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# Mobile data offloading: an agent-based modelling study on the effectiveness of Wi-Fi offloading

Yorick Breukers\*, Mark de Reuver\*, Michel Oey\*, and Harry Bouwman\* \*\*

\*Delft University of Technology, The Netherlands

\*\* Abo Akademi, Turku, Finland

## Abstract

To reduce the load on cellular networks, offloading to Wi-Fi has long been discussed as a technological solution. Despite advances in scheduling algorithms and incentive schemes, most mobile operators do not actively promote Wi-Fi offloading and most Wi-Fi usage is limited to stationary in-home contexts of use. This study assesses the proportion of users on the street that can be offloaded to Wi-Fi access points, taking into account different city topologies, speed of movement and technical characteristics of Wi-Fi access points. We show that the proportion of users on the street that can be offloaded to Wi-Fi heavily depends on their speed of moving around, the reach of access points and the delay in logging on to access points. However, even when using standard configurations for access points, base stations and smartphones, half the outdoor users can be offloaded to Wi-Fi. These results are consistent for any type of realistic topology of roads in the city. Based on the results, operators are recommended to promote Wi-Fi offloading as it massively reduces the load on cellular networks.

## 1. Introduction

Ever since the introduction of smartphones, telecom operators have been struggling to meet growing demands for cellular network capacity. Although 4G networks increase capacity and data rates, deploying base stations still yields considerable costs for mobile operators. Challenges for mobile operators will increase as mobile data traffic is expected to grow rapidly in the coming years.

A potential solution for reducing the load on cellular networks is Wi-Fi offloading, i.e. transmitting data via a Wi-Fi access point in the vicinity of the smartphone instead of the cellular network (Bulut & Szymanski, 2013). Mobile operators are slowly starting to experiment with expanding their networks with Wi-Fi access points (Aijaz, Aghvami, & Amani, 2013). While a substantial amount of smartphone data traffic is transmitted via Wi-Fi without active promotion from mobile operators (Lee, Lee, Yi, Rhee, & Chong, 2013), usage is typically limited to indoors contexts (Fukuda & Nagami, 2013). We therefore assume that operators would have to actively promote Wi-Fi offloading by offering incentives for opening up Wi-Fi access points to strangers.

Wi-Fi access points have specific technical characteristics that impact the effectiveness of Wi-Fi offloading. First, reach of Wi-Fi access points is typically limited to tens of meters since it utilizes non-licensed frequencies with limited signal strength. Second, data rates are also constrained, both by the distance to the Wi-Fi access point and the maximum speed of the wired internet connection. Third, the time to log on to a Wi-Fi access points is constrained. Only after authenticating the user and exchanging security keys, can a user connect to the Internet, which delays the time until people can use the Internet.

It is yet unclear how Wi-Fi offloading may be effective for users on the street who are not always in the vicinity of Wi-Fi access points, and how the effectiveness may depend on the topology of cities, speed of movement and technical characteristics of the access points being opened to mobile users. Existing studies show many methods to increase the effectiveness and efficiency of Wi-Fi offloading by using advanced technologies and scheduling algorithms, but in practice these are not being implemented by operators. Studies that assess the opportunities of Wi-Fi offloading based on standard Wi-Fi access points without any advanced scheduling algorithms are lacking in literature.

The objective of this paper is to provide more insight into the effectiveness of mobile data offloading via Wi-Fi without the operator having to implement advanced scheduling algorithms, and the factors that affect the effectiveness. Effectiveness is defined as the proportion of users on the street that can offload their data traffic via a Wi-Fi access point.

To answer this research question, a simulation is conducted through agent based modelling, using NetLogo version 5.0.5 (Uri Wilensky, 1999). The model simulates an urban area with roads and residential blocks. Within the residential blocks, Wi-Fi access points are placed. The model generates users who move in random patterns across the roads and connect to Wi-Fi access points when in reach.

