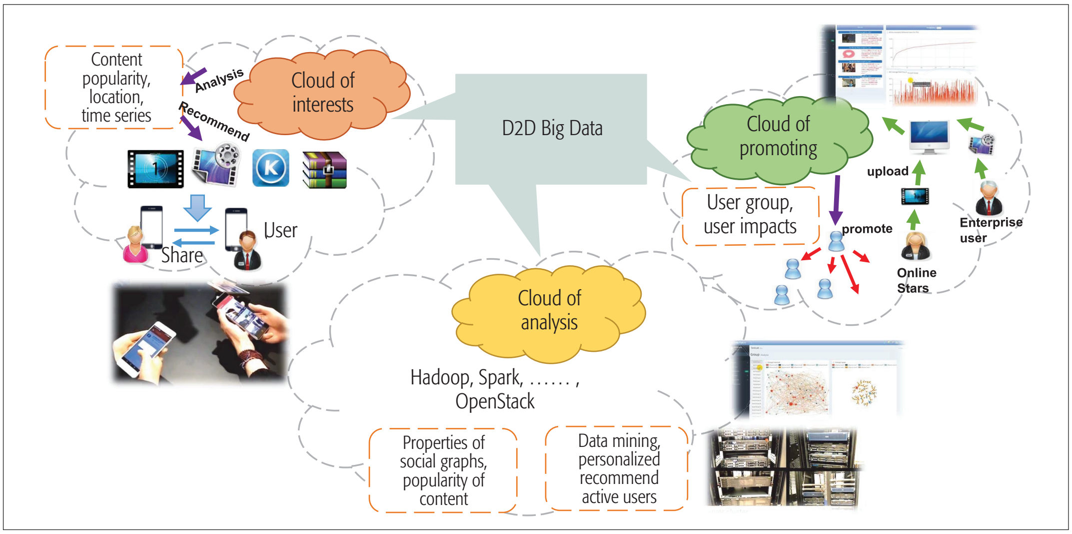

FIGURE 2. Illustration of three essential parts of the D2D big data framework.

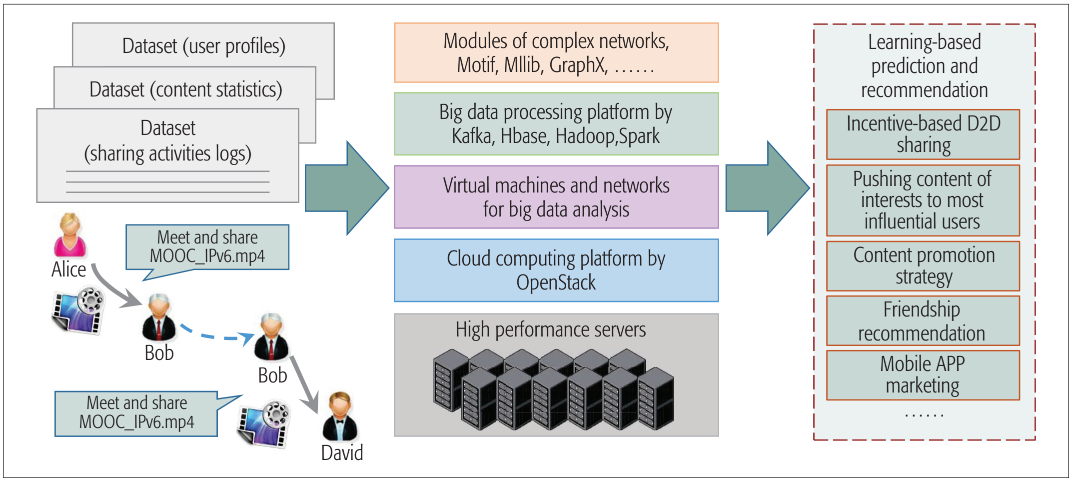

FIGURE 3. The framework of the D2D big data system, and the related processing work flow.

