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School of Electrical Engineering

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Game-theoretic Analysis of Deployment Schemes for Mobile Network Offloading

Master's thesis submitted in partial fulfillment of the requirements for the degree of Master of Science.

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Abstract

Aalto University **Abstract of master's thesis**

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Mobile network connectivity is currently mainly provided by wide area technologies utilizing outdoor-located base stations. However, the provisioning of services consuming more and more data at a higher bit rate requires new network deployment strategies for mobile operators. In this context, a strategic option for the evolution of radio access networks, especially in dense urban areas, is mobile network offloading. Offloading is a win-win solution since both mobile operators and end-users are benefited by such a deployment. In this thesis, we describe several deployment schemes for mobile offloading using femtocells or WiFi. The objective is to evaluate for each offloading solution where and when it should be deployed by mobile operators. To achieve this goal, we have led a qualitative and a game-theoretic analysis which have enabled us to figure out for each of those offloading solutions their strengths and weaknesses as well as their specificities in different competitive environments. The qualitative analysis conducted concludes that femtocells are more likely to be deployed in business areas since they guarantee a better quality of service, meet higher security requirements and are manageable by operators even if they are installed on private places. On the other hand, WiFi networks already exist in most residential areas and consumer customers are familiar with the technology. Thus, it will probably be easy for operators to use these wireless access points to redirect part of their mobile traffic. Finally, the results of game theory propose for each offloading solution a market penetration plan.

Keywords:	Mobile offloading, Game theory, Deployment strategy, Femtocell, WiFi, Indoor mobile networks

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L'accès aux réseaux mobiles se fait aujourd'hui principalement à travers des technologies à grande échelle qui utilisent des antennes relais implantées en milieu extérieur. Cependant, délivrer des services qui consomment de plus en plus de données à des débits plus élevés exige de la part des opérateurs mobiles de nouvelles stratégies de déploiement du réseau. Dans ce contexte, un choix stratégique pour l'évolution des réseaux d'accès, particulièrement dans les zones urbaines denses, est de reporter une partie du trafic mobile vers d'autres types de réseaux sans fil ; on parle de désengorgement du réseau mobile. Le désengorgement est une situation gagnante-gagnante puisque à la fois les opérateurs et l'utilisateur final vont pouvoir tirer des bénéfices d'un tel déploiement. Dans cette thèse, nous décrivons plusieurs scénarios de déploiement pour le désengorgement des réseaux mobiles qui utilisent les femtocells ou le WiFi. L'objectif étant d'évaluer pour chacune d'entre elles quand et où elles doivent être déployées par les opérateurs mobiles. Pour atteindre ce but, nous avons mené une analyse quantitative et une autre utilisant la théorie des jeux, ce qui nous a permis de trouver les forces et les faiblesses de chacune d'entre elles ainsi que leurs spécificités dans des environnements compétitifs différents. L'analyse qualitative nous a conduit à conclure que les femtocells sont plutôt destinées à être déployées dans les quartiers d'affaires puisqu'elles garantissent une meilleure qualité de service, sont plus sûres et gérées par les opérateurs malgré le fait qu'elles soient installées dans des locaux privés. D'un autre côté, les réseaux WiFi existent déjà dans la plupart des zones résidentielles et les clients grand public sont très familiers avec cette technologie. Il sera donc probablement facile pour les opérateurs d'utiliser ces points d'accès sans fil pour rediriger une partie du trafic mobile. Enfin, les résultats de la théorie des jeux proposent pour chaque solution de désengorgement un schéma de pénétration sur le marché.

Mots clés:	Désengorgement des réseaux mobiles, Théorie des jeux, Stratégie de déploiement, Femtocell, WiFi, Réseaux mobiles d'intérieur

Preface

This Master's Thesis completes my work for the Master of Science degree in Aalto University and was written as a part of the MoMI research project at the Department of Communications and Networking at Aalto University School of Electrical Engineering. I am grateful to all the MoMIE collaborators for providing me with the opportunity to learn academic research.

I would like to express my appreciation to my supervisor Professor Heikki Hämmäinen for his guidance, professional views and continuing interest on my thesis topic.

I would also like to express my gratitude to those people who have supported and encouraged me: my instructor Michail Katsigiannis, Kimmo Berg for his relevant advice in Game Theory, Mika Husso for his help and knowledge about the telecom market.

Of course, completing my studies would not have been possible without the support of friends, family and other important persons in my life. My most sincere thanks go therefore to them as well.