## 2. Related work

Mobile data offloading is a broad concept. It refers to methods to ensure data is not transmitted and received over the mobile networks. There are multiple options to do so. The main two options are Wi-Fi and femtocells (Aijaz et al., 2013). A femtocell is a smaller version of a normal cell and supports the same standards such as 3G and 4G. However,

mobile data offloading via Wi-Fi is deemed more cost effective because use is made of the unlicensed radio spectrum in place of the expensive frequencies required for 3G and 4G (Dimatteo, Hui, Han, & Li, 2011). Hence, providers primarily focus on mobile data offloading via Wi-Fi.

In principle, Wi-Fi offloading has been technologically feasible ever since smartphones were equipped with Wi-Fi receivers. By default, already 65% of all smartphone data traffic is transmitted via Wi-Fi without any active promotion by mobile operators, as a field study on 100 iPhones by Lee et al. (2013) shows. However, in a similar study by Fukuda and Nagami, it becomes clear that most Wi-Fi usage by smartphone is typically limited to the home or office, and is generally uncommon in public places. In this paper, we focus on the scenario where mobile telecom operators actively offer Wi-Fi access points as an extension of their cellular networks (Aijaz et al., 2013).

Technical studies on Wi-Fi offloading delivered various algorithms and procedures to increase the effectiveness of Wi-Fi offloading. Bulut and Szymanski (2013) develop an offloading algorithm based on user data request frequency and demonstrate effectiveness in a simulation study. Kang, Chia, and Sun (2013) show that successive interference cancellation increases the utility for mobile operators of Wi-Fi offloading.

Wi-Fi offloading may not lead to benefits for the user in some circumstances. For instance, low throughput Wi-Fi access points may increase energy consumption of handsets, which may be countered through the algorithms proposed by Ding et al. (2013). Jung, Song, and Sung (2014) show that throughputs may be optimized by allowing only a part of the traffic to be offloaded to Wi-Fi. Wi-Fi offloading effectiveness may also depend on velocity of users, for instance Cheng et al show that for vehicular usage, Wi-Fi offloading poses several specific challenges.

Several technical studies on Wi-Fi offloading focus on delayed offloading, in which transmission of data traffic is delayed until a Wi-Fi access point is within reach. Such delayed offloading may negatively affect quality of service depending on the extent to which data transmission can be postponed for a specific application scenario, also referred to as delay tolerance. Bennis et al develop a self-organizing method in which base stations can decide between cellular and Wi-Fi offloading based on delay-tolerance, and demonstrate effectiveness through a simulation study. Siris and Kalyvas (2013) develop advanced procedures to improve Wi-Fi delayed offloading effectiveness by predicting the Wi-Fi access points that will be encountered as well as the amount of data that has to be cached for delayed transmission. For the same procedures, Siris and Anagnostopoulou (2013) show that throughput, data size and number of access points are the main predictors for performance and energy efficiency. Im et al. (2013) develop a method to optimize user costs, throughput and delay when delaying offloading to Wi-Fi. Yetim and Martonosi (2014) develop a framework to schedule what type of applications are offloaded (with delay) through what type of networks.

From a more techno-economics perspective, various studies have been done to assess the benefits of Wi-Fi offloading and how to incentivize users. Lee et al. (2013) study economic benefits from offloading through a game theoretical study as well as trace analysis, and show both provider revenue and user surplus increases. Kliks, Dimitriou, Zalonis, and Holland (2013) show that Wi-Fi offloading may not only lead to reduced load on cellular networks but also lead to energy savings for base stations. Zhuo et al (Zhuo, Gao, Cao, & Hua, 2014) suggest an incentive framework that distinguishes users based on their delay tolerance and offloading potential, based on reverse auctioning, and show the effectiveness using trace-driven simulations. Joe-Wong et al (Joe-Wong, Sen, & Ha, 2013) show that pricing models from internet service providers may lead to non-intuitive adoption behavior, in which for instance increased connectivity leads to lower adoption.

Our study focuses on the business scenario in which a mobile telecom operator offers Wi-Fi offloading without alterations to the protocols and algorithms in access points, base stations and smartphones. By not including advances, although we are aware they are proposed in literature, we stay as close as possible to the status quo and answer the business-relevant question on what gains can be effectuated without major upgrades in the infrastructure of the networks. We also focus on Wi-Fi offloading for users on the street, as mobile Internet traffic indoors already largely takes place via Wi-Fi.

