A SURVEY ON MOBILE DATA OFFLOADING: TECHNICAL AND BUSINESS PERSPECTIVES

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ABSTRACT

Over the last few years, data traffic over cellular networks has seen an exponential rise, primarily due to the explosion of smartphones, tablets, and laptops. This increase in data traffic on cellular networks has caused an immediate need for offloading traffic for optimum performance of both voice and data services. As a result, different innovative solutions have emerged to manage data traffic. Some of the key technologies include Wi-Fi, femtocells, and IP flow mobility. The growth of data traffic is also creating challenges for the backhaul of cellular networks; therefore, solutions such as core network offloading and media optimization are also gaining popularity. This article aims to provide a survey of mobile data offloading technologies including insights from the business perspective as well.

INTRODUCTION

The cellular industry has seen tremendous growth over the past few years, particularly in terms of data traffic, which, already surpassing voice traffic, is continuously increasing by an order of magnitude every year. Global mobile data traffic is expected to grow to 10.8 exabytes (1 exa = 10^{18}) per month by 2016, which is an 18-fold increase over 2011 [1]. This unprecedented increase in data traffic is creating challenges for existing cellular networks. Mobile data offloading, or simply data offloading, refers to the use of complementary network technologies and innovative techniques for delivery of data originally targeted for mobile/cellular networks in order to alleviate congestion and make better use of available network resources. The objective is to maintain quality of service (QoS) for customers, while also reducing the cost and impact of carrying capacity-hungry services on the mobile network. It is expected that mobile data offloading will become a key industry segment in the near future as the data traffic on mobile networks continues to increase rapidly.

The primary driver for mobile data offloading is obviously the rise of data traffic on cellular networks, which is causing congestion and ultimately degrading customer experience. This rise can be attributed to a number of factors: first, the introduction of high-end devices such as laptops, tablets, and smartphones, which can multiply traffic (e.g., a smartphone can generate up to 35 times the traffic generated by a basic feature phone); second, the growth in average traffic per device, particularly due to increasing mobile network connection speeds and improvement in the battery life of mobile devices. Both of these factors increase an individual's contact time with the network. Third is the increase in mobile video content, which has much higher bit rates than other mobile content types. Besides higher data rates provided by the current generation of cellular networks, which enhance the users' viewing experience, large screen sizes and optimization of video for mobile devices also contribute to the growth of video traffic. Fourth, the availability of mobile broadband services at prices and speeds comparable to those of fixed broadband, together with the increasing trend toward ubiquitous mobility are other contributing factors in growth of data traffic on mobile networks. Other drivers for mobile data offloading include cost reduction, improving customer experience, and new business opportunities.

Most mobile operators have introduced and started to implement a mobile data offloading strategy. So far, Wi-Fi and femtocells have emerged as the preferred offloading technologies. In addition to data offloading solutions, operators have also been considering a number of optimization approaches to relieve congestion on their networks. The traditional approach of scaling network capacity with additional network equipment (installing more base stations per area) is always available, but not cost-effective and viable considering the pace at which the demand for data services is increasing. The main objective of this article is to provide the state of the art in mobile data offloading, covering both technological and business aspects. To the best of the authors' knowledge, such a survey does not exist in the literature. The rest of the article is organized as follows. We cover the existing mobile data offloading solutions. Since Wi-Fi and femtocells have evolved as mature technologies, they are covered in relatively more detail compared to other emerging technologies. Business perspectives on mobile data offloading are presented, including vendor and operator strategies. The question of how to evaluate the effect

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of offloading is addressed, followed by a discussion of challenges associated with offloading. Finally, we conclude the article.

Mobile Data Offloading Solutions

Mobile Data Offloading via Wi-Fi

Wi-Fi stands for wireless fidelity, which is a wireless connectivity solution based on IEEE 802.11 standards. It is primarily used for broadband access in indoor environments. Compared to conventional mobile communication technologies such as Universal Mobile Telecommunications System (UMTS), high-speed packet access (HSPA), and Long Term Evolution (LTE), Wi-Fi provides higher data rates but with limited coverage and mobility. Nowadays, Wi-Fi is undergoing a paradigm shift toward ubiquity and outdoor/city-wide Wi-Fi networks are gaining popularity.

Wi-Fi comes as a natural solution for offloading due to the built-in Wi-Fi capabilities of smartphones. Due to degradation of cellular services in overloaded areas, an increasing number of users are already using Wi-Fi to access Internet services for better experience. From the service provider's perspective, Wi-Fi is attractive because it allows data traffic to be shifted from expensive licensed bands to free unlicensed bands (2.4 GHz and 5 GHz). Studies have shown that expanding networks using Wi-Fi is significantly less expensive than a network rollout.

