

Vehicular WiFi Offloading: Challenges and Solutions

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Abstract

WiFi offloading is envisioned as a promising solution to the mobile data explosion problem in cellular networks. WiFi offloading for moving vehicles, however, poses unique characteristics and challenges, due to high mobility, fluctuating mobile channels, etc. In this paper, we focus on the problem of WiFi offloading in vehicular communication environments. Specifically, we discuss the challenges and identify the research issues related to drive-thru Internet access and effectiveness of vehicular WiFi offloading. Moreover, we review the state-of-the-art offloading solutions, in which advanced vehicular communications can be employed. We also shed some lights on the path for future research on this topic.

Keywords: Mobile data, WiFi offloading, Drive-thru Internet, Vehicular communication

1. Introduction

In recent years, the demand for high-speed mobile Internet services has increased dramatically. People expect to connect to the Internet anytime, anywhere, even in their own cars. With advanced Internet connectivity on the move, drivers or passengers are allowed to personalize their in-vehicle experiences, making travels safer and more comfortable. A recent survey reveals that Internet access is predicted to become a standard feature of future motor vehicles [1], and excitingly, Internet-integrated vehicles have hit the road lately. Extending Internet connectivity to the in-vehicle environment, therefore, might be the next frontier for the mobile revolution. Not surprisingly, cellular-based access technologies, such as 3G and Long Term Evolution (LTE), play a vital role in providing reliable and ubiquitous Internet access to vehicles, as the cellular infrastructure is well planned and widely available. However, the cellular network nowadays is straining to meet the current mobile data demand, and on the other hand, the explosive growth of mobile data traffic is no end in sight, resulting in an increasingly severe overload problem. It is reported that the connected mobile devices will become more than the world's population in 2013, and the global mobile data will increase by 13 times in 2017, which will exceed one hundred exabytes [2]. Therefore, simply using cellular infrastructure for vehicle Internet access may worsen the overload problem, and degrade the service performance of both non-vehicle and vehicle users¹.

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¹We will interchangeably use the terms "vehicle" and "vehicle user" in this article.

Table 1: The advantages of WiFi access.

Advantage	Description
Widely deployed Infrastructure	WiFi hotspots are widely deployed in many urban areas. It is shown that WiFi access is available 53% of the time while walking around popular sites in some large cities [6].
Low cost	WiFi access is often free of charge or inexpensive. For example, KT Corporation in South Korea offers WiFi services with \$ 10 a month for unlimited data usage [7].
High availability of user devices	Most of current mobile devices, such as smart phones, tablets, and laptops are equipped with WiFi interfaces.
Efficient data transmission	Currently WiFi technologies (IEEE 802.11 b/g) can provide data rates of up to 54 Mbps. There are new technologies under development or test, e.g., IEEE 802.11 ac/ad, which can provide data transfer at several Gbps.

As a popular wireless broadband access technology, WiFi, operating on the unlicensed spectrum, offers the “last-hundred-meter” backhaul connection to private or public Internet users. The advantages of WiFi access are summarized in Table 1. Recent research has demonstrated the feasibility of WiFi for outdoor Internet access at vehicular speeds [3]. The built-in WiFi radio or WiFi-enabled mobile devices on board can access the Internet when vehicles are moving in the coverage of WiFi hotspots, which is often referred to as the drive-thru Internet access [4]. This kind of access solution is workable to offer a cost-effective data pipe for vehicle users [5], and with the increasing deployment of the urban-scale WiFi network (e.g., Google WiFi in the city of Mountain View), there would be a rapid growth in vehicular Internet connectivity.

WiFi is recognized as one of the primary offloading technologies [8]. By delivering data originally targeted for cellular networks by WiFi, which is referred to as WiFi offloading, the congestion of cellular networks can be alleviated. WiFi offloading has been extensively studied for stationary or slow moving users² [9, 8, 10, 11]. It is shown that around 65% of the cellular traffic can be offloaded by merely using the most straightforward way of simply switching the IP connection from the cellular network to WiFi when the WiFi connectivity is available (*on-the-spot offloading*). In addition, significant amount (above 80%) of data can be offloaded by delaying the data application [9] (*delayed offloading*). For moving vehicle users, one natural question needs to be answered: how much data can be offloaded? WiFi offloading in vehicular communication environments (or *vehicular WiFi offloading*) refers to delivering the data traffic generated by the vehicles or vehicle users via opportunistic WiFi networks, i.e., the drive-thru Internet access. However, due to high dynamics of vehicular communication environments, e.g., the highly dynamic network topology due to high vehicle mobility, fast fluctuating wireless channels, etc., the effectiveness of WiFi offloading for vehicle users requires careful studies. The overview of vehicular WiFi offloading is

²We refer to these users as non-vehicle users.