### **3. Conceptual model**

The model that is used in this research is based on simulations of an urban area where there is a network of roads. Between the roads there are inaccessible areas that represent housing blocks. Wi-Fi access points are randomly positioned in housing blocks. The model generates users that roam around randomly on the roads. When they are within the range of a Wi-Fi access point, they automatically connect. How many users are connected to a Wi-Fi access point is continuously monitored. This way it can be examined which percentage of users on average are connected to Wi-Fi access point. By varying the variables of the model, the effects on the time that a user is connected to a Wi-Fi access point can be observed.

We include five variables in the model that affect the effectiveness of Wi-Fi offloading. First, we include the number of Wi-Fi access points per square kilometer. This variable will affect coverage and thus the probability that a user can transmit data via Wi-Fi rather than via cellular connections. Second, we include density of the urban area, i.e. the number of roads, buildings and users per square kilometer. Third, we include the login delay, i.e. the number of seconds it will take to connect to a Wi-Fi access point. The longer the login delay, the less a user is able to use Wi-Fi to offload data. Fourth, we include speed of roaming users, i.e. the velocity with which a user is moving in the geographical space.

The higher the velocity, the more logins are needed to Wi-Fi access points, which in turn reduces effectiveness. Finally, we include reach of the Wi-Fi access points, which is highly diverse between the different Wi-Fi standards.

#### **4. Model specification**

This study requires a realistic simulation of mobile data off-loading. Agent based modelling is especially suitable when the spatial characteristics of a system play an important role, which is the case for this study since we are interested in the effects of diverse city topologies. We use NetLogo as a tool since it provides the opportunity to flexibly adapt variables in the agent based model.

##### **4.1. Key assumptions**

Although the outline of city roads can highly differ across cities, this will likely not impact the results of the study since our main focus is distance between the user and the location of the access point. For pedestrians, distance to Wi-Fi access points is similar regardless of the layout of the city road network, since pedestrians walk close to the buildings. Similarly, bicyclists move around on the edge of the road close to the buildings. Car drivers may have more diverse distances to buildings, but this will likely have a small effect since the reach of an access point is included in the model. Therefore, we assume that the shape and width of a road does not affect the effectiveness of mobile data offloading. Similarly, the size and shape of front yards is not included in the model. Besides roads, buildings also affect the model. We focus on urban areas rather than scarcely populated areas since Wi-Fi networks and users are mainly present in cities.

We assume that users can connect to all Wi-Fi access points in the model, i.e. there is no discrimination of users depending on for instance their telecom operator. Moreover, we assume that users are continuously present on the street, moving or at a standstill. The total number of users on the street is set to a constant, assuming that people entering and exiting buildings will be at an equilibrium.

Wi-Fi access points are placed on random positions in buildings. All Wi-Fi access points have the same specifications, i.e. 802.11b/g/n, which is currently the predominant standard in most countries.

Regarding data usage, we assume that users consume on average the same amount of bandwidth. We also assume that the data consumption will not exceed the bandwidth of the Wi-Fi access point. Therefore, we assume that the proportion of users connected to a Wi-Fi access point equates the proportion of data offloaded through Wi-Fi.

##### **4.2. Model description**

The NetLogo model covers 100 x 100 patches, each patch representing 10 by 10 meters. Roads are modelled as grids with patches in between that represent buildings. Distance between roads and size of buildings can be adapted using the method used in the NetLogo Traffic Grid model by Wilensky (2003).

While initiating the model, the users and Wi-Fi access points are instantiated as agents. Depending on the number, users are positioned at random locations on the roads. Similarly, Wi-Fi access points are positioned at random locations within the built areas. Depending on the reach of a Wi-Fi access point and the size of a building, a Wi-Fi access point can be placed, such that no connection can be made to it from the street.

When starting the model, users will move in random directions or stand still. When a user comes in reach of a Wi-Fi access point, a connection is made. When the user moves out of reach, the connection is dropped, and the user attempts to connect to other Wi-Fi access points.