There are three main approaches for operators to offload data traffic onto Wi-Fi networks, depending on the level of integration between Wi-Fi and cellular networks [2]. The first approach is the *network bypass* or *unmanaged data offloading*, in which case the users' data is transparently moved onto the Wi-Fi network, whenever they are in Wi-Fi coverage, completely bypassing the (cellular) core network for data services. Voice services, on the other hand, continue to be delivered via the core network. While this approach seems attractive as it does not require the deployment of any network equipment, it has some drawbacks. First, the operator loses visibility (and hence control) of its subscribers whenever they are on the Wi-Fi network. Second, the operator is unable to deliver any subscribed content (Blackberry, corporate VPN, ringtones, etc.), leading to potential loss of revenue. Despite its disadvantages, this approach can be adopted as an immediate offloading solution due to its ease of deployment. It is also attractive from the users' perspective due to control over data connectivity. It should be noted that this approach is similar to users switching on the Wi-Fi interface whenever they are in Wi-Fi coverage for a better experience. The operator can deploy such an offloading solution by simply placing an application in handsets that switches on the Wi-Fi interface upon detecting Wi-Fi coverage.

A *managed data offloading* approach can be adopted by those operators who do not want to lose control of their subscribers. This is achieved by placing an intelligent session-aware gateway through which the subscriber's Wi-Fi session traverses on its way to the Internet. Complete integration of cellular and Wi-Fi networks is not required in this case. While the operator gains control of subscribers, it still cannot deliver any subscribed content.

An *integrated data offloading* approach provides the operator with full control over subscribers as well as the ability to deliver any subscribed content while the users are on the Wi-Fi network. This is achieved by the integration of cellular and Wi-Fi networks so that a bridge can be formed between the two networks through which data flow can be established. There are two architectures for coupling cellular and Wi-Fi networks: loose coupling and tight coupling. In loose coupling , the networks are independent, requiring no major cooperation between them. The Wi-Fi network is connected indirectly to the cellular core network through an external IP network such as the Internet. Service connectivity is provided by roaming between the two networks. On the other hand, in a tightly coupled system, the networks share a common core and majority of network functions such as vertical handover, resource management, and billing are controlled and managed centrally. The 3GPP I-WLAN standard [3] defines the basic principles for managing the Wi-Fi networks in an integrated data offload scenario for the mobile network operator. It provides a solution to transfer data between the mobile device and the core network through a Wi-Fi access network. The underlying concept is to establish a controlled tunnel between the mobile device and a dedicated I-WLAN server in the core network in order to obtain access to operator subscribed content or public Internet.

Within the context of Wi-Fi offloading, it is important to mention White-Fi offloading. White-Fi, as currently being standardized by IEEE 802.11af, is the proposal for using conventional Wi-Fi in the TV white spaces using cognitive radio technology. TV white spaces refer to large portions of UHF/VHF spectrum that are becoming available on a geographical basis as a result of the switchover from analog to digital TV. White-Fi offers many benefits, such as wide area coverage due to better propagation characteristics of TV bands and availability of much larger bandwidths (location-dependent, e.g., on average 50–150 MHz in the United Kingdom [14]). However, channel aggregation techniques will be necessary to provide data rates comparable to Wi-Fi operating in 2.4 GHz and 5 GHz bands. It is expected that outdoor White-Fi hotspots would be deployed in the future that will play an important role in data traffic offloading from mobile networks

Mobile Data Offloading via Femtocells

A femtocell is a small cellular base station typically designed for indoor use (e.g., in a home or office). It connects to the service provider's network via broadband (e.g., digital subscriber line, DSL) and allows the service provider to extend service coverage indoors, especially in areas where access would otherwise be limited or unavailable. Femtocells are attractive to operators as they provide improvement in both coverage and capacity, especially indoors. The concept of femtocells is applicable to all standards includ-

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In femtocell environments, the traffic flows over the air interface to the femtocell (which is connected to the user's broadband connection), then over the Internet to the operator's core network and/or to other Internet destinations.