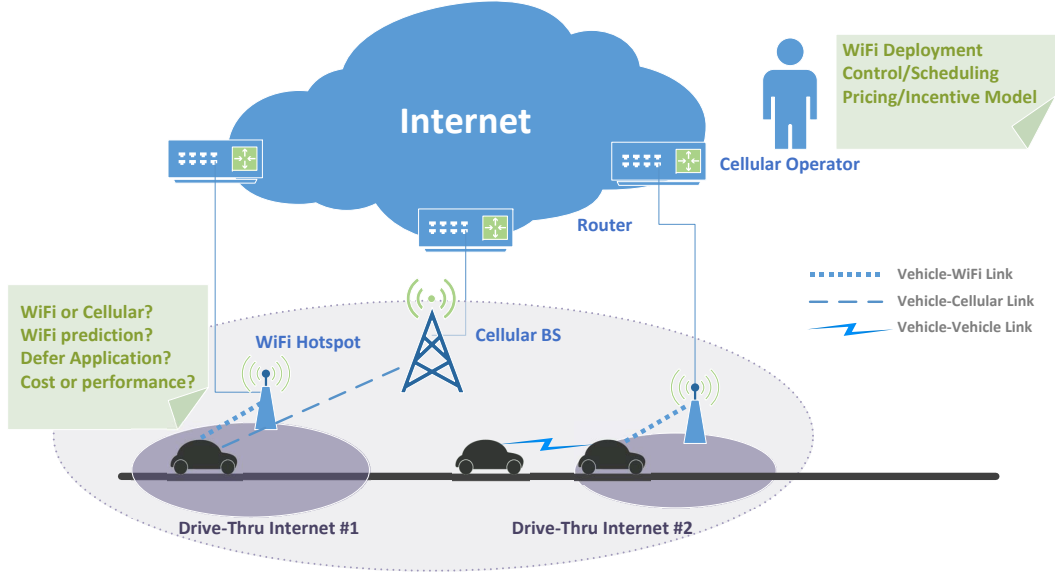


Figure 1: WiFi offloading in vehicular communication environments.

shown in Fig. 1. We elaborate the unique features and challenges of vehicular WiFi offloading from the following three aspects.

Drive-thru access: Mobility plays both a challenge and a distinguishing role in vehicular WiFi offloading. For each drive-thru, vehicle users can only obtain a relatively small data volume due to the short connection duration with the WiFi hotspot; while vehicle users may experience multiple drive-thrus in a short time period due to high mobility. This short and intermittent connectivity will have great impacts on offloading schemes, such as a WiFi offloading performance prediction and mechanisms to delay some applications, which we will discuss later. Fluctuating channels may lead to high and bursty losses, resulting in disruptions to connectivity. Thus, proper handoff schemes and transport protocols are needed to reduce the disruptions and adapt to the wireless losses.

Cellular operators: To ease congestion of cellular networks, cellular operators may adopt certain commercial strategies to encourage data offloading, such as by stimulating vehicle users to transmit their data through WiFi networks. Thus, incentive models, such as variable service prices or reward mechanisms, should be investigated. Moreover, cellular operators may deploy their own commercial or non-commercial WiFi networks to offload mobile data, e.g., the WiFi hotspots operated by AT&T [12]. How to determine the WiFi deployment strategy to attain optimal offloading performance is another research challenge.

Vehicle users: The WiFi offloading potential can be predicted, as the mobility pattern of vehicles can be predicted from the historic drive information, driver preferences, etc. Based on this prediction, with the knowledge of usage cost of cellular and WiFi services, it is possible for vehicle users to determine when to use WiFi or cellular networks upon a service request emerging, and minimize the usage cost. It is a challenging task to understand the cost-effectiveness of WiFi offloading from the vehicle users' perspective.

In this paper, we focus on the problem of WiFi offloading in vehicular communication environments. We discuss the challenges and identify the research issues related to this problem. Moreover, we review the state-of-the-art offloading solutions, providing rapid access to research results scattered over many papers. We also try to shed some lights on the path for future research on this topic. The remainder of the paper is organized as follows. Section 2 surveys the existing research works on mobile data WiFi offloading for non-vehicle users. Section 3 discusses the challenges and existing/potential solutions in drive-thru Internet access and WiFi offloading in vehicular communication environments. Section 4 discusses further research issues and provides concluding remarks.

2. Mobile Data Offloading through WiFi Networks

Mobile data offloading through WiFi access networks has been extensively studied. Due to the low-cost and high availability of WiFi access, offloading mobile data through WiFi is quite straightforward. However, the limited coverage of WiFi access points (APs), user mobility, and the dynamics of communication environments pose difficulties for analyzing and optimizing the offloading performance. In this section, we review the literature in WiFi offloading for non-vehicle users and discuss the issues, challenges, and solutions.

2.1. Offloading framework

Cellular and WiFi radio access technologies are naturally involved in the WiFi offloading framework. A certain degree of coupling, i.e., interworking, between the cellular and the WiFi networks, may facilitate to offload cellular data, e.g., 3GPP based Enhanced Generic Access Network (EGAN) [13] architecture that enables rerouting of cellular network signaling via WiFi networks. However, such interworking architectures rely on the evolution of mobile access networks with redesigned protocols. Based on off-the-shelf radio access technologies, there have been several proposed WiFi offloading frameworks in the literature [11, 7, 14, 15, 16].