After starting the model, the operational part of the model script is run, which is referred to as a 'tick'. A tick is defined in this study as one second.

##### **4.3. Starting values**

Starting values of the parameters in the model are set to the most realistic or average values. The number of users is in itself not relevant for the outcomes of the modelling study, since the assumption of the model is that Wi-Fi access points will have enough bandwidth to serve all users in their vicinity. However, the number of users in the model must be high enough to compute reliable averages. At the same time, each patch in the model can only be occupied by one user, which limits the number of users in the system. Therefore, we set the number of users to be 1000.

For the number of Wi-Fi access points, we assume that most households have a Wi-Fi access point, but not more than one. In densely populated urban areas as for instance in the Netherlands, a square kilometer covers about 1800 houses. We also assume that about 10% of the households will open up their Wi-Fi access point to people on the street, in return for payment or for other reasons. As such, as starting parameter in our model, we set the number of Wi-Fi access points to be 180.

The reach of 802.11b/g Wi-Fi access points is about 30 meters, according to extensive tests by Solarski, Vidales, Schneider, Zerfos, and Singh (2006). As we assume that the 802.11n standard will deliver longer reach, we set the starting parameter for the model to be 35 meters.

The login delay to connect to a Wi-Fi access point can differ strongly, depending also on the velocity of users. An earlier study shows that the average login delay for non-stationary users equals 1.83 seconds (Bychkovsky, Hull, Miu, Balakrishnan, & Madden, 2006), which we round up to 2 seconds for the purposes of this model study.

Velocity of users is based on the assumption that most Wi-Fi users will be pedestrians. According to Mohler, Thompson, Creem-Regehr, Pick Jr, and Warren Jr (2007), the average velocity of pedestrians equals 1.2 m/s, which is therefore the starting parameter for the model.

#### 4.4. Verification and validation

As suggested by Midgley, Marks, and Kunchamwar (2007), we first conduct an extreme values test to verify the model. Setting the reach of the Wi-Fi access points, login delay and number of Wi-Fi access points per square kilometer to extreme values, we find the model behaves as is to be expected.

Next, a sensitivity analysis is done to check if the model responds extremely to small changes in the parameters. None of the parameters show extreme sensitivity.

Next, micro validation is done following Moss and Edmonds (2005). Micro validation on the user agents is done by mapping the movement pattern of a specific user. We find that the user pattern is not realistic because each movement pattern is a random event, and because users do not exit the road network. However, since we focus on aggregate statistics this deviation is not problematic. Micro validation on the Wi-Fi access points is done by verifying that users are connected to the Internet at the right locations and by observing the login behavior of the users. Behavior on micro level fits the expected behavior.

Finally, we compare the model behavior with existing literature. The only relevant study for comparison is that by Balasubramanian, Mahajan, and Venkataramani (2010), who assess the offloading percentage that can be attained by deploying access points throughout an urban area and performing measurements with transit buses mounted with wireless radios. By inserting similar parameters in our model, we assess if similar results are reached. We find that the results for offloading effectiveness in our model and in the Balasubramanian et al study are similar.

Figure 1 provides a visual representation of the model. White dots are Wi-Fi access points and the arrow heads are users. Users without a Wi-Fi connection are blue; users that are connected to a Wi-Fi access point (indicated by a line) are green.