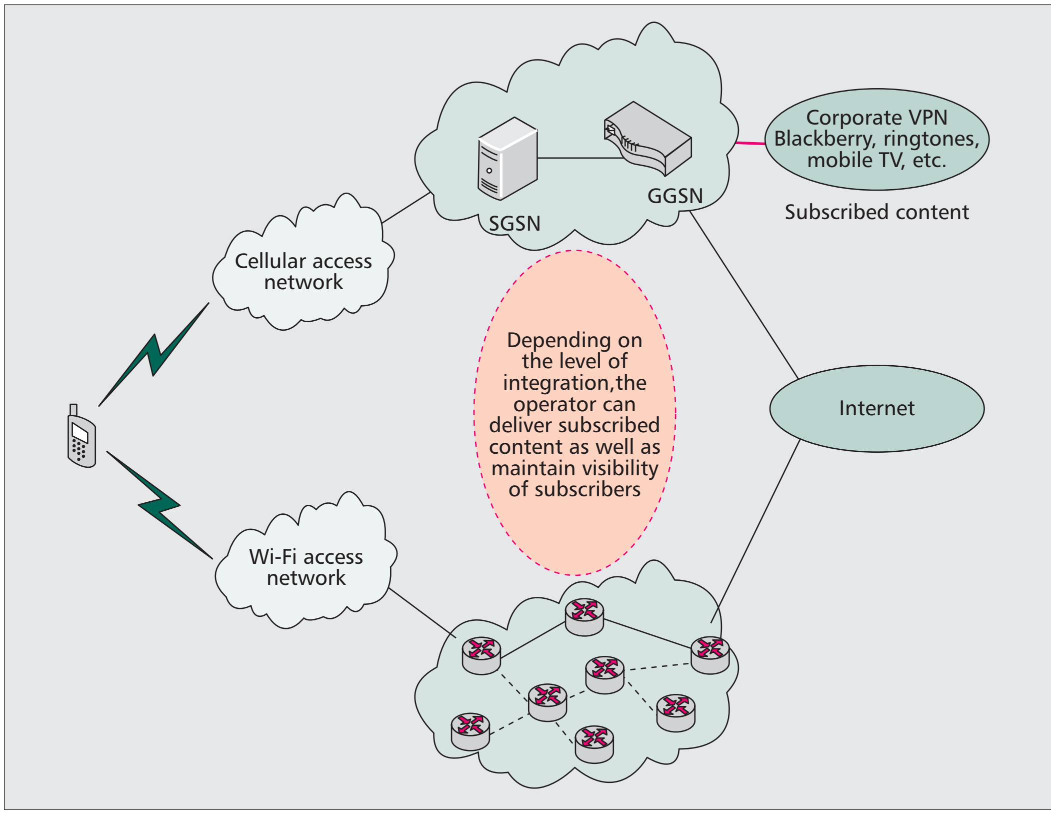

Figure 1. *Mobile data offloading via Wi-Fi.*

ing GSM, wideband code-division multiple access (WCDMA), World-Wide Interoperability for Microwave Access (WiMAX), and LTE. Femtocells provide a highly effective method of easing the traffic carried by a macrocellular network. The freed capacity improves the experience of customers on the macro network, and at the same time users connected via femtocells experience improved performance due to usually better radio conditions.

Data offloading through femtocells is effective for a number of reasons, some of which are as follows [4]. First, the usage occurs primarily indoors (homes or offices). According to one of the published studies, 55 percent of data usage occurs in the home and 26 percent occurs in the office [5]. Thus, the operators get the opportunity to offload heavy users through femtocells. Second, femtocells represent an operator deployed and managed service, and therefore provide a seamless experience to users. Third, femtocells can be deployed quickly, unlike traditional macrocellular deployments, which take much longer due to site acquisition, purchase of radio infrastructure and backhaul, and other similar considerations.

In femtocell environments, the traffic flows over the air interface to the femtocell (which is connected to the user's broadband connection), then over the Internet to the operator's core network and/or other Internet destinations. Whenever a subscriber comes into the coverage of femtocell, the user equipment (UE) automatically associates with it. Traffic that previously flowed between the macrocell and the UE now flows through the femtocell and the subscriber's broadband connection. The femtocell not only offloads the Node B but also the radio network controller (RNC), which further reduces the load on the macrocellular network.

A new standard, currently under development, known as selected IP traffic offload (SIPTO) [6], enables the operator to offload certain types of traffic at a network node close to the UE's location. The current standardization process mainly considers two types of policies for offloading: access point name (APN) based and deep packet inspection (DPI) based. A detailed discussion on SIPTO is out of the scope of this article. Interested readers are referred to [7]. However, it is important to mention that by implementing SIPTO, operators can offload the core network by allowing the traffic to flow directly from the femtocell to the Internet.

Before moving onto the next section, we briefly describe the relative advantages and disadvantages of femtocells and Wi-Fi as both are major offloading solutions. As Wi-Fi operates in unlicensed bands, operators have access to much larger free spectrum to cater for any size of Wi-Fi deployment. Femtocells, on the other hand require careful planning as they operate in costly (licensed) and limited spectrum bands. Femtocells capture 100 percent of traffic, whether it is voice or data and whether it originates from a feature phone, smart phone, or a laptop. This is usually not possible in the case of Wi-Fi. Femtocells do not increase the power consumption on the terminal side, whereas Wi-Fi enabled devices may experience increased battery drainage because of the power required to operate two radio interfaces. When it comes to data rates,