In [11], a non-coupling architecture, called Metropolitan Advanced Delivery Network (MADNet), is proposed for offloading bulk data and video streaming through metropolitan WiFi networks. MADNet, designed as a middleware between the application and physical layer, uses cellular networks to do signaling such as the transfer of users' service requests and status information, and uses both cellular and WiFi networks to transmit data. For downstream, the bulk content downloading begins through cellular network, and the content is thereafter delivered to certain WiFi APs based on the mobility prediction to mobile users, which is called prefetching. Mobile users can pick up the content through WiFi when they move into the coverage of those WiFi APs. For upstream, two sub-cases are considered: i) for mobile users with sufficient mobility, data uploading starts until the WiFi access is reliable, e.g., at office or home; and ii) for users who are stationary or with limited mobility, the data is relayed to WiFi APs through passing by mobile devices (e.g., pedestrians or vehicles) via multiple hops.

An architecture, named 3W, is introduced in [7], where 3W represents WCDMA, WIBRO (Korean name for the IEEE 802.16e mobile WiMAX), and WiFi. 3W provides a heterogeneous coverage over South Korea: 3G WCDMA network provides nationwide coverage, while WIBRO

covers 84 cities, and WiFi covers indoor and street areas. The deployment, pricing, and offloading performance of 3W are studied. To motivate data offloading, more attractive prices of using WIBRO and WiFi are applied, whereby \$25 for 50 Gbytes per month to use WIBRO, and \$10 per month for unlimited WiFi data usage. Based on the traffic status in 3W networks, the offloading effectiveness of deploying such heterogenous wireless access networks is validated .

2.2. Offloading performance

The most important issue in WiFi offloading is to know how much data WiFi can offload. The performance of WiFi offloading is closely related to the WiFi availability, user mobility, delay tolerance characteristics of user data applications, etc. In [9], a comprehensive experiment is conducted to demonstrate the performance of WiFi offloading. By collecting WiFi connectivity statistics of 97 iphone users, the WiFi availability is first examined: i) the temporal WiFi coverage (the time portion in which a user stays within the WiFi coverage area) is 70% for all day and 63% for the active hours (9:00~24:00); ii) the spatial WiFi coverage (the ratio of the area which is covered by WiFi over the total area) is about 8.3% for 50 meters WiFi coverage radius and 20.6% for 100 meters WiFi coverage radius; and iii) the connection time to a WiFi AP has an average value of 2 hours (all day) and 52 minutes (active hours), while the average inter-connection time is 40 minutes (all day) and 25 minutes (active hours), and the distributions of both connection and inter-connection times are heavy-tailed. It is reported that the average WiFi data rate is 1.97 Mbps for all day, 1.26 Mbps for active hours, and 2.76 Mbps for night. Based on the WiFi availability information, the effectiveness of WiFi offloading is then studied through simulations. It is shown that on-the-spot offloading can offload 65% of the cellular traffic. If data applications (or mobile users) are able to tolerate certain delays, the offloading becomes more effective, e.g., 82.1% of the data traffic can be offloaded with a delay of one hour. WiFi offloading also has economic benefits, as a part of the cellular traffic is carried by low-cost WiFi networks. The economic performance is investigated in [17]. It is shown that the delayed offloading can yield great economic benefits compared to the on-the-spot offloading, in which 21% to 152% in the provider's revenue and 73% to 319% in the user's surplus (defined as the summation of users' net-utility) can be increased.

2.3. Energy efficient offloading

Energy consumption is an important issue in mobile communication, as most mobile devices are battery-powered with limited energy. In [9], it is shown that a considerable amount of energy can be saved by WiFi offloading. This is because WiFi can provide a higher data rate than 3G networks, which yields a shorter data transmission time and therefore a lower energy consumption. However, as LTE can offer a higher or comparable data rate than WiFi, the energy efficient offloading in the LTE-WiFi scenario attracts more research efforts.

Offloading schemes aiming to improve the mobile devices' energy efficiency can be found in [18, 19, 20]. An effort is made in [18] to reduce the energy consumption in the application of uploading delay-tolerant videos captured by smart phones. The Stable and Adaptive Link Selection Algorithm is proposed to determine when to defer a video transmission to minimize the total energy consumption while guarantee a finite average transfer delay. Through real trace driven simulation, the proposed algorithm can save 10-40% of the total energy capacity of the smart phone battery. Motivated by the fact that WiFi radio wastes a lot of energy in scanning transmission

opportunities and remaining idle, a prediction-based offloading scheme is proposed in [19] to save energy of user devices. The operator collects its subscribers' user mobility profile (UMP) and deploys WiFi APs in the places which are mostly visited. The location information of APs and the UMP is sent to the users so that they can predict WiFi availability using such information and turn on the WiFi radio only when the WiFi access is predicted to be available. In such a way, the energy can be saved. To enhance MADNet, an energy-aware offloading algorithm is proposed in [20] in order to avoid offloading traffic to low-throughput WiFi networks in order to improve energy efficiency. Through prediction, the traffic is offloaded to a WiFi AP if the energy consumed in the WiFi transmission minus the energy consumed in transmitting the same data volume using the cellular network is larger than a predefined threshold.

2.4. WiFi deployment

WiFi availability is closely related to the density of deployed WiFi APs and the deployment strategy, which in turn have a considerable impact on WiFi offloading performance. It is shown that the average user throughput can be improved by 300% by using on-the-spot offloading strategy when the WiFi AP density is only 10 per square kilometer, and the throughput gain proportionally increases with the AP density [21]. In other words, if more WiFi APs are available in a certain geographic area, better offloading performance can be achieved. However, a large-scale dense WiFi deployment may incur high capital expenditures and operational expenditures. Hence, the tradeoff between the cost and offloading performance should be examined. Moreover, the deployment strategy also plays an important role. A good strategy candidate should consider many factors, such as population density, user mobility, mobile data usage patterns, and communication environments.