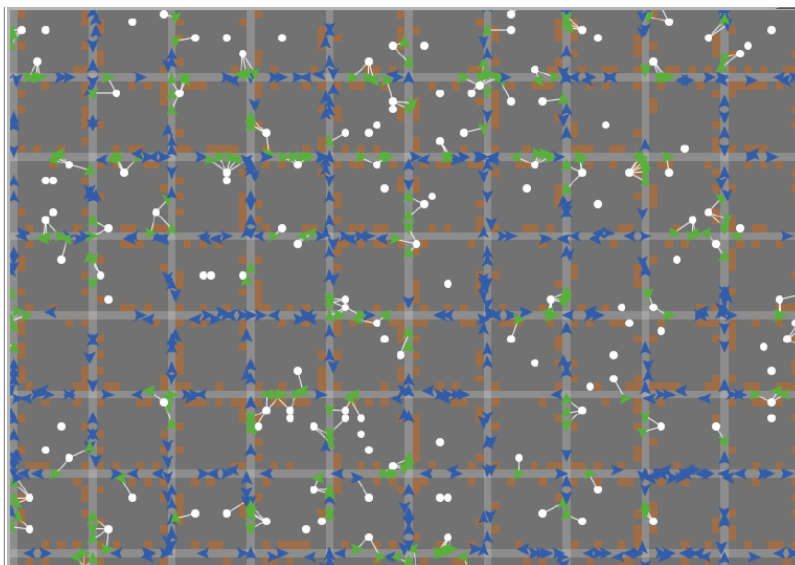


Figure 1 Visual representation of the model

## 5. Results

To test the effect of each variable in the conceptual model on the effectiveness on Wi-Fi offloading, we adapt one of the model parameters while keeping all others at their starting values. For each test, 10 runs are conducted to minimize effects due to the random positioning of Wi-Fi access points and roads. The runs are conducted using the BehaviorSpace function in NetLogo, which enables conducting multiple runs automatically with different parameters.

The results show that 100 Wi-Fi access points per square km result in 25% of mobile data to be offloaded via Wi-Fi. With 300 Wi-Fi access points per square km this percentage is even 60%. This implies that when telecom operators in a densely populated area have access to a relatively small number of Wi-Fi access points, their network can significantly be relieved, see Figure 2.

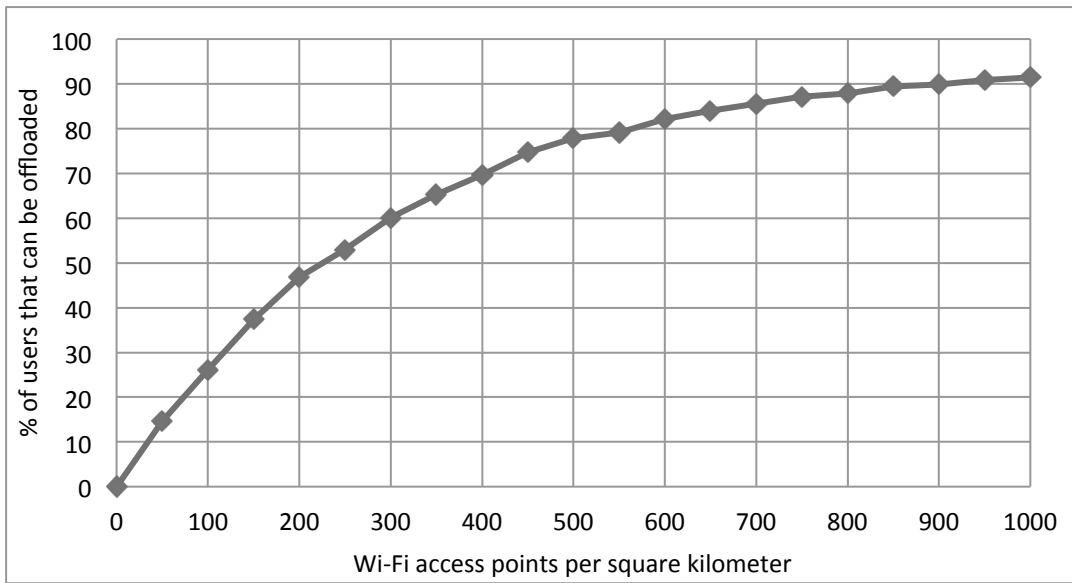


Figure 2 The effect of the number of Wi-Fi access points on the percentage of users that can be offloaded

Next, the relationship between the range of the Wi-Fi access points and the amount of mobile data that can be offloaded via Wi-Fi is analysed, see Figure 3. Results show that range has a very strong impact on the amount of data that can be offloaded. When the range of Wi-Fi access points increases from 30 to 40 meters, the number of connected users increases from 33% to almost 55%. Only when reach increases above 50 meters, the increase of connected users decelerates, because coverage of access points starts to overlap.