The industrial vision of D2D big data is to fix the problems of overloaded online Internet content, which have been severely confusing users' demands and wasting large amounts of marketing costs with low efficiency and precision instead. Hence, offloading valuable content into offline "face-to-face" (i.e., D2D) deliveries due to the truth of word of mouth effect [8] is much more accurate for satisfying mobile users. Also, from the academic perspective of D2D big data, the objective is first to effectively process a large-scale dataset generated by millions of users; second, it is not only to efficiently harmonize modules of machine learning, graph computing, complex network theory, and so on, but also to further invent novel theories and techniques. Therefore, it is desirable to deploy the D2D big data framework carefully for satisfying the needs, and we elaborate details in the following sections.

Measurement and Analytics over Realistic Data and System

The main architecture of the D2D big data framework is illustrated in Fig. 3. There are two essential conceptual components. The input of a large-scale *dataset* includes user profiles, content statistics, activity logs, traffic records, and so on. While users move and share content files, the *system* carries out streaming-based and batch-based processing. Predictions and recommendations are made by learning-based tools involving machine learning, unsupervised learning, and collaborative group recommendation algorithms to realize content promotion and friendship recommendation. Meanwhile, analytics and findings can further contribute to the mobile app marketing and developing strategies.

A robust data processing platform based on our server clusters and Spark system is built. To solve the storage problem of large datasets and processed results, Hadoop Distributed File System (HDFS) is implemented to ensure the scalability and robustness of the system. Furthermore, the in-memory computing platform of Spark is deployed to improve the big data processing ability of the framework. We used Python scripts along with the Anaconda scientific package and graph-tool library (v2.18), Hadoop, Spark, MLlib, GraphX, Spark Streaming, and batch-based data processing tools like Kafka, to support the analytics and computing of the large datasets. All tasks are supported by a cluster of 24 servers, each of which has two 2620v4 CPUs, 64G or 96G RAM, and a 6T SAS hard disk.

However, we do not deploy the big data system on the servers directly, but first implement OpenStack over the servers; then D2D big data processing tools and software packages can be set up on the virtual machines. We use OpenStack for a cloud computing infrastructure because it is open source cloud computing software with functions of building up the cloud operating system that controls large pools of compute, storage, and networking resources throughout a data center in the IaaS layer. The virtual machines with the widely used big data processing software, including Spark, Hadoop, and Hive, can thus be elastically created and used through OpenStack. This way, the platform can enjoy the elasticity and the optimality of the consolidated cloud resource all the time.

For testing and evaluating the D2D big data framework, we capture and import a large-scale dataset from Xender, which is a content delivery mobile application serving millions of users all over the world to share content files via smartphones with ease. The service has been increasingly supporting more than 100 million monthly active users and approximately 110 million content delivery activities per day. We measured the datasets from 1 August 2016 to 29 October 2016, 13 weeks in total, and a dataset of an approximate total size of 3.56 TB. We claim that the statistical information of the service and trace in this article can only be used for research purposes as it does not exactly reflect a realistic business scale, because while capturing the trace, we already filtered out a large number of incomplete or invalid records. More details of the dataset and system are shown in Table 1. Note that the scale of the dataset and system in our experimental lab are actually not very large compared to industrial big data systems run by big companies. However, we believe they are enough to ensure high computing performance and memory capacity and robust performance for discovering the potential capacity of D2D.

Multi-dimensional features, including online behaviors of users, location relations, meeting dynamics, content properties, social characteristics, popularity trends, and so on, are extracted and mined by the *Cloud of Analysis* to exploit the properties of social graphs, user behaviors, and relationships. User preferences and content properties are then analyzed by the *Cloud of Interests* and *Cloud of Promoting*, respectively. We can step to advanced utilization and exploitation over the potential of offline D2D deliveries. For example, incentive-based promotion, push over the most influential users, interest exploration, and so on are are mostly not yet well covered.

Dataset details	
Data periods	2016.08.01 – 2016.10.29
Raw dataset size	Around 3.56 TB
Cleaned dataset size	Around 96 GB
Total number of users	854 million
Number of involved users	24 million
Total number of activities	8.24 billion
Number of involved activities	886 million
Total number of files	6.22 billion
Number of involved files	4.45 million
Number of GPS records	4.19 million
Platform details	
Server nodes	24
CPU model	E2620v4
Core frequency	2.1 GHz
Memory per node	96 GB
Storage per node	6 TB

TABLE 1. Details of the social D2D big data trace and platform.

