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A Survey on Mobile Data Offloading Technologies

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ABSTRACT Recently, due to the increasing popularity of enjoying various multimedia services on mobile devices (e.g., smartphones, ipads, and electronic tablets), the generated mobile data traffic has been explosively growing and has become a serve burden on mobile network operators. To address such a serious challenge in mobile networks, an effective approach is to manage data traffic by using complementary technologies (e.g., small cell network, WiFi network, and so on) to achieve mobile data offloading. In this paper, we discuss the recent advances in the techniques of mobile data offloading. Particularly, based on the initiator diversity of data offloading, we classify the existing mobile data offloading technologies into four categories, i.e., data offloading through small cell networks, data offloading through WiFi networks, data offloading through opportunistic mobile networks, and data offloading through heterogeneous networks. Besides, we show a detailed taxonomy of the related mobile data offloading technologies by discussing the pros and cons for various offloading technologies for different problems in mobile networks. Finally, we outline some opening research issues and challenges, which can provide guidelines for future research work.

INDEX TERMS Mobile data offloading, small cell networks, WiFi networks, opportunistic mobile networks, heterogeneous networks.

I. INTRODUCTION

Due to the increasing popularity of using mobile devices (or nodes interchangeably) (e.g., smartphones, ipads and electronic tablets) in people's daily life, demands for multimedia services (e.g., voice over IP (VoIP), web-browsing, video-watching and file-downloading) are experiencing an explosive growth, which also brings a rapid increase in mobile traffic. For instance, according to a Cisco's report in [1], global mobile traffic is estimated to significantly increase to about 50 exabytes (1 exabyte $=$ 10^8 bytes) per month by 2021, which is a 5-time growth over 2017. However, without degrading mobile users' quality of service or experience (QoS/QoE), supporting the increasing mobile traffic has become a serve burden on mobile network operators (MNOs), which is further worsened by the lack in available network resources particularly in the current radio access networks (RANs) and backhaul networks [2], [3]. To alleviate the burden, it is essential to deploy revolutionary approaches in terms of network architectures and data transmission techniques.

Mobile data offloading, also simply referred to data offloading or traffic offloading,[1] is an effective approach to address the above challenges by utilizing complementary and revolutionary networking techniques to deliver mobile data originally planned for transmissions over cellular networks. Considering the continuous and rapid increase of mobile traffic in the future, mobile data offloading is expected to play an important role in mobile networks for reducing MNOs' capital expenditure (CPEX) and operational expenditure (OPEX) while maintaining or improving mobile users' QoS/QoE.

According to the initiator diversity of the data offloading, we classify the data offloading techniques into four categories, i.e., data offloading through small cell networks (SCNs), WiFi networks, opportunistic mobile networks or heterogeneous networks (HetNets), respectively [4]. Generally, SCNs and WiFi networks have evolved as the preferred and traditional offloading technologies in current mobile networks so as to enhance network capacity with

[1]We use the terms *mobile data offloading*, *data offloading* and *traffic offloading* interchangeably.

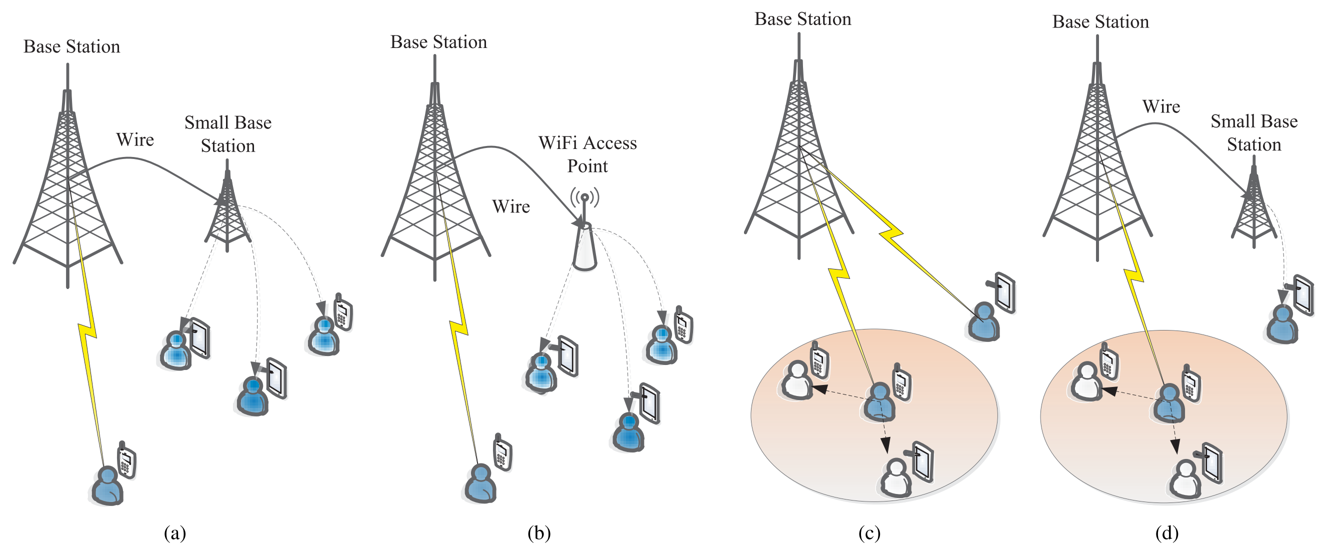

FIGURE 1. Illustration of the four data offloading technologies: (a) data offloading through small cell networks, (b) data offloading through WiFi networks, (c) data offloading through opportunistic mobile networks, and (d) data offloading through heterogeneous networks.