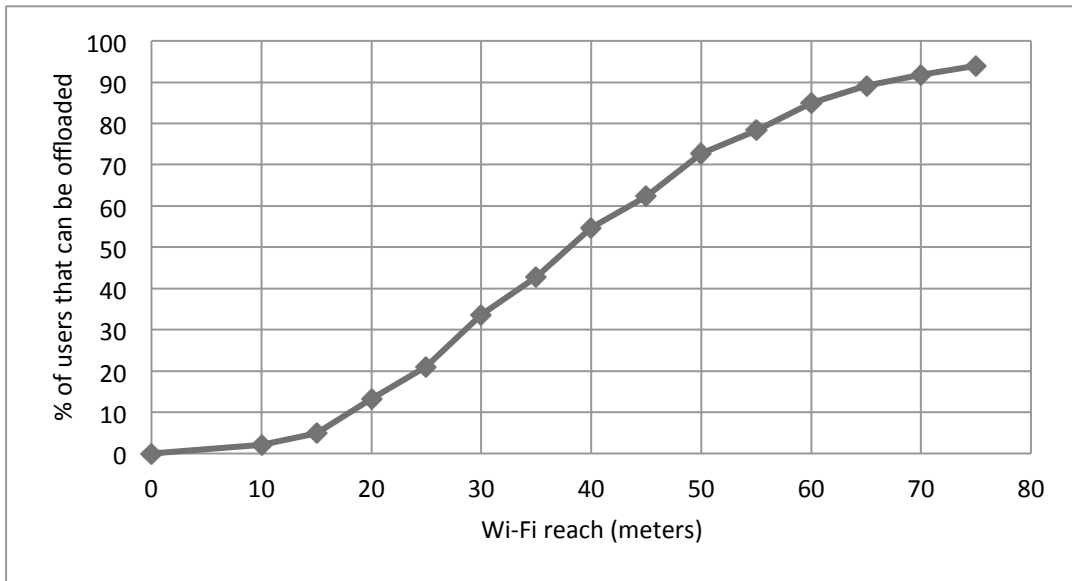


Figure 3 The effect of Wi-Fi reach on the percentage of users that can be offloaded

Next, we test the effect of density of urban area (i.e. number of roads per square kilometer) on the number of connected users via Wi-Fi, see Figure 4. We find that if the number of roads increases from 6 to 16 per square kilometer, the number of connected users via Wi-Fi hardly increases, which suggests the results of the model are generalizable to different city topologies.

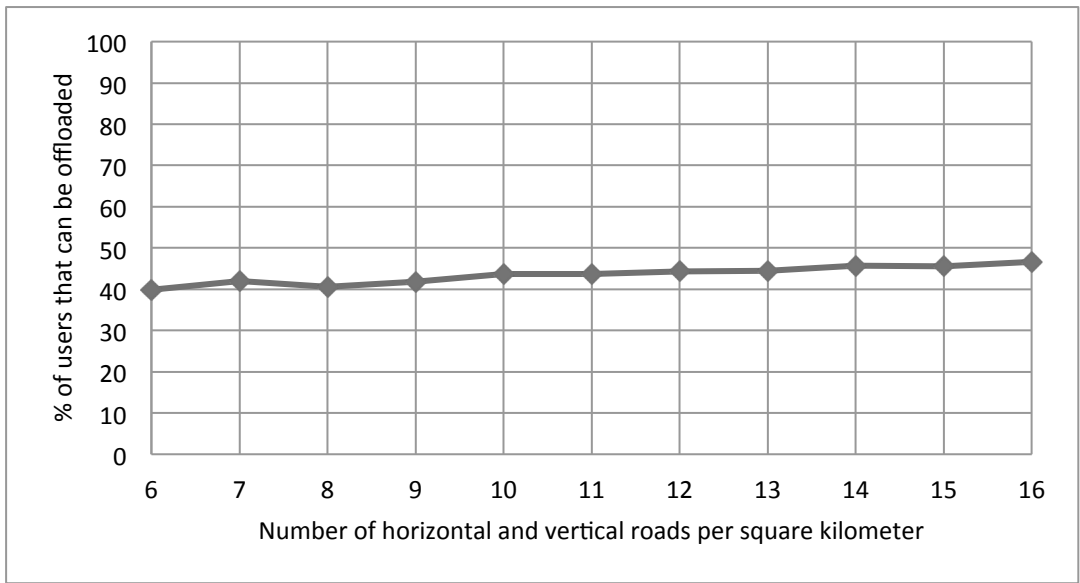


Figure 4 The effect of city topology on the percentage of users that can be offloaded