Note that the scale of the data set and system in our experimental lab are actually not so large compared with industrial big data systems run by big companies. But we believe they are enough to ensure high computing performance, memory capacity and robust performance for digging potential capacity of D2D.

Results of Measurement, Analysis, and Prediction by the D2D Big Data Platform

Over the proposed D2D big data platform, more and more results have been generated regarding general statistical measurement, and analytics on users and contents. We explore the social graph properties by complex network theory, temporal and spatial user relationships, and so on [9]. Due to limited space in this article, we cannot show all of our recent results, but several interesting research items regarding predictive content propagation based on D2D big data.

From Fig. 4, we can see that a conventional cellular-based sharing activity can be changed by wireless D2D communications where the BS is not necessarily needed. When many mobile users share files via D2D communications, as time goes on, the wireless links among users formulate "virtual" connectivities that transform the sharing records into an offline social network in which user behavior patterns and social properties of offline MSNs are quite similar to those of online social networks. Due to the temporal and spatial constraints of D2D deliveries, which are much more difficult to carry out compared to online sharing activities, the graph in the D2D social network is not strongly connected but a bit sparse, and our strategy is to split just by physical encounters, that is, if two users have ever shared at least one content file via D2D, they are in the same group. Thus, we can approximately split the large user base into multiple groups in which members are tightly connected. As shown in Fig. 6b, the sizes of the groups follow the power law exactly, which means there are few groups with large sizes, and most of the groups have small sizes. This provides us with the space to emphasize some system optimization as well as group recommendation policies. Also, we are further applying in-depth social network analysis based on complex network theory, trying to find out the properties of user groups (e.g., global cluster and local cluster, average path length, and diameters), which are illustrated in Fig. 4 as well. For instance, the diameters of the social groups in D2D sharing are around 6 to 10, which are much larger than online social network services (SNSs), indicating that the sharing by D2D happens not as easily as that in online SNSs. Instead, D2D activities take place with strict conditions on space and time, as well as very strong demands among users.

The key function driven by D2D Big Data must be the accurate prediction of user activities. This way, platform resource can be allocated in prior to the practically happening, and also we can show proper recommendation system to improve the quality of service.

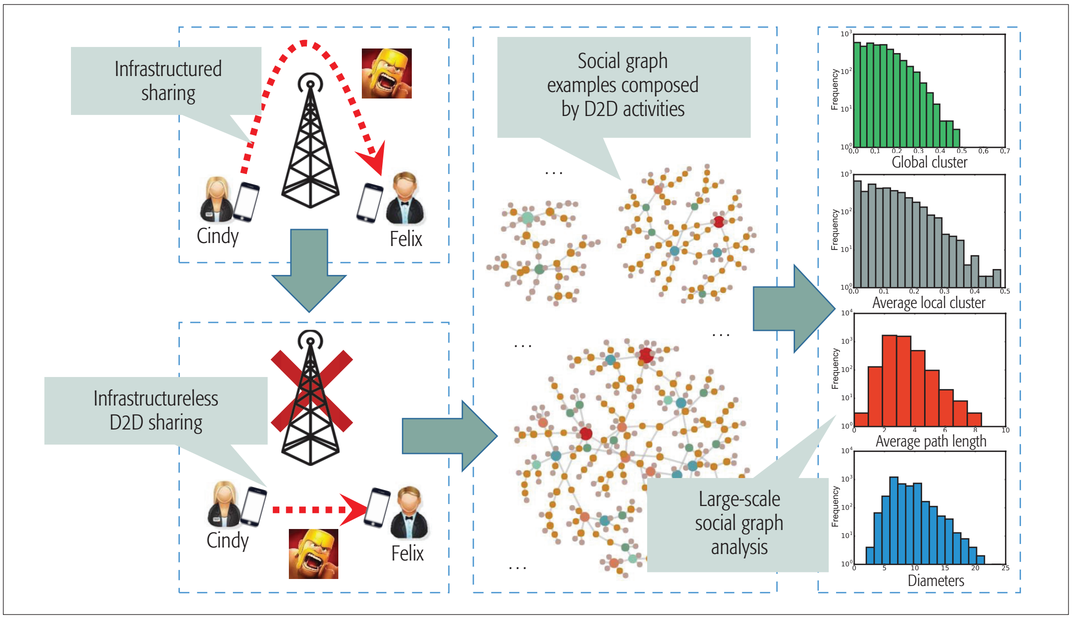

FIGURE 4. Example of a social graph composed by D2D activities from infrastructured sharing to D2D sharing.