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Abbreviations

2G	**2nd Generation**
3G	**3rd Generation**
3GPP	**3rd Generation Partnership Project**
API	**Application Programming Interface**
APN	**Access Point Name**
ARPU	**Average Revenue per User**
BG	**Border Gateway**
BSS	**Base Station Subsystem**
DNS	**Domain Name System**
EDGE	**Enhanced Data rates for Global Evolution**
FTP	**File Transfer Protocol**
GERAN	**GSM EDGE Radio Access Networks**
GGSN	**Gateway GPRS Support Node**
GPRS	**General Packet Radio Service**
GPS	**Global Positioning System**
GSM	**Global System for Mobile communications**
GSN	**GPRS Support node**
HLR	**Home Location Register**
HSDPA	**High-Speed Downlink Packet Access**
HSPA	**High speed packet data access**
HSUPA	**High-Speed Uplink Packet Access**

HTML	**Hypertext Markup Language**
HTTP	**Hypertext Transfer Protocol**
IMS	**IP Multimedia Subsystem**
IP	**Internet Protocol**
LTE	**Long Term Evolution**
ME	**Mobile Equipment**
MNO	**Mobile Network Operator**
MVNO	**Mobile Virtual Network Operator**
OS	**Operating System**
P2P	**Peer-to-Peer**
PC	**Personal Computer**
PDN	**Packet Data Network**
PS	**Packet Switched**
RADIUS	**Remote Authentication Dial In User Service**
RNC	**Radio Network Controller**
SGSN	**Serving GPRS Support Node**
SP	**Service Provider**
UE	**User Equipment**
UMTS	**Universal Mobile Telecommunications System**
URL	**Uniform Resource Locator**
USB	**Universal Serial Bus**
UTRAN	**UMTS Terrestrial Radio Access Network**

WAP	**Wireless Application Protocol**
WiMAX	**Worldwide Interoperability for Microwave Access**
WLAN	**Wireless Local Area Network**
VOIP	**Voice over IP**

1 Introduction

1.1 Motivations

Mobile networks are currently experiencing their first revolution since they were built. The demand for mobile broadband access and data traffic increases rapidly. A few years ago, in 2007, the first data consumer smartphones have been released in the consumer market and they marked the beginning of data traffic explosion on mobile networks.

Mobile network traffic volume was initially dominated by voice traffic but gradually data traffic grew to overtake voice around 2010. The way the users consume mobile services has also been considerably modified and the majority of smartphone usage takes place while people are at the office and at home[1]. Hence, around 70-80% of the mobile data traffic is generated indoors[2]. Additionally, the capabilities of smart terminals along with the new mobile applications and laptops connected to mobile networks create an increasing amount of data, and traffic forecasts predict that the traffic will grow significantly. In dense urban areas, mobile operators have noticed that the existing outdoor networks will probably not be sufficient to handle all the traffic demand. Therefore, mobile operators have to address the challenges for achieving sufficient coverage, capacity and quality targets under the aforementioned conditions.

A strategic option for the evolution of radio access networks is mobile network offloading. Offloading as a deployment strategy, especially in dense urban areas, might provide a good solution for mobile operators.

The co-existence of indoor base stations and macro cellular networks provides many benefits for both mobile operator and end-user. The better coverage and capacity cause customer satisfaction which results in a lower churn rate[3]. By reducing the amount of traffic demand from indoor areas, mobile operators would be able to continue to provide reliable services for all their customers despite growing traffic. Furthermore, mobile operators can offer value-added services and applications to the end-users via indoor base stations which can increase the user's utility and eventually the average revenue per user (ARPU) for mobile operators. The mobile operator benefits also from capital (CAPEX) and operational expenditures (OPEX) reduction which may have impact on pricing. Consequently, mobile data offloading with indoor base stations is a favorable deployment strategy for both sides.

The main technologies for mobile network offloading are 3GPP femtocells (3rd Generation Partnership Project) and IEEE WiFi (Institute of Electrical and Electronics Engineers, Wireless Fidelity). Both imply smaller cells, covering mainly indoor areas which could complement the wide area networks and deliver the traffic, originally targeted for mobile networks, through fixed networks.

1.2 Purpose of the thesis

The purpose of this thesis is to provide qualitative analysis of mobile network offloading solutions in the context of a future deployment. Firstly, thanks to technology comparisons and real case examples, we evaluate strengths and weaknesses of several offloading solutions. Then we find out which offloading solution is preferable for business areas and which is preferable for residential areas. Secondly, applying game theory, we try to determine when each of the offloading solutions may be deployed in the future.

To sum up in one question, the purpose of the thesis can be set out as follow:

Considering the ongoing growth of mobile data traffic, in which context should operators deploy offloading solutions and when should they start deploying in order to cope with customer demand?