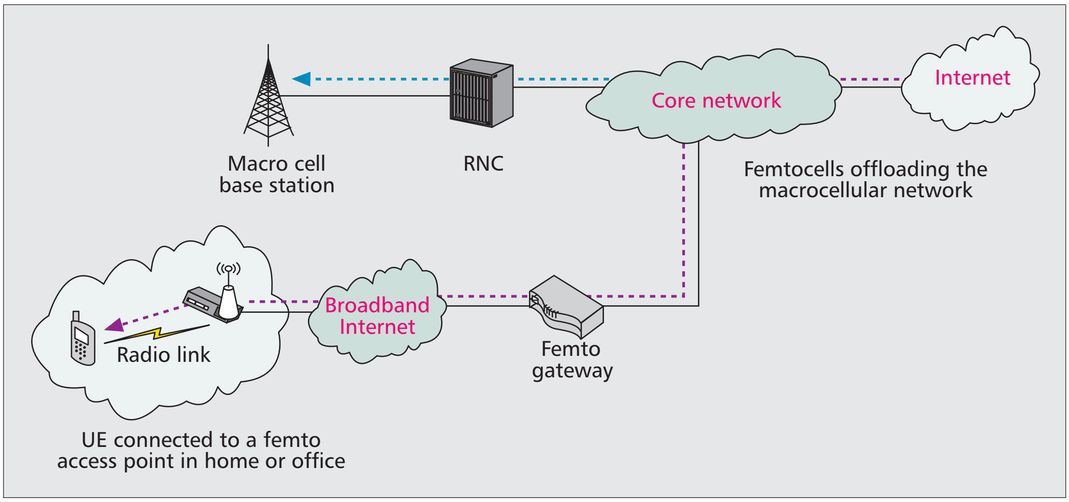

Figure 2. *Mobile data offloading via femtocells.*

IP flow mobility provides operators with a better traffic management solution by selectively offloading heavy users and thus alleviating congestion on their networks; at the same time users enjoy high bandwidth connections and a better experience.

Wi-Fi is the only technology that can deliver rates as high as 600 Mb/s. Typically, users on cellular networks need a lot of patience to download heavy multimedia files. Last but not least, femtocells can provide guaranteed QoS using licensed bands, whereas Wi-Fi cannot.

Mobile Data Offloading via WiMAX

WiMAX is a communication technology based on IEEE 802.16 standards for wireless broadband access over large geographical regions. From the data offloading perspective, WiMAX plays an indirect role by providing the backhaul for large-scale Wi-Fi networks. An alternative solution is Wi-Fi mesh technology, which has been used for municipal Wi-Fi networks. However, point-to-multipoint links using WiMAX for backhaul and Wi-Fi for access is a preferred solution as it does not introduce latency, reliability, and performance issues associated with the Wi-Fi mesh technology due to its non-direct multihop nature.

The authors in [8] describe a similar 3W data offloading strategy for offloading and efficiently handling the mobile data traffic. It comprises WCDMA, Wi-Fi, and WIBRO (the Korean name for WiMAX) networks. Users can access the Internet with WCDMA packet service or Wi-Fi. The Wi-Fi network has two backhaul networks: a conventional wired network and a WIBRO network.

Mobile Data Offloading via Opportunistic Communication

A recent approach to offloading mobile data traffic using opportunistic communications has been proposed in [9]. Most of the information delivered over mobile networks comes from content service providers and may include multimedia newspapers, small computer games, weather reports, and so on. The service providers can benefit from the delay-tolerant nature of such applications and may deliver the information to only a small group of users (target users). The target users can further disseminate the information to subscribed users when their mobile phones are in proximity and can communicate opportunistically using Wi-Fi or Bluetooth technology. Apart from these two technologies, device-to-device (D2D) communication using cellular resources can also be employed for such opportunistic communication.

Such an offloading approach is attractive as there is little or no monetary cost associated with it. However, it is challenging due to a number of factors such as the heterogeneity of data traffic from service providers (varying in delay and content size), varied user demands and preferences for data traffic, incentives for target users, and battery and storage constraints of mobile devices.

Mobile Data Offloading via IP Flow Mobility

IP flow mobility [10] is a recent technology that is currently being standardized in the Internet Engineering Task Force (IETF). This technology allows an operator to shift a single IP flow to a different radio access without disrupting any ongoing communication. Consider a user connected to a cellular base station having multiple simultaneous flows (e.g., a voice call and a file download) moving into the coverage of a Wi-Fi access point (hotspot). The terminal or network, upon detection of the Wi-Fi access, decides to shift the file download on the Wi-Fi network. Once the user leaves the Wi-Fi coverage, the file download is seamlessly shifted back to the cellular network.

IP flow mobility provides operators with a better traffic management solution by selectively offloading heavy users and thus alleviating congestion on their networks; at the same time, users enjoy high bandwidth connections and a better experience.

Core Network Offloading

In the core network offloading approach, a gateway is placed in the data path between the RNC and the serving GPRS support node (SGSN) to offload the traffic destined for the Internet. The gateway detects, by using different identifiers such as access point name (APN), if the incoming session request is for Internet bound services

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or operator bound services. In the former case, the gateway alters the traffic path, bypassing the packet switched (PS) core network and forwarding it directly to the nearest Internet peering point.

Media Optimization Solutions

Media optimization solutions, although not directly related to mobile data offloading, attempt to relieve network congestion by reducing the data traffic volume through a variety of techniques, and consequently improving user experience and network resource usage among different users and traffic types to ensure an overall optimal response to the user. Such solutions are normally implemented by placing a media optimization server between the PS core network and the Internet. Some of the most commonly used media optimization solutions [11] are described as follows.