The key function driven by D2D big data must be the accurate prediction of user activities. This way, platform resource can be allocated prior to the practical occurrence, and also we can show a proper recommendation system to improve the quality of service. We consider several important features, including time-varying online behaviors and customs, content properties and user preference entropy, meeting dynamics and mobility models, location relations and trajectory similarity, characteristics of social groups by complex networks, social arborescence and friendship tree analysis, as well as privacy preserving and sharing security as shown in Fig. 5. The privacy preserving and sharing security here can be realized by setting different permission levels to users according to their relationships. Only users with the same permission levels like family or friends can access each other's content files; hence, privacy is ensured. We are trying to carry out nowcasting experiments on D2D sharing activities, based on support vector machine (SVM) and MLlib, given several occurring factors [9]. As shown in Fig. 5, multiple features are extracted from the empirical data (e.g., six weeks' data) to train the learning tools of SVM or Spark Mlib. We nowcast the potential D2D sharing activities among users with test data (e.g., seven weeks' data). For example, when a user who likes playing free mobile games is taking a rest at a cafeteria, we can analyze and predict potential D2D sharing of the user with nearby users with common interests, and thus utilize push service to encourage a D2D sharing activity with highest probability. Results in Fig. 5 show that with different combinations of features, the prediction accuracy varies. From the perspective of efficiency, when we desire a higher prediction rate of forecasting by multiple features, we can selectively analyze two or three of the features mentioned above, not all of them. There is a significant trade-off between features put into the model.

We can easily obtain a number of statistical measurement results by time. One interesting finding is that, as shown in Fig. 6a, there is a huge amount of duplicate transmissions among millions of users. Particularly, apps and videos have very high percentages of duplicate traffic, which indicates the skewed content popularity of the two types. It may motivate us to apply related prioritization algorithms for related resource optimization, like content delivery network (CDN) deployment and content recommendation strategies.

Another key function of D2D big data is to find the most influential users within a large number of mobile users, considering various properties of the users, content files, groups, and so on. We have designed algorithms to discover the seeding users [9] by finding the main roots of the tree structures in the social groups of the large user base from the first half of the trace. Figure 6c shows the results of the evaluation on the efficiency of propagating contents in 100 randomly selected groups as representatives, and note that we only find the most influencing seed for each group to spread the content to others by assuming that two users may share the content once they practically encounter each other in the second half of the trace. It is clearly shown that in the groups, nearly half of the mobile users can get the content via offline D2D sharing, and it appears that similar patterns of spreading popular contents are rapidly boosted by seeding users' recommendations in online SNSs [10].

Opportunities and Challenges

We hereby discuss a few essential promising research directions of D2D big data, and highlight several pending problems from the perspective of elaborating and widening the usage of D2D techniques.

Privacy, Security, and Energy Issues for D2D Big Data

Despite the tremendous benefits of D2D delivery and the attached values of big-data-driven intelligence, D2D still has many security and privacy challenges that are not yet well solved. There