additional network devices, i.e., installing small base stations (SBSs) in SCNs and access points (APs) in WiFi networks. However, the practical deployment of both SCNs and WiFi networks relies on network infrastructures and has some disadvantages, such as limited coverage and high costs of device installation and network maintenance [5]. These disadvantages limit the usage of SCNs and WiFi networks, especially in outdoor and mobile environments. To make up it, introducing opportunistic communications (e.g., device-to-device (D2D) communications) in mobile networks is an effective approach for further data offloading. The opportunistic communications can be built among mobile users based on their historical/current/future information, e.g., geographical locations, service preferences and social behaviors [6], [7]. However, data offloading through opportunistic mobile networks are constrained by mobile devices' limited resources, e.g., short battery life and low transmit power. To overcome the disadvantages of the above three categories of data offloading techniques, introducing HetNets can be regarded as the last sort for data offloading in mobile networks, or say hybrid data offloading, which can effectively combine the two approaches of data offloading through both SCNs and opportunistic communications. In this paper, we are motivated to present a comprehensive survey on the above classified four categories of mobile data offloading techniques, and discuss the corresponding open research issues.

The abbreviations in this paper is shown in Table 1. The remainder of this paper is organized as follows. In Section II, we generally classify the existing techniques of mobile data offloading into four categories. In Sections III, IV, V and VI, we review and discuss the current literature of each category, i.e., data offloading through small cell networks, WiFi networks, opportunistic mobile networks and heterogeneous networks, respectively. Section VII concludes this paper and discusses future research areas.

TABLE 1. Abbreviations.

ANDSF	Access network discovery and selection function
AP	Access point
APO	Access point operator
BS	Base station
CPEX/OPEX	Capital/Operational expenditure
D2D	Device-to-device
HeNB	Home eNode B
HetNet	Heterogeneous networks
HNB	Home Node B
MADNet	Metropolitan Advanced Delivery Network
MBS	Macro base station
MNO	Mobile network operator
QoS/QoE	Quality of service/experience
RAN	Radio access network
SBS	Small base station
SCN	Small cell network
SINR	Signal-to-interference-plus-noise ratio
SSP	Small cell service provider
TASA	Tag-assisted social-aware
VCG	Vickrey-Clarke-Groves
VoIP	Voice over IP

II. CLASSIFICATION OF MOBILE DATA OFFLOADING TECHNOLOGIES

In this section, we review the main strategies and provide a comprehensive categorization of existing mobile data offloading technologies. A lot of innovative technologies have emerged to offload data and reduce the load of cellular networks, as well as increase the capacity of cellular networks. As shown in Fig. 1, these technologies of mobile data offloading can be classified into four categories: data offloading through SCNs, data offloading through WiFi networks, data offloading through opportunistic mobile networks, and data offloading through HetNets (or hybrid data offloading). In the following, we give a brief introduction of the four mobile data offloading technologies.

Data offloading through SCNs uses a variety of low-power SBSs, such as micro, pico, and femto BSs to offload the cellular traffic in SCNs. SCNs can also be realized with distributed radio technology by utilizing centralized baseband units and remote radio heads (RRHs). The technology of beamforming (aiming at enhancing radio signal in a very specific area) can further improve the coverage of small cells. These approaches to small cells can make MNOs operate central management. The coverage of small cells can range from 10 meters within urban and in-building locations to 2 km for a rural location. Picocells and microcells can also have a range of a few hundred meters to a few kilometers, but they differ from femtocells since they do not always have self-organizing and self-management capabilities.

Particularly, small cells are available for a wide range of air interfaces, e.g., GSM, CDMA2000, TD-SCDMA, W-CDMA, LTE and WiMax. In 3GPP terminology, a Home Node B (HNB) is a 3G femtocell while a Home eNode B (HeNB) is an LTE femtocell. WiFi is also a small cell but does not operate in licensed spectrum, thus cannot be managed as effectively and dynamically as small cells using licensed spectrum. The details and best practices associated with the deployment of small cells are always changing based on practical use cases and radio technologies employed. Small cells can provide a greatly effective approach of offloading mobile data traffic carried by macrocell networks. Due to better radio conditions (e.g., channel conditions) of cellular links between mobile users and SBSs, the performance on data transmission can be effectively enhanced. Thus, data offloading through SCNs has been regarded as an effective method due to their advantages such as their quick deployment, providing seamless experiences to mobile users and so on.