Smart Video Caching — A popular video on the Internet can go viral in a short period of time. This increases the load on the mobile network infrastructure. One way of dealing with viral videos is to cache them closer to the user, instead of repeatedly retrieving from the server. To implement a more effective solution, the media optimization server should pre-fetch the set of most popular videos, encode and store them according to device type, and thus deliver the optimized videos from cache whenever they are requested.

Dynamic Bandwidth Shaping — The media optimization server dynamically adjusts the bit rate of encoded video according to the bandwidth available to the users. This enhances the end user experience by avoiding the screen freeze that happens when the incoming video bit rate is higher than available network bandwidth.

Web Optimization — Web optimization solutions provide faster browsing and more immediate access to the content by increasing data transfer rate over mobile networks, through different techniques such as analyzing traffic and storing the optimized version of the most requested sites in the cache for quicker access, improving the load time for web pages by pipelining of HTTP requests, removing redundant white spaces and comments from HTML documents, and so on.

Business and Commercial Perspectives

Monetization Opportunities

Data offloading in general, and especially through Wi-Fi and femtocells, provides business prospects to everyone in the value chain including device manufacturers, service providers, and hotspot operators. The most important aspect is cost savings as offloading has direct impact on different components of operating expenditures (OPEX). First, through offloading the operator can keep the existing backhaul (leased lines, fiber, microwave, etc.) with fewer or no upgrades as the congestion on the radio access network is relieved. Second, fewer hardware and software upgrades are needed in the radio access network. Third, the number of active sites per area can be reduced, which gives significant energy savings. Besides cost savings, data offloading can provide incremental revenue opportunities through different value added services (VAS) and upselling of existing mobile data bundles as either flat fee, roaming charges, or even a free feature that can be charged through usage. It also creates an effect of customer acquisition and retention through richer mobile experience, which in turn reduces the churn-out of subscribers.

Vendor Strategies

In order to overcome the problem of data overload on cellular networks, vendors, solution providers, and equipment manufacturers are adopting different strategies. Depending on the solutions provided, these vendors can be broadly classified into following categories.

The first group of vendors are those who are providing only Wi-Fi-based solutions, mainly focusing on providing outdoor and metro Wi-Fi base stations. Compared with indoor Wi-Fi, outdoor Wi-Fi presents a number of challenges in order to effectively offload traffic. Besides the requirements of improved coverage and increased capacity, superior indoor penetration and enhanced interference immunity (against both Wi-Fi and non Wi-Fi interference) are also required. Thus, a blend of different technologies, such as beamforming, dynamic channel selection, and space-division multiple access (SDMA) is essential to create an effective Wi-Fi offloading solution. Along with providing outdoor Wi-Fi hotspots, another option is to effectively complement 3G macrocell coverage with Wi-Fi picocells in areas of high user density as they provide many times the capacity of macrocells. *Wavion*, *Ruckus Wireless*, and *BelAir Networks* are among the notable vendors providing Wi-Fi-based solutions.

The second group of vendors are those who are providing cellular-based small cell solutions in order to meet the growing capacity requirements of operators. The emphasis is mainly on femtocell solutions with major investments from vendors like *Ubiquisys*, *Airvana*, and *IP.Access*. An interesting solution developed by Alcatel-Lucent is of metro cells, which are based on femtocells technology but with enhanced capacity and coverage. Available in both indoor and outdoor versions, the first generation of metro cells can serve 16 to 32 users and provide a coverage range from less than 100 m in dense urban locations to several hundred meters in rural environments.

The third group of vendors are those who are providing gateway-based solutions that are independent of access network and support multiple data offloading solutions on a single platform. One such solution is developed by *IntelliNet Technologies* in the form of a converged data offloading gateway that can support both Wi-Fi and femtocell offloading solutions. As a Wi-Fi offload gateway, it implements the Third Generation Partnership Project (3GPP) I-WLAN standard; as a femtocells gateway, this platform conforms to the 3GPP standards for interfacing the customer premises equipment and communicates with the core network elements using GSM/UMTS specifications. A similar solution is also provided by *Bridgewater Systems*.

It should be noted that the above mentioned gateway-based offloading solutions should not be confused with core network offloading solutions as described earlier. *Stoke* and *Nokia Siemens Networks* are among notable vendors providing core network offloading solution, the former introducing a data offload gateway (SMDO) and the latter introducing a software upgrade in the packet core network.

Another group is constituted of vendors who are focusing on media optimization solutions, which are increasingly gaining popularity. The most notable vendors providing such solutions are *Openwave* and *Bytemobile*.

Last but not least, some vendors are focusing on developing applications for efficiently using dual mode handsets. For example, an innovative solution has been developed by *Kineto Wireless*. At the heart of this solution lies a smart Wi-Fi application that allows operators to take full advantage of the inherent benefits of Wi-Fi technology. It provides smart service routing, sending web-based applications directly to the Internet, while routing all mobile services (voice, SMS, mobile TV, etc.) through a secure connection to the mobile core network over the Wi-Fi interface. The cellular radio is put into hibernation state while the Wi-Fi connection is active to reduce the power consumption of the mobile terminal. The application, based on 3GPP UMA/GAN standard, is designed to be preloaded into smartphones.