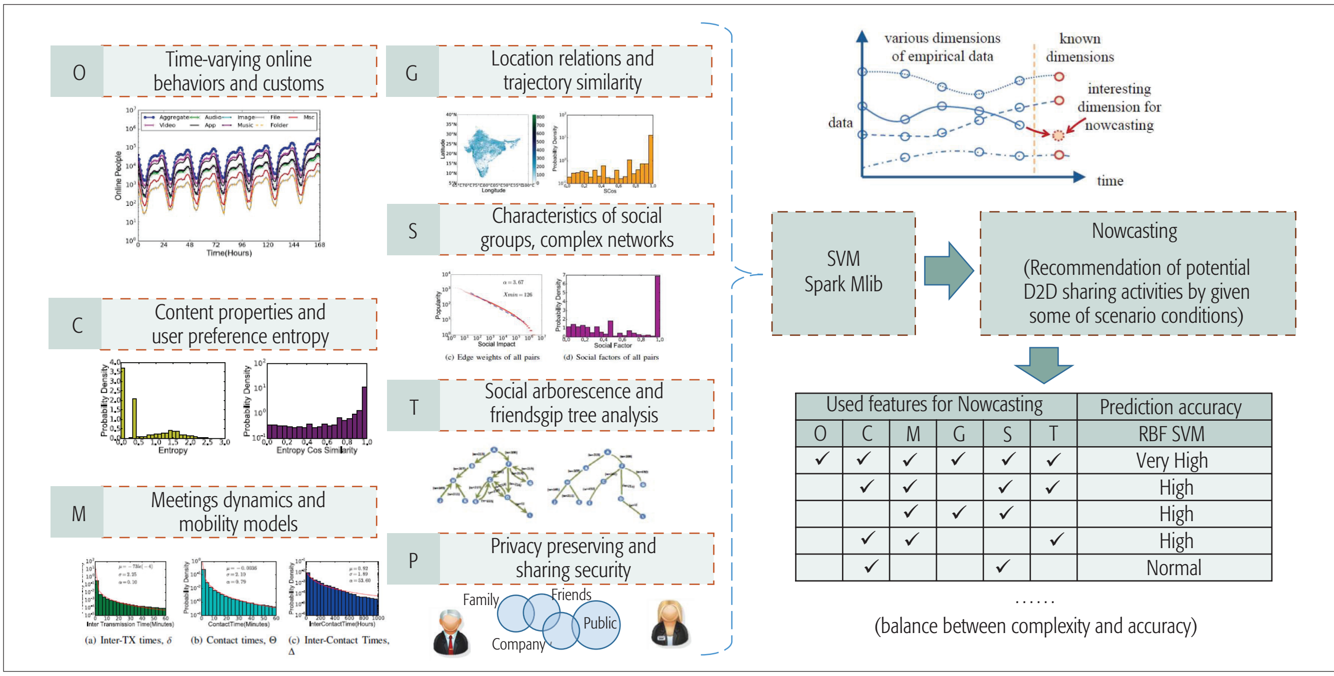

FIGURE 5. Procedure of multi-feature learning and prediction of wireless social D2D deliveries based on D2D big data.

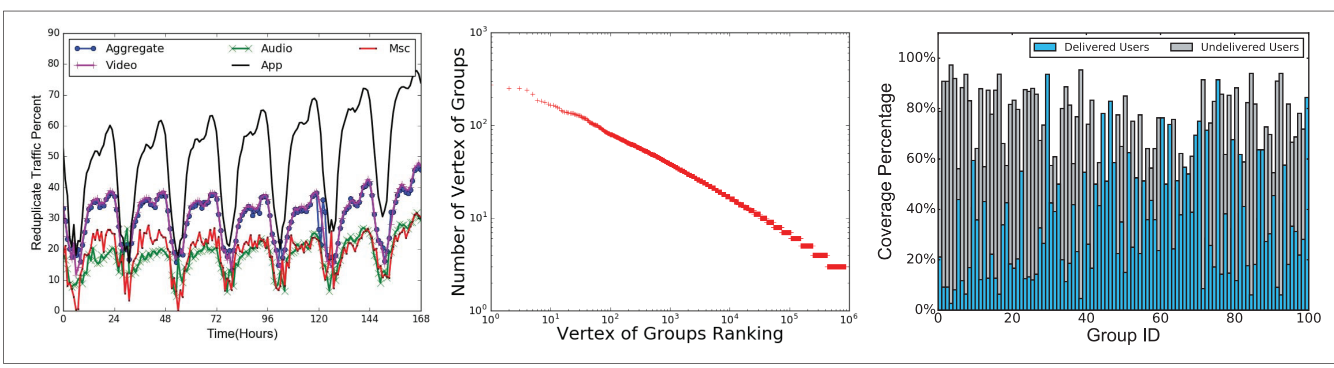

FIGURE 6. Selected results from D2D big data platform on measurement, social graph analysis, predictive propagation: a) duplicate traffic load via D2D sharing; b) groups sizes by vertex; c) coverage percentages by selecting effective seeding users.