The impact of WiFi deployment on the offloading performance is investigated in [9]. The methodology is to gradually eliminate the APs with least user connection times, in order to evaluate the performance at different AP densities. It is shown that even when 80% of APs are eliminated, the overall offloading efficiency has a only 10% to 20% drop, which indicates that a few of most "active" APs contribute to the majority of the offloading traffic. Therefore, a well-planned WiFi deployment can offer a good offloading performance at a low cost. The WiFi deployment strategies considering the popularity of locations are proposed and evaluated in [11] and [19]. The main idea is to deploy WiFi APs at locations with high popularity, i.e., visited by users with high frequency. Results from [11] show that deploying several hundred of APs at the popular sites of the investigated 313.83 km² area can efficiently offload half of the cellular traffic. It is also pointed out in [22] that the mostly visited places are not definitely the places where the heaviest data traffic is generated. Therefore, a large-scale WiFi deployment strategy is proposed in [22] considering the frequency of user data requests.

In [21], three WiFi deployment strategies, namely, Traffic-centric, Outage-centric, and Uniform Random, for large-scale dense-urban areas are proposed and compared. Specifically, Traffic-centric and Outage-centric are to place APs at the locations with the highest traffic density and the severest outage (defined as the user throughput is less than 512 kbps), respectively; whereas Uniform Random is to deploy APs uniformly randomly without considering any deployment metrics. The former two strategies can provide a basis for operator controlled WiFi deployment, while the

Table 2: Drive-thru Internet performance measurements - configuration.

	Scenario	WiFi	AP deployment	Antenna
[4]	Highway	802.11b	Planned	External/VU
[29]	Highway	802.11g	Planned	8 dBi/AP; 5dBi/VU
[30]	Traffic free road	802.11b	Planned	N/A
[31]	Highway	802.11a/b/g	Planned	7 dBi/AP
[3]	Urban	802.11b	Unplanned	5.5 dBi/VU
[32]	Urban	802.11b/g	Unplanned	3 dBi/VU

VU: vehicle user

third one corresponds to home offloading scenarios. Simulation results show that with 10 APs deployed per square kilometer, the average throughput gains by 300% using Traffic-centric strategy, and the indoor outage reduces by 14% using Outage-centric strategy.

2.5. Other research issues

There are other related research issues in addition to the above discussions. In [23], an offloading scheme is proposed to schedule applications with different size and delay tolerance requirement in order to minimize cellular usage, which is adaptive to the varying coverage and bandwidth of the WiFi and cellular networks. The prediction of mobility and offloading performance is investigated in [19, 24, 25]. The security issues in WiFi offloading are studied in [26]. The incentive models of WiFi offloading can be found in [25, 27, 28].

3. WiFi Offloading in Vehicular Communication Environments

Vehicular WiFi offloading mostly relies on the drive-thru Internet access opportunities, provided by open or planed WiFi networks. Therefore, we first review the recent experimental and theoretical studies on drive-thru Internet. After that, we discuss the vehicular WiFi offloading, including the challenges, research issues, and existing and potential solutions.

3.1. Drive-thru Internet

Drive-thru Internet refers to the Internet connectivity provided by roadside WiFi APs for moving vehicles within the coverage area. The performance of such a drive-thru access network is different from that of a normal WiFi network which only serves non-vehicle users. The reasons are three-fold. Firstly, high vehicle mobility results in a very short connection time to the WiFi AP, e.g., only several tens of seconds, which greatly limits the volume of data transferred in one connection. Moreover, one has to consider the time spent in WiFi association, authentication, and IP configuration before data transfer which is not negligible. Secondly, communications in vehicular environments suffer from the high packet loss rate due to the channel fading and shadowing [32]. Thirdly, the WiFi protocol stack is not a specific design for high mobility environments. We will elaborate our discussion from the following aspects.

Table 3: Drive-thru Internet performance measurements - results.

	Connection establishment time	Connection time	Inter-connection time	Max rate	Data transfer in once drive-thru
[4]	Max 2.5 s	9 s @ 80	N/A	TCP: 4.5 Mbps UDP: 5 Mbps	TCP: 6 MB @ 80 5 MB @ 120 1.5 MB @ 180 UDP: 8.8 MB @ 80 7.8 MB @ 120 2.7 MB @ 180
[29]	N/A	N/A	N/A	15 Mbps	Max 110 MB
[30]	8 s	217 s @ 8 13.7 s @ 120	N/A	TCP: 5.5 Mbps UDP: 3.5 Mbps	92 MB @ 8 6.5 MB @ 120
[31]	Mean 13.1 s	58 s	N/A	TCP: 27 Mbps	Median 32 MB
[3]	366 ms	13 s	Mean 75 s	30 KBytes/s	Median 216 KB
[32]	8 s	N/A	Median 32 s Mean 126 s	86 Kbps;	Median 32 MB

@ α : at α km/h; N/A: not applicable.

3.1.1. Characteristics and performance

To characterize and evaluate the performance of the drive-thru Internet, several real-world measurements have been done based on diverse test bed experiments. The configurations and key results are summarized in Tables 2 and 3.