Data offloading through WiFi networks offloads data traffic from traditional cellular networks to WiFi networks, aiming to reduce costs and traffic load of cellular networks when mobile users enter WiFi-covered areas. Due to the scarcity of cellular network resources like network bandwidth, mobile network operators (MNOs) are forced to frequently upgrade their infrastructures to satisfy explosively increasing service demands from mobile users. In addition to the burden on MNOs, user phone bills also increase with the increase of cellular data usage [8]. Meanwhile, mobile devices are also equipped with the functionality of connecting with WiFi networks as an alternative to cellular connectivity. Thus, offloading a part of cellular data traffic to WiFi networks is attractive to both mobile users and MNOs. For mobile users, using such offloading can effectively reduce their monthly bill incurred by cellular data usage, or can enhance the battery life of their mobile devices since per-bit energy consumption of WiFi is one order of magnitude less than that of using cellular connectivity [9]. For MNOs, offloading cellular data to WiFi networks can reduce severe congestions in cellular networks and improve network capacity management. Thus, data offloading through WiFi networks has been regarded as one of the most promising techniques for addressing the challenge from the explosive growth in mobile data traffic in cellular networks due to WiFi networks' advantages, e.g., high data transmission rates and low requirements on mobile devices.

Data offloading through opportunistic mobile networks utilizes opportunistic communications of opportunistic mobile networks to offload mobile data traffic from cellular networks to opportunistic mobile networks. In opportunistic mobile networks, neighboring mobile devices can communicate without using network infrastructure and the proximity of mobile devices can provide high data rates and low power consumption [10], [44]. Most of the data delivered over opportunistic mobile networks comes from content service providers including traffic conditions, music, small multimedia, weather reports, and so on [11]. Content service providers can benefit from such delay-tolerant applications and only need to deliver the content to a small number of mobile nodes (i.e., initial seeds), so as to save monetary cost. The initial seeds can further propagate it to other subscribed nodes when they are in the communication range of each other using their equipped WiFi or Bluetooth interfaces. Such an data offloading technology is very attractive, because there is little or no monetary cost associated with it. However, there also exist many challenges due to a number of factors, e.g., data with different delay constraints and different content size, different user demands and preferences for contents, incentives for initial seeds, battery and buffer constraints of mobile devices, and so on [12], [31], [33].

Data offloading through heterogeneous networks or hybrid data offloading tries to overcome the drawbacks of above three types of data offloading technologies by combing the first and the third type of data offloading technologies together. For traditional single-tier cellular networks, it is hard for them to provide sufficient services to meet all mobile users' requirements by using the high-power tower-mounted base stations (BSs). To solve this urgent problem, some researchers have proposed a promising cost-effective architecture: multi-tier heterogeneous networks with low-power small base stations (SBSs), such as micro, pico, and femto cells, as well as opportunistic communications (or opportunistic mobile networks) underlaying macro base stations (MBSs), to increase the capacity of cellular networks greatly.

In the following sections, we will survey the current studies of the above mentioned four mobile data offloading technologies respectively, which are summarized in Table 2.

III. DATA OFFLOADING THROUGH SMALL CELL NETWORKS

There have been a number of studies focusing on mobile data offloading through SCNs. Most of them aim to investigate the involved economics and content delivery. In the following, we review the data offloading technologies through SCNs.

TABLE 2. A Classification of Mobile Data Offloading Technologies, Together with Their Research Issues and Surveyed Works.

Data Offloading through Small Cell Networks	Economics [13], [15]–[21] Content Caching [14], [18], [22]
Data Offloading through WiFi Networks	Architecture and Model [14], [24], [27], [28] Economics [13], [29] Utility or Costs [24]–[26], [30] Framework Design [8], [23]
Data Offloading through Opportunistic Mobile Networks	Seed Selection [32], [34], [35], [37], [36] Load Allocation [38], [39], [40], [41], [42], [45] Framework Design [46], [47], [48]
Data Offloading through Heterogeneous Networks	Caching Policy [49], [50], [51], [3] Content Dissemination [53], [54], [55] Framework Design [56], [57], [59]

In [13], Aijaz *et al.* surveyed mobile data offloading through Femtocells from technical and business perspectives, and discussed the current standardization process that mainly considers two types of offloading policies (i.e., access point name based and deep packet inspection based). In [14], Rebecchi *et al.* present a comprehensive survey of data offloading in cellular networks by using small cells, and extracted the main requirements of content delivery that need to integrate data offloading capabilities into today's mobile networks. In [15], Yu *et al.* surveyed the recent advances in the techniques and economics of two types of mobile data offloading: operator-initiated offloading and user-initiated offloading. Particularly in [15], in the type of operator-initiated offloading, mobile data can be offloaded by operators' APs, residential subscribers' APs and third-party APs.