Operator Strategies

In the literature, limited information exists regarding offloading strategies adopted by operators, which makes it challenging to present a complete overview. However, an effort has been made to include as much information as possible to give an impression of what sort of strategies are being and will be adopted by mobile operators in the future.

An increasing number of mobile operators are considering Wi-Fi offloading to relieve network congestion. Wi-Fi access is free in many public locations, and most home and office locations with smartphone users have Wi-Fi. One option is to nudge the subscribers toward Wi-Fi, which is not difficult as the majority of users have already switched to Wi-Fi for better experience. Although such an offloading approach is easy to deal with, it is not efficient. A more effective approach to Wi-Fi offloading is the extension of an operator's access network to include hotspots directly managed by the operator (owned by the operator itself or leased from a hotspot operator). Such approaches are increasingly gaining popularity. For example, *AT&T* has deployed a large number of hotspots in New York City. *China Mobile* planned to increase the number of Wi-Fi hotspots to 1 million throughout China by the end of 2012. Similarly, *KT Telecom* in South Korea has 62,000 hotspots that are actively used for offloading traffic. The operator plans to double the number of hotspots by the end of 2012. It should be noted that Wi-Fi hotspots are not designed to capture network-wide traffic but to reduce congestion where the cellular infrastructure does not have enough capacity. Operators can encourage subscribers to use Wi-Fi hotspots by providing different attractive data packages. For example, *Vodafone* UK has introduced a data package that includes a monthly allowance of 1 Gbyte of data at any of BT Openzone Premium hotpots.

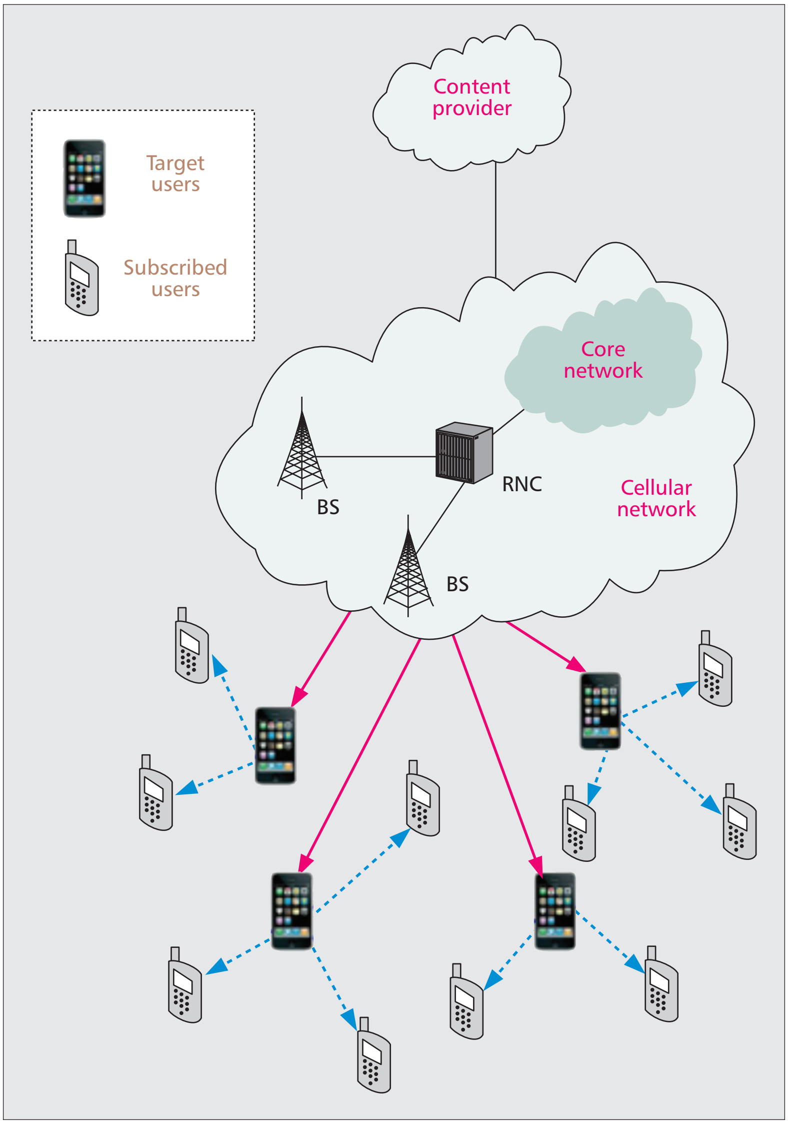

Figure 3. *Mobile data offloading via opportunistic communication.*

KDDI Corporation, a principal telecommunication provider in Japan, has launched the world's first and largest "instant-on" Wi-Fi access and mobile data offload service. Subscribers of KDDI's flat rate packet plans can now use the new KDDI "au Wi-Fi SPOT" service free of charge with their au Android smartphones in over 10,000 locations initially, scaling to 100,000 locations by March 2012. With no tedious manual configuration of the phone, KDDI subscribers can automatically access and be authenticated to KDDI au Wi-Fi hotspots using credentials embedded within each phone over highly secure and encrypted connections.