In [4] and [29], the drive-thru Internet is evaluated in a planned scenario where two APs are deployed closely along a highway, using IEEE 802.11b and 802.11g, respectively. The performances of User Datagram Protocol (UDP) and Transmission Control Protocol (TCP) at different speeds (80, 120, and 180 km/h) and scenarios (AP to vehicle, vehicle to AP) are evaluated. A very important characteristic is observed that the drive-thru Internet has a three-phase feature, i.e., entry, production, and exit phases. In the entry and exit phases, due to the weak signal, connection establishment delay, rate overestimation, etc, the performance is not as good as when in production phase. In [30], a similar test is conducted on a traffic free road which indicates an interference-free communication environment. It is shown that in such an environment, the performance of the drive-thru Internet suffers most from the backhaul network or application related issues rather than the wireless link problems. For example, with a 1 Mbps bandwidth limitation of backhaul network, the TCP bulk data transferred within a drive-thru reduces from 92 MB to 25 MB. In addition, a backhaul with 100 ms one-way delay greatly degrades the performance of web services due to the time penalty of HTTP requests and responses. The problems that may cause

the performance degradation of the drive-thru Internet are thoroughly discussed in [31].

In [3] and [32], large-scale experimental evaluations of the drive-thru Internet with multiple vehicles in urban scenarios have been conducted. Both of the data sets are collected from the city of Boston with in situ open WiFi APs. [3] focuses on the TCP upload performance, and shows that with fixed 1 Mbps MAC bit rate, the drive-thru Internet is able to provide an (median) upload throughput of 30 KBytes/s, and the median volume of uploading data in once drive-thru is 216 KB. The average connection and inter-connection time are 13 seconds and 75 seconds, respectively. This demonstrates that although vehicles have short connection time with WiFi APs, they can experience drive-thru access opportunities more frequently, compared with low-mobility scenarios (median connection and inter-connection time 7.4 minutes and 10.5 minutes, respectively [9]). The experiment in [32] shows a 86 kbps long-term average data transfer rate averaged over both connection and inter-connection periods. Moreover, two mechanisms to improve the performance are proposed, namely Quick WiFi and CTP, to reduce the connection establishment time and deal with the negative impact of packet loss on transportation layer protocols, respectively.

3.1.2. Network Protocol

To improve the performance of the drive-thru Internet, new protocols or modification in existing protocols should be developed. The efforts in the literature include: i) reducing connection establishment time [32]; ii) improving transport protocols to deal with the intermittent connectivity and wireless losses [32]; iii) enhancing MAC protocols for high mobility scenarios [33]; and iv) MAC rate selection schemes [32] and [31].

The AP connection time is typically only seconds to tens of seconds in drive-thru scenarios, and in fact not every second can be used for data transfer. It takes some time to conduct AP association, authentication, IP configuration, etc., before Internet connectivity is available. We call this time as connection establishment time. It is helpful if this time duration can be reduced as much as possible. In [32], a mechanism named Quick WiFi is proposed to reduce the connection establishment time and improve data transfer performance. The main idea of Quick WiFi is to incorporate all processes related to connection establishment into one process, to reduce the timeouts of related processes, and to exploit parallelism as much as possible. It is shown that the connection establishment time can be reduced to less than 400 ms. If the WiFi network is deployed and managed by one operator, a simple yet effective method is presented in [34], in which vehicles are allowed to retain their IP address among different associations, and thus the authentication and IP configuration are carried out only once.

To deal with the high and bursty non-congestion wireless losses in vehicular communication environments, a transport protocol called Cabernet transport protocol (CTP) is proposed in [32]. In CTP, a network-independent identifier is used by both the host and the vehicle user, allowing seamless migration among APs. Large send and receive buffers are also utilized to counter the outages (i.e., the vehicle is out of range of any WiFi AP). More importantly, CTP can distinguish wireless losses from congestion losses, by periodically sending probe packets. Through an experimental evaluation, CTP is demonstrated to achieve twice the throughput of TCP.

The IEEE 802.11 MAC protocols are designed for low-mobility scenarios, and thus require modifications and redesigns for the drive-thru Internet. [33] theoretically studies the performance of IEEE 802.11 distributed coordination function (DCF) of the large-scale drive-thru Internet base

Table 4: Modified MAC bit rate selection scheme in [31].

Parameter	Original [35]	New Value
Probe Packet	10%	40%
Sample Window	10 s	1 s
Decision Interval	Every 1000 ms	Every 100 ms

on a Markov chain model, and provides some guidelines to enhance the MAC throughput. The impact of vehicle mobility and network size (i.e., vehicle traffic density) on the MAC throughput is also discussed. The key observation is that the normal operations of DCF result in a *performance anomaly* phenomenon, i.e., the system performance is deteriorated by the users with the minimum transmission rate. Based on this observation and the analytical model, a contention window optimization is proposed, which is adaptive to variations of transmission rates, vehicle velocity, and network size. The MAC rate selection is discussed in [32] and [31]. In [32], a fixed 11 Mbps IEEE 802.11b bit rate is selected for the drive-thru upload scenario based on the following observations: i) the loss rates for IEEE 802.11b bit rates (1, 2, 5.5, 11 Mbps) are similar; and ii) the IEEE 802.11g bit rates, though may be higher (up to 54 Mbps), all suffer from high loss rate (about 80%). In [31], it is observed that the original bit rate selection algorithm is not responsive enough to the vehicular communication environments, and higher rates are rarely selected. By a simple modification shown in Table 4, 75% improvement of TCP goodput can be achieved. However, an optimal MAC bit rate selection scheme which is suitable for the drive-thru Internet is still missing, and will be a challenging research task for future work.