In [16], Gao *et al.* firstly studied the economic interaction between one MNO and multiple APOs in mobile data offloading by using the Nash bargaining game theory. Particularly, they introduced a one-to-many bargaining game among the MNO and access point owners (APOs) and analyzed the bargaining solution systematically with two different protocols, i.e., sequential bargaining and concurrent bargaining. In the sequential bargaining, the MNOs sequentially bargains with each APO in each time in a given order, while the MNO concurrently bargain with all APOs in the concurrent bargaining. The benefits of these two bargaining protocols were quantified. Besides, in the studied group bargaining scenario where multiple APOs form a group bargaining with the MNO jointly, their analysis show that grouping of APOs may benefit the APOs whether they are in the group or not.

In [17], Iosifidis *et al.* proposed an iterative double-auction mechanism to ensure the efficient operation of the market where MNOs lease SBSs that are already deployed by residential users, aiming to maximize the differences between the MNOs' offloading benefits and SBSs' offloading costs without global information about the MNOs and APs. The proposed scheme considers the coupling of MNOs' offloading decisions and SBSs' capacity constraints, and can create non-negative revenue for the market broker.

In [18], Poularakis *et al.* proposed an architecture of leasing deployed privately-owned SBSs for mobile data delivery and a joint leasing, caching and routing framework for mobile data offloading by modeling the interaction between the MNO and SBS owners as a Stackelberg game. Numerical results show that the proposed mechanism can achieve a substantial potential for deceasing the costs of MNOs, depending on the SBS owners' resource leasing willingness and the demand characteristics of mobile users.

In [19], Mansouri *et al.* considered a data offloading market including both price-taking and price-setting third-party APOs and formulated the interactions among the MNO and these two types of APOs as a three-stage Stackelberg game, aiming to maximize the MNO's profit. To solve the non-convex game, they proposed iterative methods for the MNO and price-setting APOs to obtain the subgame equilibrium by transforming the strategy space into a convex set. Numerical results show that compared with the non-offloading case and existing schemes, the proposed offloading methods can increase the MNO's profit by 3 times and 18%, respectively.

In [20], Li *et al.* investigated the economics of mobile data offloading through APs deployed by small cell SPs (SSPs), implementing uniform volume prices for all the mobile users in each SSP's coverage including the overlapping areas. Particularly, a data offloading game was used between a MNO and two SSPs with overlapping coverage areas, where each SSP can announce a uniform price for offloading the cellular traffic within its coverage and the MNO can determine the traffic volumes to offload.

In [21], Wang *et al.* proposed a distributed market framework to price the mobile data offloading service, and conducted a detailed analysis of the incentives for offloading SPs and conflicts incurred by the interactions of different participators. Particularly, a multileader multifollower Stackelberg game was used to model the interactions between the offloading SPs and the offloading service consumers in the considered market framework. Extensive numerical results show that the Stackelberg equilibrium is close to the social optimum for both of two considered cases with/without capacity limit.

In [22], Baştuğ *et al.* explored the potentials of social and spatial proactive caching in small cell networks in terms of mobile data offloading. In particular, the proactive caching scheme considered users predictable demands, storage, and their social relationships to minimize peak mobile data traffic demands. Numerical results show that the proposed scheme can save backhaul and increase the ratio of satisfied users by up to 22% and 26%, respectively. Besides, with the increase of the cache storage at the edges of the network, more gains can further be achieved.

IV. DATA OFFLOADING THROUGH WIFI NETWORKS

Many studies have been developed to exploit mobile data offloading through WiFi networks. Most of them focus on investigating network architecture design and modeling, economics, system utility/costs (e.g., energy consumption) and so on. In the following, we review the data offloading technologies through WiFi networks.

In [13], Aijaz *et al.* also discussed mobile data offloading through WiFi networks from the perspectives of techniques and business. Particulary in [13], according to the level of WiFi and cellular networks, they discussed three offloading approaches, i.e., network bypass or unmanaged data offloading, managed data offloading and integrated data offloading. In [14], Rebecchi *et al.* also comprehensively surveyed data offloading from cellular networks to WiFi networks and analyzed the main requirements of content delivery, aiming to integrate data offloading capabilities into current mobile networks.

In [8], Yetim and Martonosi proposed, implemented and evaluated four low-overhead and effective decision schemes (i.e., Adaptive, Decision Tree-based, Hybrid and Lazy) to dynamically and adaptively deduce an email application's delay tolerance by offloading cellular data to WiFi when available. The trace-driven experiment results show that the proposed schemes can reduce cellular usage by at least 2 times compared with non-delay-tolerant schemes. Besides, the proposed adaptive decision scheme can further reduce cellular data by up to 15% compared with the scheme using static delay tolerance.

In [23], Kim *et al.* proposed an access network discovery and selection function (ANDSF) assisted WiFi control method according to users' high-level motion states (e.g., inactive, walking and driving), thereby avoiding unnecessary WiFi scanning and connections, and offloading mobile data between 3GPP access networks and WiFi networks. Experiment results confirm that the proposed scheme can achieve high performance gains in WiFi control and connectivity with 3G/WiFi.