Orange (United Kingdom) and *T-Mobile*

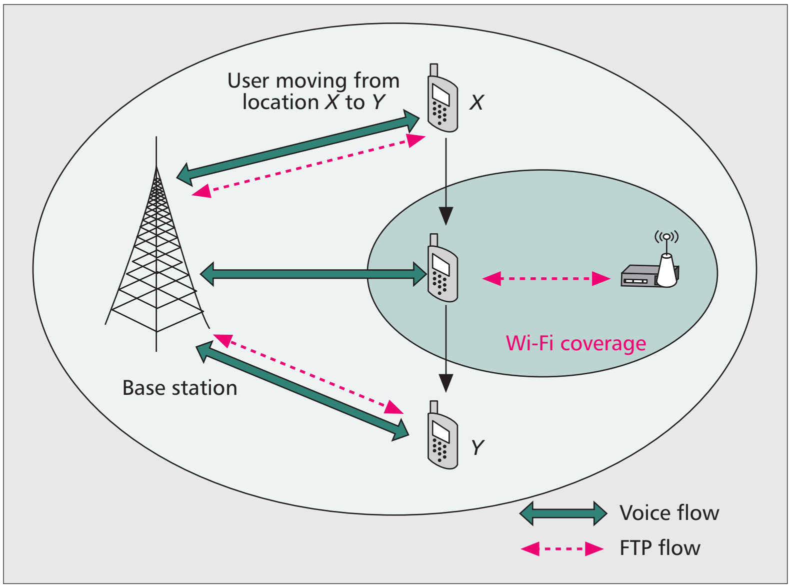

Figure 4. *Mobile data offloading via IP flow mobility*

(United States) have deployed an Android Wi-Fi calling application from *Kineto Wireless* that automatically activates to route calls and SMS services through the Wi-Fi network when in range of Wi-Fi. Approximately 1.25 million T-Mobile handsets are already using this application, and it is expected to be preloaded in more than 30 Android phone models by 2012.

Besides Wi-Fi, femtocells are also gaining popularity as a potential offloading solution. According to a market research by Femto Forum, as of December 2010 18 operators had launched commercial femtocell services with a total of 30 committed to deployment. *Verizon Wireless* and *AT&T Wireless* have the most significant deployments in the United States. In Japan, *SoftBank Mobile* has launched its residential third generation (3G) femtocell service. Similarly, in Singapore *Starhub* has rolled out nationwide commercial 3G femtocell services.

Evaluating the Effect of Offloading

An important question in the context of mobile data offloading is how to evaluate its effect. This question can be answered from two different perspectives: a network (or operator) perspective and a user perspective, since data offloading is beneficial to both.

From the network perspective, users are offloaded from cellular networks to avoid congestion for optimum performance of both voice and data services. The main effect would be the reduction in traffic which can be evaluated by different key performance indicators (KPIs) depicting congestion or blocking for packet switched services and/or comparing the traffic load during a busy hour before and after offloading. It can also be measured by using metrics such as *offloading efficiency* defined in [12] for the case of Wi-Fi, but can be generalized as the ratio of total bytes offloaded (transferred through Wi-Fi, femtocells, etc.) to the total bytes generated on the mobile network. The authors in [12] provide a quantitative study of Wi-Fi offloading performance based on an iPhone application that tracks Wi-Fi connectivity. By analyzing the temporal coverage (time spent in Wi-Fi coverage), interconnection times (duration between returning to Wi-Fi coverage after a user leaves it), and artificially assigned deadlines (in terms of delay) to different types of traffic (video, data, peer-to-peer [P2P], and audio), it has been shown that "on-the-spot" offloading achieves up to 60 percent efficiency. Short (5–10 min), medium (0.5–2 h), and long (~6 h) delayed offloading achieves up to 71, 76, and 92 percent efficiency, respectively.

From the users' perspective, offloading should provide a better or at least consistent experience. The effect can be evaluated in terms of different KPIs that depict the quality of experience (QoE) of users. For example, for VoIP, the important KPIs are packet delay and jitter. For web browsing, KPIs include average download time (total time to download a page measured in seconds from the start of the first HTML request to the last request), download time variation (variability or dispersion of download time), and average goodput (application layer throughput).

Challenges in Mobile Data Offloading

In this section, we discuss some of the key challenges that arise while implementing a data offloading solution, especially offloading through Wi-Fi. Such challenges must be addressed properly.