3.1.3. Handoff

Handoff is also an important issue in the drive-thru Internet. Current WiFi devices initiate a handoff only when disconnected, and connect to an AP with the strongest signal strength [36]. However, such a hard (maintain until broken) handoff mechanism does not fit the vehicular communication environments. This is because the quality of the drive-thru connectivity changes over time so that vehicles being connected may experience poor connectivity periods and miss the opportunity to handoff to an AP with a stronger signal strength. The hard handoff also incurs large handoff delays (18 seconds on average [37]). Therefore, applicable handoff mechanisms should be specifically designed for the drive-thru Internet.

Handoff mechanisms in vehicular multi-tier multi-hop mesh networks are proposed in [37]. In such a mesh network architecture, the data traffic is routed from/to the AP with the backhaul connection via one or multiple hops to APs without the backhaul connection. It is shown that APs in the network may achieve different long-term throughput performance due to factors such as backhaul capability and topology. Hence, a metric called *AP quality score* is used to evaluate APs' long-term performance. APs with higher AP quality scores are capable to deliver more data traffic to vehicles than others with lower scores. Jointly considering both the channel quality and the AP quality score, a handoff mechanism is proposed to select the best AP connection. In addition, a scheme to avoid frequent and unnecessary handoffs is also proposed. Experimental evaluation

Table 5: Handoff policies evaluated in [38].

Policy	Operation
RSSI	Associate to the BS with higher signal strength
BRR	Associate to the BS with highest average beacon reception ratio
Sticky	Remain connection until connectivity is unavailable for a predefined time period
History	Associate to the BS with best historical average performance
BestBS	Associate to the BS with best performance in next one second (NOT practical)
AllBSes	Use all nearby BSes simultaneously (NOT practical)

in an urban environment shows that the proposed handoff mechanisms gain 300% throughput compared with the hard handoff policy.

A handoff scheme called ViFi is proposed in [38] to deal with the frequent *disruptions* in vehicular WiFi access which may degrade the performance of interactive applications, such as voice over IP (VoIP). It is shown that even when a vehicle is in the WiFi coverage area, it may experience some unexpected “grey periods” during which the connection quality is so poor that bursty losses occur. Such grey periods lead to frequent connectivity disruptions. Handoff policies are evaluated, as listed in Table 5, which shows that AllBSes (AP is called BS in [38]), though impractical itself, outperforms other policies in disruptions reduction due to the use of multiple BSes simultaneously. Motivated by this observation, to minimize the number of such disruptions, ViFi utilizes the BS diversity. That is to use BSes in the vicinity of the vehicle to relay a packet with a certain probability if the acknowledgement of that packet is not overheard by the BSes. The rationale of such a relay scheme is as follows. First, wireless losses are often bursty, if a packet is lost, it is very likely that the retransmission packets will also be lost. Furthermore, losses are path dependent rather than receiver dependant. Although a vehicle may experience bursty losses with one BS, other BSes may be able to deliver the packets. Simulation results show that ViFi has a superior performance and benefits both TCP transfer and VoIP services.

Besides, a handoff mechanism is proposed in [36] based on the prediction to the vehicle mobility and WiFi connectivity. In [39], different handoff schemes between the WiFi and cellular networks, i.e., vertical handoffs, are proposed and compared. Current solutions have some limitations. For instance, in [37], the long-term performance of APs is assumed to be known by vehicle users, which is not realistic in most scenarios; in [38], inter-AP communication is used, which is not available for open APs. In addition, relaying packets by nearby APs may introduce interference and overhead. Future works may include handoff protocol designs with little or no priori knowledge about the AP performance and not relying on the inter-AP communication, which can adapt to different scenarios.

3.2. Vehicular WiFi offloading

The roadside WiFi network and vehicles with high mobility constitute a practical solution to offload cellular data traffic, namely, vehicular WiFi offloading. The research issues mainly focus

on the performance analysis and evaluation, i.e., to answer the key question of how much data can be offloaded, and strategies to improve the offloading performance, especially for non-interactive applications which can tolerate certain delays.