In [24], Ding *et al.* proposed a collaborative WiFi-based mobile data offloading architecture - Metropolitan Advanced Delivery Network (MADNet), aiming to enhance the energy efficiency for smartphones based on the intelligent aggregation of the collaborative power of cellular operators, WiFi service providers and end-users. Using the proposed prototype on smartphone (i.e., Nokia N900), experiment results show that the proposed MADNet can save at leats 80% energy consumption, and also show that it can tolerate minor prediction errors in localization, mobility and offloading capacity.

In [25], Kang *et al.* explored mobile data offloading through WiFi APs for cellular mobile networks from the cellular operator's perspective, aiming to maximize the network utility by introducing a usage-based charging model and the technique of successive interference cancellation (SIC). Particularly, they considered three scenarios: 1) SIC available at both the BS and the AP; 2) SIC not available at either the BS or the AP; 3) SIC available at only the BS. Simulation results show that the proposed scheme can effectively offload mobile data, and also show that SIC decoders can help maximize the utility of the cellular operator.

In [26], Poularakis *et al.* proposed a mobile data offloading scheme by leasing wireless bandwidth and cache space of residential 802.11 (WiFi) APs, which can effectively reduce cellular network congestion and improve the user-perceived network performance without overloading the APs' backhaul links. Meanwhile, a framework was proposed for the joint optimization of incentive, caching and routing policies, aiming to decrease operators' total cost from serving mobile data requests and leasing resources. The trace-driven simulation results show that the proposed scheme can effectively reduce the operator's total cost while reimbursing each residential user by up to 9 euros monthly.

In [27], Sou and Peng present an analytical model for multipath WiFi offloading in deriving the aggregate offloading time via an alternative path for the use of multipath offloading. Extensive simulation results show that the proposed model can further help the cellular operators when designing resource allocation schemes, and also show that multipath offloading can greatly enhance the performance on supporting minimum-rate guaranteed services compared with opportunistic offloading.

In [28], Mehmeti and Spyropoulos proposed a queueing analytic model for delayed mobile data offloading through WiFi networks, and derived the mean delay, offloading efficiency and other metrics of interest as a function of the users' patience and key network factors for two different service disciplines (First Come First Service and Processor Sharing). The trace-driven simulation results confirm the accuracy of the proposed analytic model, and also show how the user can optimally choose deadlines when maximizing his own benefits.

In [29], Qiu *et al.* proposed a procurement mechanism with contingent contracts for cellular service providers to leverage the advantages of both cellular and WiFi networks, aiming to improve mobile bandwidth availability and offload mobile data to WiFi networks. Besides, they shown how to compute the optimal procurement mechanism using economics and computational techniques. Simulation results show that the proposed scheme has much better performance than the standard Vickrey-Clarke-Groves (VCG) auction w.r.t. the expected payoff of the cellular SP.

In [30], Lee *et al.* present a quantitative study focusing on exploring the performance of mobile data offloading through WiFi networks, and two observations can be achieved from the trace-driven simulation results as: 1) WiFi can offload about 65% of the total mobile data traffic and save 55% of battery power without employing any delayed transmissions;

2) Employing delayed data transfers with some deadlines until users enter a WiFi zone, substantial gains can be achieved only when the deadlines are fairly larger than tens of minutes.

V. DATA OFFLOADING THROUGH OPPORTUNISTIC MOBILE NETWORKS

A number of studies have been developed to explore the opportunistic mobile network for mobile data offloading. Most of them focus on investigating seed selection, load allocation, and framework design. In the following, we review the data offloading technologies through Opportunistic Mobile Networks in this section.

In [32] and [34], Han *et al.* were the first to exploit opportunistic mobile networks to relieve the mobile data traffic of cellular networks. They consider the scenario in which one message needs to be disseminated from a content service provider to all subscribers before a given deadline. They study how to select k nodes(called initial seeds), such that the mobile data traffic over cellular networks is minimized. Since this problem is NP-hard, they propose three algorithms to solve this problem: Random, Heuristic, and Greedy. The real trace-driven simulation results show that the proposed Heuristic algorithm can offload mobile data traffic by up to 73.66%. Furthermore, they also implement a prototype of the mobile data offloading framework using Nokia N900 and study its feasibility for moving smartphones. Furthermore, in [35], Chuang and Lin proposed a community-based mobile data offloading scheme, to offload cellular traffic through opportunistic mobile networks. Different from preliminary studies which select initial seeds only based on the contact probability between nodes, they select initial seeds based on both the contact frequency and social relationships. Social communities is proposed to define social relationships between nodes, so as to distribute the object to nodes belonging to different communities. In addition, to guarantee most of nodes can obtain the object, they proposed community-based opportunistic dissemination to automatically select a sufficient number of initial seeds. Extensive real trace-driven simulations show that the proposed scheme performs much better than the encounter-based data offloading scheme. In [36], Liu *et al.* proposed a multiple initial seeds selection method to find the optimal number of initial seeds through opportunistic mobile network-based mobile data offloading. They defined the problem as a utility optimization problem with considering both the data diffusion time and the transmission cost from cellular networks to the initial seeds. They proposed different models to calculate the accurately estimate the data diffusion time for the dense and sparse contact network scenarios, respectively. Extensive simulations were conducted to analyze the impact of parameters on the proposed scheme, and compare the proposed scheme with other existing schemes.