have been many studies on privacy and security issues over DTNs/ONs/MSNs, like [11, 12]. Nonetheless, the problems may be enlarged seriously when the platform grows to a huge one for nation-wide or even worldwide MNOs, big content provider companies, and millions of mobile users. Offloading content traffic onto D2D with big data techniques should provide a fair mechanism for appropriately negotiating the cost, profit, and quality of service among all the involved entities. Particularly, an effective balance between privacy protection and freedom of sharing in mobile devices should be investigated further, and also the trade-off between passive transparent sharing or pull-based active sharing via D2D should be discussed with more experiments and user-centric trials. The achievement of a "triple-win" for the safe and secure D2D industry benefiting content providers, users, and platform developers will be complicated, and the success highly relies on innovative privacy schemes, copyright mechanisms, and security protections for D2D big data for a large-scale user base, which are still undiscovered. One more critical issue of D2D sharing is the precious energy of mobile devices [13], and hence how to utilize the emerging energy harvesting techniques for D2D communications becomes interesting but challenging.

Big-Data-Assisted Base Station Caching Integrated with D2D

There have been a number of studies toward mobile edge computing, content-centric networks, and so on, which mostly rely on the caching and offloading capability of the base stations (BSs) [14]. BSs' edge cache can formulate a collaborative "buffer" to significantly optimize the mobile applications in the last hop. There have been a few proposed techniques and systems for integrating edge caching functionality into an MNO's network to analyze and facilitate mobile services; however, combining BS caching with D2D communications for a more pervasive and more universal caching space around mobile users remains to be discussed or even tested. We are faced with interesting but challenging research issues, like how to optimally allocate the networking and caching resource among BSs and smart devices, and even how to deploy big data techniques to analyze and disseminate contents to nation-wide coverage of mobile users with the best performance.

For our future work, we will concentrate not only on more satisfactory group recommendation techniques and more accurate prediction of content popularity and user behaviors, but also the consolidated multi-disciplinary collaboration of D2D Big Data with MNOs' wireless systems, industrial vendors, content service providers, and governments' copyright policies.

Business Models for D2D Big Data

There has been an explosive growth of online peer-to-peer (P2P) techniques since the beginning of the 21st century, along with the growth of Internet topology and the number of Internet hosts, which has enabled people to collaborate for sharing contents online massively in a distributed manner. For now, can we expect a second round of P2P, that is, thriving offline D2D delivery via face-to-face encounters among people? One motivation for mobile users to share content with each other is common interest, but beyond that D2D big data should carry out a fine-grained incentive-based forwarding mechanism to push content promotion activities naturally. For example, while there are so many mobile app markets online, can we distribute most of the free app files (i.e., APK files for Android) via user-to-user sharing [15]? Also can we deliver music and video files to proper audiences, while each user is both a viewer and a marketing participant? More business models over D2D big data should be explored in the near future.

Conclusions

In this article, we discuss the potential of utilizing wireless D2D communications to offload mobile traffic and to disseminate contents among mobile users assisted by the integration of big data techniques. We discussed the D2D big data framework, which can encourage D2D delivery among users effectively, promote contents for providers accurately, and carry out offloading intelligence for operators efficiently. We implement a realistic experimental D2D big data platform, and exploit a real dataset of significant volume. Based on the measurement, analysis, and evaluation, we exploit and discuss important implications, underlying techniques, opportunities and challenges to improve quality of D2D sharing services, and enhancing the functionality and capability of D2D big data. For our future work, we will concentrate not only on more satisfactory group recommendation techniques and more accurate prediction of content popularity and user behaviors, but also the consolidated multi-disciplinary collaboration of D2D big data with MNOs' wireless systems, industrial vendors, content service providers, and governments' copyright policies.

Acknowledgment

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