In WiFi offloading for non-vehicle users, offloading schemes often focus on the availability and performance of the next forthcoming AP, since the user is expected to meet one AP and has a relatively stable connection with that AP. This, however, does not apply to vehicular communication environments. Since vehicle users may meet multiple APs with different quality of connections in a short time period, offloading schemes should incorporate the prediction of WiFi availability to better exploit multiple data transfer opportunities. Characteristics of data application, e.g., delay requirement, would have considerable impacts on offloading schemes. For example, non-interactive applications, such as email attachments, bulk data transfer, and regular sensing data upload, are often throughput-sensitive, whereas the delay requirements are not very stringent generally. For such applications, a good offloading scheme is to use WiFi as much as possible while guaranteeing that the delay requirement is not violated. On the other hand, interactive applications, such as VoIP and video streaming, are typically delay-sensitive. It is more challenging to design offloading schemes for interactive applications, and first of all the effectiveness of offloading should be examined. Strategies to improve the offloading performance have to be considered. In mobile data offloading, incentive methods are often important to motivate user to offload their data traffic, or to achieve the goals such as traffic offloading at specific times or locations. In addition, cooperation among vehicle users and centralized scheduling mechanisms by operators are often necessary to enhance the offloading performance, or to reduce the usage costs of vehicle users or operators. WiFi deployment also plays an important role. A well-planned urban WiFi networks may yield a high WiFi availability, and therefore a good offloading performance. Generally, techniques improving the performance of drive-thru Internet, as we discussed in Section 3.1, can also be applied to enhance the offloading performance. We review the literature on vehicular WiFi offloading as follows.

There have been several vehicular offloading schemes proposed in the literature [40, 36, 41]. In [40], an offloading scheme called Wiffler is proposed to determine whether to defer applications for the WiFi connectivity instead of using cellular networks right away. Wiffler incorporates the prediction of the WiFi throughput on vehicles' route and considers delay requirements of different types of applications. An experiment is first conducted to study the availability and performance characteristics of WiFi and 3G networks, and shows that at more than half of the locations in the target city, at least 20% of 3G traffic can be offloaded through drive-thru WiFi networks, although the WiFi temporal availability is low (12% of the time) due to the vehicle mobility. Wiffler enables the delayed offloading and fast switching to 3G for delay-sensitive applications. The delay tolerance of data applications is determined according to vehicle users' preference or inferred from the application port information or binary names. The effective WiFi throughput, i.e., the data volume can be handled through WiFi APs before the delay period is expired, can be predicted by estimating the number of encountered APs. For the bursty AP encounters, the prediction is done assuming the inter-contact time durations in the future are the same as the history average. Using such a prediction, the traffic is offloaded to WiFi networks when $W > S \cdot c$, where W is the predicted effective WiFi throughput, S is the data size required to be transferred within the delay, and c is called *conservative quotient* to control the tradeoff between the offloading effectiveness

and the application completion time. For delay-sensitive applications, a fast switching to 3G is used when the WiFi link-layer fails to deliver a packet within a predefined time threshold.

Motivated by the observation that the mobility and connectivity of vehicles can be well predicted, a prefetching mechanism is proposed in [36], in which APs along the predicted vehicle route cache the contents and deliver them to vehicles when possible. This benefits the WiFi offloading since the vehicle-to-AP bandwidth is often higher than the backhaul bandwidth, and vehicle-to-AP transmissions can use specialized transport protocols which are less sensitive to wireless losses than TCP (e.g., CTP which is discussed in Section 3.1.2). The prefetching is based on the mobility prediction model, and to deal with the impact of prediction errors, the data is allowed to be redundantly prefetched by subsequent APs. However, as the WiFi backhaul capability has been greatly enhanced in recent years, the advantage of the prefetching solution might be reduced.

In [41], a vehicular WiFi offloading scheme is proposed from a transport layer perspective. A protocol called oSCTP is proposed to offload the 3G traffic via WiFi networks and maximize the user's benefit. The philosophy of oSCTP is to use WiFi and 3G interfaces simultaneously if necessary, and schedule packets transmitted in each interface every schedule interval. By modeling user utility and cost both as a function of the 3G and WiFi network usage, the user's benefit, i.e., the difference between the utility and the cost, is maximized through an optimization problem. The experimental evaluation shows a 63% to 81% offloaded traffic by using oSCTP, validating the effectiveness of the proposed offloading scheme.

It has been shown that merely using in situ WiFi APs cannot provide any performance guarantee of the drive-thru Internet. To achieve a satisfied and stable offloading performance, new and planned WiFi deployment has to be considered and in fact is already an ongoing effort. Since providing a ubiquitous WiFi coverage is cost prohibitive, how to deploy a set of WiFi APs to provide a better WiFi availability for vehicles has received many research attentions. For example, WiFi deployment strategies in vehicular communication environments are studied in [42]. A notion called *alpha coverage* is introduced, which guarantees the worse-case interconnection gap, defined as the distance or expected delay between two successive AP contacts experienced by moving vehicles on the road. The metric α is defined in the following way: a WiFi deployment that provides α -Coverage guarantees that there is at least one AP on any path which is of length at least α . Using such a metric to evaluate the AP deployment is reasonable. First, the delay in vehicular WiFi access is usually caused by intermittent connectivities; and second, with such a delay bound, the WiFi offloading potential can be well predicted given the connection time and throughput statistics of one AP connection. As discussed above, predictions of WiFi availability play a vital role in the design of offloading schemes, since such knowledge can facilitate to determine whether to defer applications. Algorithms to achieve budgeted alpha coverage, that is, to find a set of bounded number of APs to provide the alpha coverage with minimum α , are also proposed and evaluated. The limitation of [42] is that the AP deployment is sparse so that the AP coverage radius is negligible compared to the distance between neighboring APs. This is not the case for urban scenarios where a cluster of APs may cover a dense area seamlessly. Optimizing the WiFi deployment for urban scenarios with diverse vehicle densities is a demanding task.