In [37], Whitbeck *et al.* investigated the problem of utilizing opportunistic mobile networks to minimize the mobile data traffic over cellular networks while a tight delivery delay of the message should be met. To solve this problem, they propose a content dissemination framework called Push-and-track, which gives multiple strategies to determine how many copies should be injected to each node and to whom the copies should be injected. To determine the number of injected copies, they consider different objective functions of different aggressiveness levels. For determining to whom the copies should be injected, they consider Random, Entry time, GPS-based, and Connectivity-based strategies. Simulation results on a real vehicular dataset show that the proposed Push and-Track method can offload mobile data traffic by over 90% while guaranteeing 100% delivery.

In[38] and [39], Li *et al.* studied the opportunistic mobile network-based mobile data offloading problem by considering many realistic assumptions, e.g., content size, content lifetime, nodes' subscribing interests and limited buffer size of nodes. Assuming that all helpers in the network are cooperative in the data offloading process, they formulate the optimization problem as a submodular function maximization problem with multiple linear constraints. To solve the optimization problem, they design three approximate algorithms: Greedy Algorithm, Approximation Algorithm and Homogeneous Algorithm, suitable for different data offloading scenarios. Through theoretical analysis and extensive simulations, they show that the proposed algorithms can effectively offload cellular data to Opportunistic Mobile Networks.

In [40], Al-Kanj *et al.* studied the opportunistic mobile network-based mobile data offloading problem by considering the following scenarios: 1) multi-hop data dissemination, 2) multi-cast transmission among mobile nodes, and 3) fairness constraints on the energy consumption of mobile nodes for cooperation. They formulated the optimal data offloading problem as a mixed integer linear programming problem, and gave the complexity analysis about the optimization problem. Then, they proposed a dynamic programming approach based on the network dynamics to address the challenges brought by the mobility of mobile nodes in the network. Since the optimization problem is NP-complete, they proposed polynomial time greedy algorithms to obtain computationally fast solutions with proper performance. Extensive simulations are conducted to evaluate the proposed methods, and the results show that the proposed methods can obtain significant data offloading gains.

In [41], Kouyoumdjieva and Karlsson proposed the progressive selfishness algorithm, an adaptive and scalable energy-aware algorithm for improving energy efficiency in mobile data offloading through opportunistic mobile networks. They combined the merits of two mutually exclusive energy saving mechanisms: duty cycling and selfishness in the design of the proposed progressive selfishness algorithm. Furthermore, they also proposed a modified version of the algorithm, named enhanced progressive selfishness for dense scenarios. Extensive real trace-driven simulations were conducted to evaluate the performance of the proposed progressive selfishness algorithm in terms of goodput and energy consumption. The results showed that the proposed algorithm can decrease energy consumption of mobile nodes during the opportunistic offloading with up to 85% in different node densities while sacrificing less than 1% in goodput.

In [42], Lu *et al.* aimed to improve the delivery probability of cooperatively offloading data which is transmitted from a mobile node to an intermittently connected remote infrastructure in opportunistic mobile networks. They first gave the probabilistic framework to calculate the data delivery probability over opportunistic paths with consideration of both data size and contact duration. Then, based on the proposed framework, they proposed a centralized heuristic algorithm to solve the cooperative offloading optimization problem, which is NP-hard. Since it is hard to obtain global information of the whole network, they further proposed a distributed algorithm. Extensive simulation results show that the proposed cooperative offloading can greatly improve the data delivery probability and the proposed heuristic algorithms performs much better than other existing schemes.

In [43], Sciancalepore *et al.* proposed a novel approach, named HYPE, to offload cellular data traffic through opportunistic mobile networks. They first developed a theoretical model to analyze the performance of disseminating data through opportunistic mobile networks when data were selectively injected through the cellular network. Based on the proposed theoretical model, they obtained the optimal strategy for injecting data through the cellular network, e.g, how many copies of the data to inject, to which nodes and when to inject through the cellular network. To implement the optimal strategy derived from the theoretical analysis, they proposed an adaptive algorithm based on the control theory to guarantee the stability and substantiality of the proposed algorithm. Extensive simulation results show that the proposed algorithm performs better than other existing approaches listed in the literature with very low signaling overhead.