The foremost challenge associated with data offloading is user experience. Service providers must ensure consistent user experience and service continuity, independent of the underlying offloading solution. This includes providing a transparent login across different networks to avoid any disruptions in service continuity. A subscriber's authentication data is present in the home location registry (HLR) in 3GPP networks, which cannot be accessed easily through non-3GPP networks such as Wi-Fi. An integrated offloading approach and SIM-based authentication procedure, by including an authentication, authorization, and accounting (AAA) server in the core network, will ensure transparent sign-on and seamless in-session handover between 3GPP and Wi-Fi networks. The latter requires network readiness prior to device readiness. Furthermore, as the Wi-Fi network cannot provide QoS guarantees, a QoS-driven vertical handover from Wi-Fi to 3GPP networks is essential in order to ensure the QoS for users, especially when the Wi-Fi network is experiencing congestion.

From the users' perspective, it is not suggested to keep both Wi-Fi and cellular interfaces simultaneously turned on due to significant battery drain, especially when the Wi-Fi interface is in idle mode. Moreover, the network cannot force a device to switch on the Wi-Fi interface. This creates challenges for those operators who want to implement a Wi-Fi offloading solution.

It is important to mention here that currently no outdoor Wi-Fi planning tools are available in the market. This creates challenges in optimal deployment of outdoor Wi-Fi access points. Also, roaming agreements between different Wi-

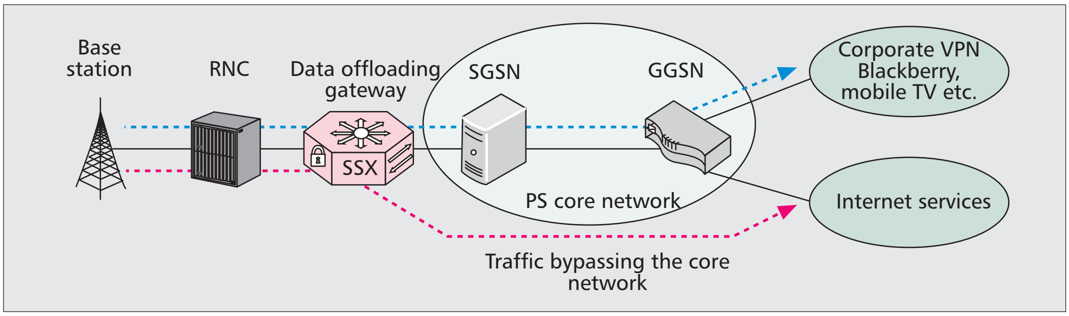

Figure 5. *Core network offloading.*

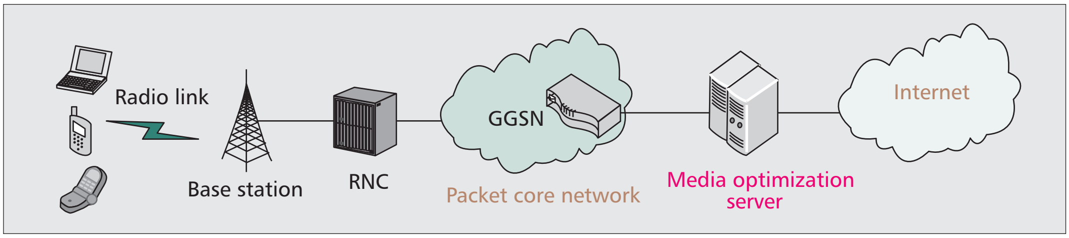

Figure 6. *Media optimization server in a mobile network.*

It is expected that a wide range of strategies will be adopted by service providers, possibly deploying a mix of different solutions to effectively handle the tsunami of data traffic on their networks.

Fi networks is an important issue that needs to be addressed if Wi-Fi offloading solutions are deployed on a large scale.

A major challenge in femtocells is interference management. Femtocell deployments create a two-tier network, as a result of which interference can be either co-tier or cross-tier. In case of co-tier interference, a femtocell causes interference to a neighboring femtocell, which may be severe in the case of dense deployments. The cross-tier interference results when a femtocell causes interference to the downlink of a nearby macrocell user. Similarly, a macrocell user can cause interference on the uplink of a nearby femtocell. The interference problem becomes severe if the femtocell is operating in closed access mode.

Perhaps the most important challenge in mobile data offloading through any offloading solution is to distinguish between different user segments and network conditions [13]. Application, device, and subscriber awareness are required for making real-time decisions regarding selective offloading and thus effectively managing the overall process.

Conclusion

This article surveys the state of the art in mobile data offloading. It is expected that mobile data offloading will become a key industry segment in the near future due to the unprecedented pace at which data traffic is rising on mobile networks. Data offloading not only provides smart traffic management solutions to service providers for alleviating congestion from their networks, but also provides them with new business opportunities. An ideal offloading solution should keep service disruptions for users to a minimum, while at the same time optimizing the performance of cellular networks. It is expected that a wide range of strategies will be adopted by service providers, possibly deploying a mix of different solutions to effectively handle the tsunami of data traffic on their networks.

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