Finally, the relationship between the speed of movement of the users and the effectiveness of mobile data offload is examined, see Figure 5. One factor that plays an important role is the delay that occurs during login-procedure to a Wi-Fi access point. With a login delay of 4 seconds, and moving speed of 1 m/s on average 40% of the users are connected via Wi-Fi. As speed increases towards the 14 m/s, the average number of connected users decreased to 9%. Speed of movement has a great influence on the effectiveness.

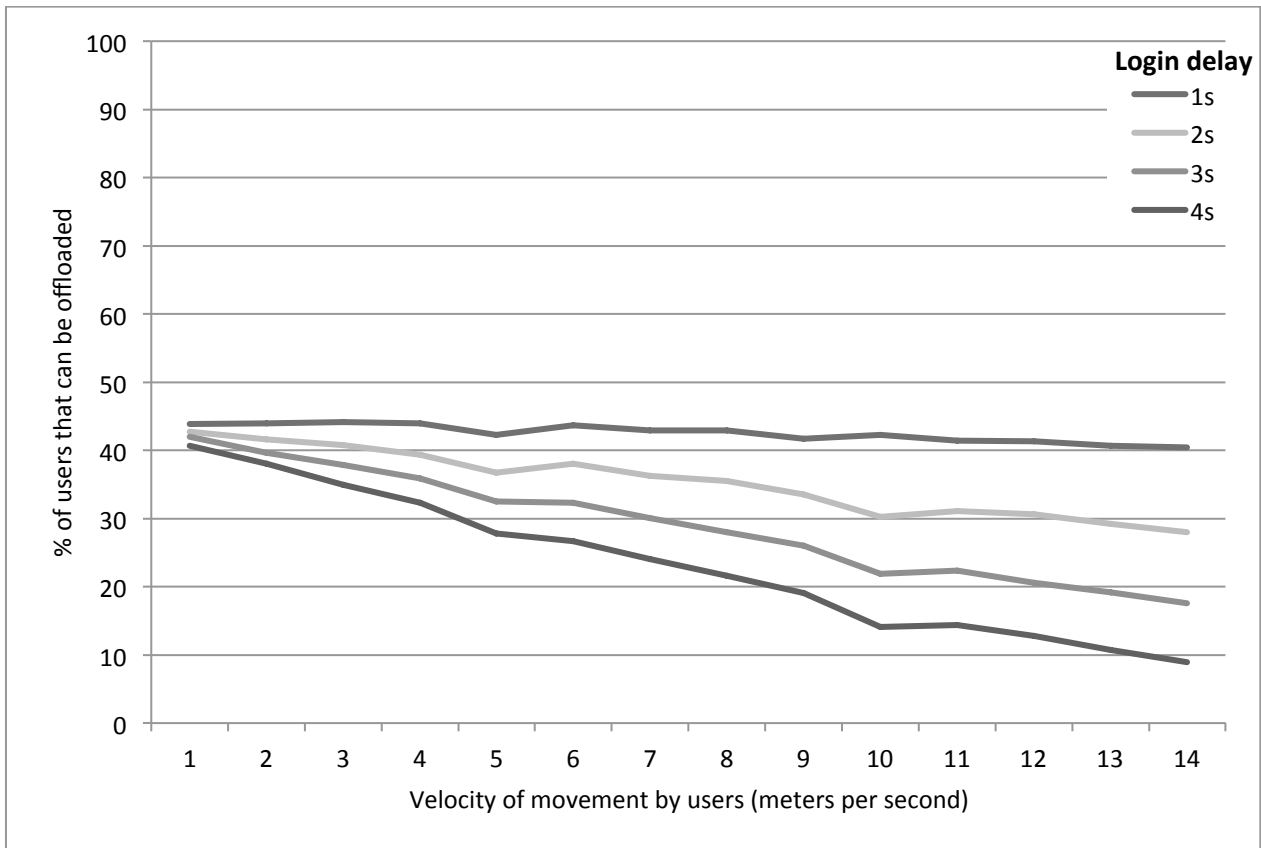


Figure 5 The effect of velocity of movement and login delay on the percentage of users that can be offloaded