In [45], Li *et al.* investigated the impacts of data size on the performance of opportunistic mobile network-based mobile data offloading schemes. Taking into account both the short contact duration and the large data size existed in reality, they proposed a contact-duration-aware offloading scheme, named Coff, which applies the network coding to better utilize the short contact durations. They formulated the optimal load allocation problem in Coff as a nonlinear integer programming problem, which is proved as a NP-hard problem. To solve the optimization problem, they proposed a greedy load allocation algorithm approximately. Extensive real and synthetic traces-based simulations were conducted to evaluate the performance of the proposed scheme. The results show that the proposed scheme Coff outperforms other existing offloading schemes that are extended from state-of-the-art opportunistic mobile network-based offloading schemes considering content fragmentation and network coding.

In [46], Li *et al.* aimed to establish a new paradigm for addressing challenging problems in mobile data offloading through opportunistic mobile networks. They proposed a social-aware enhanced opportunistic mobile network-based mobile data offloading architecture that exploits social networking characteristics for better mobile data offloading performance. By exploiting a profound understanding and insight of the main social characteristics (e.g., social ties, social community, social centrality, and social bridges) existing in the social networks formed by mobile nodes, they qualitatively analyzed how opportunistic mobile networks can benefit from social characteristics among mobile nodes, and quantitatively assessed the achievable gains in opportunistic mobile network-based mobile data offloading system. They state that their study can open a new research direction for designing the next-generation opportunistic mobile network-based mobile data offloading system.

In [47], Wang *et al.* proposed an opportunistic mobile network-based mobile data offloading framework, named TOSS, to offload cellular traffic by opportunistic mobile network. In the design of TOSS, they considered both nodes' content spreading impacts in online social network services and their mobility patterns in offline opportunistic mobile networks to select initial seeds. Since the observation of Social Network Services user activities revealed that individual nodes had distinct access patterns, they further exploited the user-dependent access delay between the content generation time and each node's access time for data offloading purpose. They analyzed the data offloading and content spreading among users by taking into account various options in online and offline real trace data. Extensive real trace-driven simulation results show that the proposed TOSS can reduce up to 86.5% of the cellular traffic while satisfying the access delay requirements of all nodes. Furthermore, in [48], Wang *et al.* proposed a framework, named Tag-Assisted Social-Aware (TASA), for effective mobile data offloading through opportunistic mobile networks. They selected the optimal subset of initial seeds based on nodes' online social spreading impact and offline social mobility patterns. Furthermore, they utilized the user-dependent access delays for matching the delay-tolerant content deliveries. Extensive real trace-driven simulation results show that the proposed framework can reduce up to 78.9% of mobile data load, while guaranteeing all nodes' delivery delay requirements.

VI. DATA OFFLOADING THROUGH HETEROGENEOUS NETWORKS

Many researchers have proposed various traffic offloading schemes for Heterogeneous Networks. Traffic offloading can be fulfilled by exploiting either small cell networks, or WiFi networks, or Opportunistic Mobile Networks, or even combination of small cell networks and Opportunistic Mobile Networks. In the following, we review the data offloading technologies through Heterogeneous Networks (or hybrid traffic offloading) in this section.

In [49], Liu and Yang investigated the optimal content placement in cache-enabled Heterogeneous Wireless Networks. To maximize the successful offloading probability, they derived the closed-form expression of the successful offloading probability and the optimal caching probability.

Furthermore, they also analyzed the impact of some system parameters, e.g., Base Station density, user density, transmit power, and signal-to-interference-plus-noise ratio (SINR) threshold on the optimal caching policy. Extensive simulation and numerical results showed the effectiveness of their proposed scheme. Similarly, in [50], Li *et al.* focused on content caching in Heterogeneous Wireless Networks to offload the weighted network traffic. They formulated the optimization problem as a minimization of the weighted expected sum of traffic loads. Since this optimization problem is NP-hard, they transformed the formulated irregular optimization problem into a binary integer linear programming problem, and then proposed a suboptimal greedy heuristic algorithm to solve the optimization problem. Simulation results showed that compared with non-caching methods, the proposed caching methods can greatly increase the data offloading performance. Furthermore, in [51], Liu *et al.* investigated the deployment of cache-enabled Heterogeneous Wireless Networks over conventional Heterogeneous Wireless Networks with limited capacity backhaul to increase the area spectral efficiency. They derived closed-form expressions of the approximated area spectral efficiencies of two kinds of Heterogeneous Wireless Networks. Numerical results showed that the deployment of cache-enabled Heterogeneous Wireless Networks can double the area spectral efficiency over conventional Heterogeneous Wireless Networks.

In [3], Li *et al.* proposed an efficient collaborative multi-tier caching framework in Heterogeneous Wireless Networks. Considering node requests, link capacities, cache sizes, and network topology, they modeled the maximum capacity of the network infrastructure so as to offload the network traffic and support nodes' content requests locally. Since this optimization problem is NP-hard, they approximately decomposed it into some subproblems based on the obtained network topology. Extensive real trace-driven simulation results showed the effectiveness of the proposed framework.