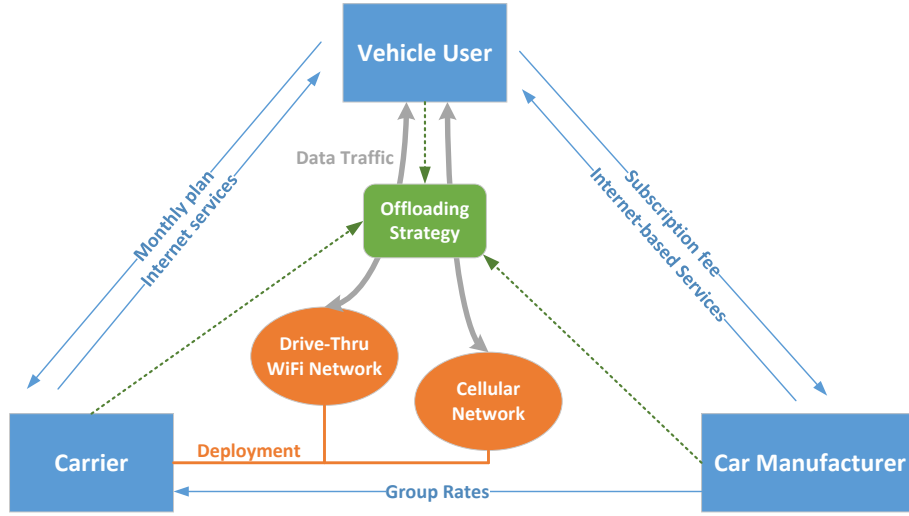


Figure 2: Potential marketing relations between vehicle users, cellular operators, and car manufacturers.

3.3. Future works

We give some thoughts on future research directions on the topic of vehicular WiFi offloading as follows.

- *Advanced prediction mechanisms.* The high mobility of vehicles makes the accurate prediction of WiFi availability and performance difficult, even when priori knowledge about AP locations and performance or the drive history of vehicles is available. The prediction error in [40] is about 20% when estimate the future 100 s, while in [36], the 90% confidence interval of the prediction of vehicle moving distance for the future 100 s is 150 m in expressway scenario. To optimize offloading performance, more accurate prediction mechanisms, especially for long prediction interval, are then necessary for designing offloading schemes.
- *Centralized scheduled offloading schemes.* Cellular operators are typically aware of the network context, such as vehicle density, user data request, and WiFi availability, and are capable of determining network policies such as pricing of using different networks. Thus, it is conjectured that operator-controlled offloading schemes can better optimize offloading performance and achieve special offloading targets, e.g., traffic offloading at particular times or locations.
- *Incentive models.* Incentives should be considered to motivate vehicles to offload their traffic. Such incentives may include low price rate, rewarded cellular or WiFi bandwidth, etc. Pricing mechanisms have been studied in the literature, such as in [25]. However, with the flat rate pricing widely employed, such low-price mechanisms may not be feasible. For vehicular WiFi offloading, the role of car manufacturers should be considered. For Internet-integrated vehicles, e.g., BMW ConnectedDrive models, vehicle users may pay a subscription fee for Internet-based services to their car manufacturers. Since car manufacturers would pay for the traffic of such services to operators, an incentive model may be developed by car manufacturers to encourage vehicle users to offload the traffic. Therefore, workable

and attractive incentive models should consider the potential marketing relations between vehicle users, cellular operators, and car manufacturers, as shown in Fig. 2.

- *Practical WiFi deployment strategies.* Optimizing the WiFi deployment, especially for urban scenarios, is a demanding task. To achieve better vehicular offloading effectiveness, WiFi deployment strategies should jointly consider the vehicle density and traffic characteristics, users' drive patterns, data traffic spatial and temporal distribution, etc.
- *Multi-hop and peer-to-peer communications.* Multi-hop vehicle relay schemes are studied to extend the coverage of the drive-thru Internet [43, 44]. However, no offloading schemes using multi-hop communication is proposed nor the effectiveness of doing so is discussed. Peer-to-peer opportunistic content distribution between vehicles can improve the offloading performance especially when the AP deployment is sparse. However, it may pose challenges such as the selection of subscribing vehicles which download and forward the contents. Thus, incorporating such an opportunistic peer-to-peer scheme into WiFi offloading needs further study.
- *Theoretical analysis of offloading effectiveness.* Although offloading schemes are proposed and evaluated, the theoretical analysis of the overall effectiveness of vehicular WiFi offloading is still missing in literature. Given the WiFi deployment, vehicle mobility statistics, application arrivals, and specific delay tolerance, the WiFi offloading performance can be theoretically analyzed, e.g., by using the queue theory. Such analysis can be then used to design and improve offloading schemes and WiFi deployment strategies, etc.

4. Conclusion

In this paper, we have provided a comprehensive overview of the mobile data WiFi offloading in vehicular communication environments. WiFi offloading for non-vehicle users has been first discussed. Currently, WiFi offloading for non-vehicle users is proved to be efficient, in both data offloading effectiveness and energy efficiency. Then, we have focused on the vehicular WiFi offloading, and discussed its unique characterizations, effectiveness, technical challenges, and existing solutions, followed by future research directions. we argue that offloading cellular traffic via drive-thru WiFi and inter-vehicle communications are promising and will gain substantial research attentions. This paper is expected to serve as a useful reference in this area.

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