## 6. Conclusions and discussion

The study showed that mobile data offloading can contribute significantly to relieving mobile network traffic. Even for telecom providers who only have limited access to Wi-Fi access points, there are interesting opportunities, assuming these are used in densely populated areas. For mobile operators that already have a large market share in the fixed Internet market, opportunities are even larger. For them, 300 Wi-Fi access points per square kilometer will be feasible implying they can utilize the offloading strategy to reduce the load of their network by more than 50%. Only a relatively small set share of Wi-Fi access points that is opened up for pedestrians can already reduce a lot of load on the cellular networks.

There are two factors they have to take into account. First, the range of the Wi-Fi access points has a large effect on the effectiveness of mobile data offloading. Technological advances leading to higher reach in Wi-Fi access points will therefore contribute to effectiveness of offloading strategies. Especially in sparsely populated areas, reach of access points is a major predictor for effectiveness of offloading. Second, login delay has impact on the effectiveness of mobile data offloading via Wi-Fi. When users are moving quickly and login takes a few seconds, there is not enough time to connect to a Wi-Fi access point and exchange data. When login delay is only 1 second, velocity of movement hardly affects effectiveness. But when login delays increase, velocity of movement has a strong negative effect. In other words, to have Wi-Fi offloading effective for non-pedestrians, login delay should not exceed 2 seconds. Technological advances to reduce login delays or realize proactive handovers between Wi-Fi access points thus has high potential to increase offloading effectiveness.

Results in this paper are generalizable to different city topologies. We have shown that the average number of roads per square kilometer hardly affects the effectiveness of Wi-Fi offloading. A limitation of the present study is that effectiveness on the level of data transfer protocols has not been included, nor the patterns of data usage by users. Possibly, users that are moving around have different data usage patterns than stationary users. A second limitation is that the performance of Wi-Fi access points has been modelled to a limited extent. Solarski et al. (2006) show that performance of Wi-Fi access points within buildings can differ and affect overall effectiveness. Especially when an access point is located further from the road, the amount of built environment the signal needs to permeate increases. This negatively affects battery usage as well as maximum throughput. Third, we did not take into account delayed offloading, i.e. postponing data transmission until a Wi-Fi access point comes within reach. However, Lee et al (Lee et al., 2013) show that such delayed offloading does not contribute highly to overall effectiveness. Fourth, we did not take into account the maximum capacity per Wi-Fi access point. In areas with large numbers of users, the capacity per access point may become the bottleneck factor, see Jung et al. (2014). Fifth, new algorithms offering more efficient handovers and login delays are not included, but this study does show that login delay has a major effect on offloading effectiveness.

Besides demonstrating the efficacy of Wi-Fi offloading, the paper also serves to illustrate the use of agent-based modelling in evaluating strategic choices of telecom operators. Especially for research issues that, as in the present paper, deal with geospatial factors that influence the effectiveness of telecom infrastructure choices, agent-based modelling can be utilized. This paper demonstrates that agent-based modelling can thus replace costly experimentation in the real world to evaluate the effectiveness of offloading strategies.

Evaluating the cost effectiveness of Wi-Fi offloading for mobile operators also requires taking into account the incentives that need to convince access point owners to open up their Internet connection to strangers. Such techno-economic evaluation should also include the potential energy gains of using Wi-Fi rather than cellular connections for the smartphone. Further research should also consider potential privacy, security and liability issues that emerge when consumers open their Wi-Fi access point to strangers, for instance who is accountable when the connection is used for illegal activities.



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