In [52], Kang and Sun proposed a salary and bonus reward scheme as the incentive mechanism to stimulate WiFi Access Points to provide data offloading service for the MNO. Particularly, WiFi Access Points is rewarded based on both the amount of offloaded data and the quality of the offloading service. They used the Stackelberg game to model the interactions between the WiFi Access Points and the MNO, and derived the best response functions for WiFi Access Points which lead to the Nash Equilibrium. Then, they studied the optimal salary rate and the optimal bonus rate for the MNO so as to maximize its utility. Numerical results showed that the proposed incentive scheme is effective in stimulating WiFi Access Points to provide data offloading services.

In [53] and [54], Mao *et al.* proposed a novel cooperative content dissemination strategy to offload a significant proportion of cellular data traffic to WiFi networks, Opportunistic Mobile Networks, and vehicular ad hoc networks. They provided detailed analysis for the content dissemination process adopting the strategy, and discussed the optimal parameter settings for the content dissemination strategy. Extensive simulation and numerical results showed that the proposed strategy can greatly offload data traffic for cellular networks.

In [55], Cao *et al.* proposed an optimal Opportunistic Mobile Network-based data offloading scheme to improve network capacity and nodes' energy efficiency in Heterogeneous Wireless Networks. They formulated the data offloading optimization problem as a 0-1 Linear Programming, and proved it to be NP-hard. To solve this problem, they proposed an efficient optimization algorithm by using dynamic programming, which is close to the exact optimal solution with reasonable computational complexity. Numerical results showed that the proposed algorithm can greatly improve data offloading efficiency, network capacity and nodes' energy efficiency.

In [56], Liu *et al.* investigated the mobile data offloading problem under the architecture of mobile cloud computing (MCC), where mobile data can be delivered by cellular, WiFi and Opportunistic Mobile Networks. To minimize the overall cost through cellular networks, they proposed a model to offload a portion of the mobile data to WiFi and Opportunistic Mobile Networks. They formulated the data offloading problem as a finite horizon Markov Decision Process, and proposed a hybrid offloading algorithm to solve this optimization problem. Extensive simulation results showed that their proposed offloading scheme performed much better than other three offloading schemes.

In [57], Duan *et al.* proposed a Software-Defined Networking based module framework to offload partial cellular data to WiFi networks in Heterogeneous Wireless Networks. In order to analyze the performance of the proposed partial offloading algorithm, they considered two performance metrics: the threshold miss probability and the amount of offloaded data. Extensive simulation results showed that the proposed partial offloading algorithm can save resources and decrease threshold miss probability by 20%-40%. Furthermore, in [58], Liu *et al.* also focused on the mobile data offloading optimization problem in software defined network. They formulated a total revenue maximization problem by considering both the offloading utility of Base Stations and cost of Access Points for offloading decision. To solve the optimization problem, they proposed a distributed algorithm by utilizing the proximal Jacobian multi-block alternating direction method of multipliers. Numerical simulation results showed the effectiveness of the proposed algorithm.

In [59], Singh and Andrews proposed a general analytical framework for data offloading and resource partitioning in Heterogeneous Wireless Networks. Based on the analytical framework, they derived the down-link rate distribution and an optimal strategy for joint data offloading and resource partitioning. Extensive simulation and numerical results showed the effectiveness of the proposed framework, and the importance of combining load balancing with resource partitioning.

VII. CONCLUSIONS AND FUTURE RESEARCH AREAS

Mobile data offloading is an effective approach to ease the burden of the cellular network, which not only provides effective mobile data management solutions to service providers for relieving congestion, but also provides them with new business chances. Due to the explosive increase of data traffic on mobile networks, it is very urgent to study the mobile data offloading technologies. In this paper, we surveyed the state of the art in mobile data offloading technologies. We studied the concept of mobile data offloading technologies, and classified existing mobile data offloading technologies into four categories: data offloading through SCNs, data offloading through WiFi networks, data offloading through opportunistic mobile networks, and data offloading through heterogeneous networks (or hybrid data offloading). Then, we introduced the detail of existing studies on mobile data offloading technologies from these four categories.

Mobile data offloading is still a very new and hot research area. Despite the existing studies that we have introduce above, there still exist many open research challenges when the data offloading technology is implemented. One of the main challenges associated with mobile data offloading is the lack of global network information. In order to perform initial seed selection process more effectively as discussed in Section V, it is very important for base stations and mobile nodes to collect global network information, e.g., social relationships, congestion situations, buffer states, traffic rates and so on. However, because of security and privacy reasons, some mobile nodes are not willing to provide their local or personal information to others, including base stations [60]. Some ongoing industry standards have tried to provide more network information, but the sharing of a comprehensive information still needs further development. Another challenge associated with mobile data offloading is the lack of accurate nodes' demands and behaviors. In reality, in order to motivate nodes to take part in the data offloading process, the service provider needs to design proper incentive schemes. However, it is hard for the service provider to accurately estimate the nodes' demands and predict their behavior, which greatly affects the performance of data offloading.

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