1.3 Scope of research

The game-theoretic analysis is conducted from a mobile operator's point of view. A holistic view of the communications ecosystem is however needed to take into consideration the influence of other actors like competitors, user, vendors, regulators on the market.

The choice of an adequate offloading solution differs depending on the environment. This thesis focuses only on the dense urban areas where the mobile network congestion is probably going to occur. In these areas the mobile market can be segmented into two parts: business and residential areas respectively corresponding to business and consumer customers.

1.4 Structure of the thesis

The first part of the thesis is an analysis of mobile traffic forecasts. The point is to understand how mobile traffic is going to evolve in the next few years. It takes into account traffic characteristics to see what future stakes on mobile networks will be. Then, in a second part, we define the notion of mobile network offloading and go through the two main solutions studying their advantages and disadvantages. It leads us to a clear assessment of their respective deployment potential. Finally in a third part, we make a game-theoretic analysis of four offloading solutions in order to figure out when each of them should be deployed.

2 Demand evolution

2.1 Mobile data growth

In this part, we will try to understand future stakes for mobile networks through an analysis of usage and demand evolution.

Mobile data growth

Several changes in the mobile devices landscape have considerably impacted the way we use mobile networks. Since 2007, when the first iPhone was released, mobile data has experienced significant growth[4]. Some analysts show that global mobile data traffic growth is comparable to what the whole Internet traffic experienced in the late 1990s. We can see below in Table 1: Global Internet Traffic Growth from 1997 to 2001 and in Table 2: Global Mobile Data Traffic Growth from 2008 to 2012 that the figures for the growth rate are similar and this enables analysts to make some reliable forecasts for coming years.

1997	178%
1998	124%
1999	128%
2000	195%
2001	133%

Table 1: Global Internet Traffic Growth from 1997 to 2001

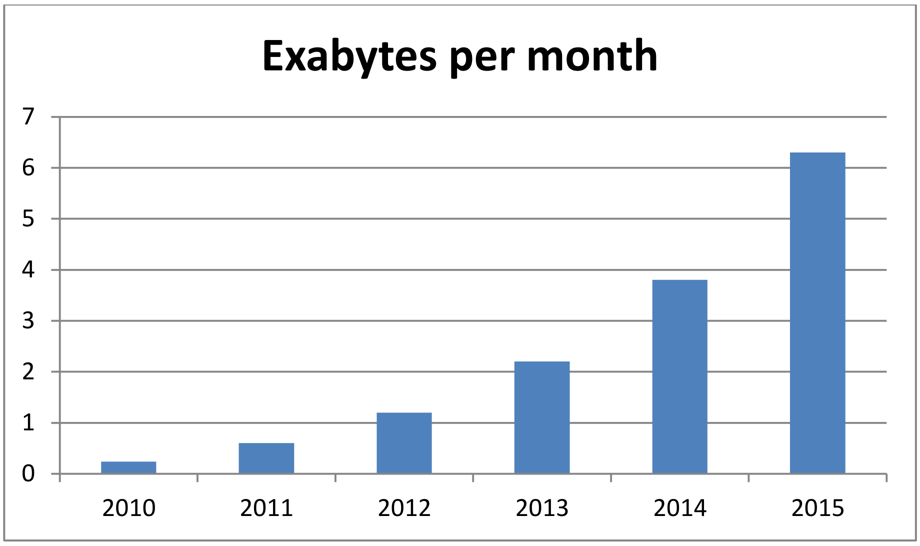
(Source: Cisco VNI Mobile, 2011)

2008	156%
2009	140%
2010	159%
2011 (estimate)	131%
2012 (estimate)	113%

Table 2: Global Mobile Data Traffic Growth from 2008 to 2012

(Source: Cisco VNI Mobile, 2011)

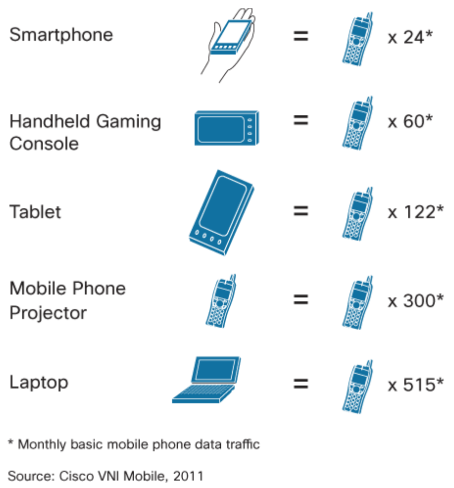
On the graph below, we can see that forecasts expect that Mobile Data Traffic will reach 6.3 Hexabytes by 2015.



Graph 1: Mobile Data Traffic Forecasts until 2015 (Source: Cisco VNI Mobile, 2011)

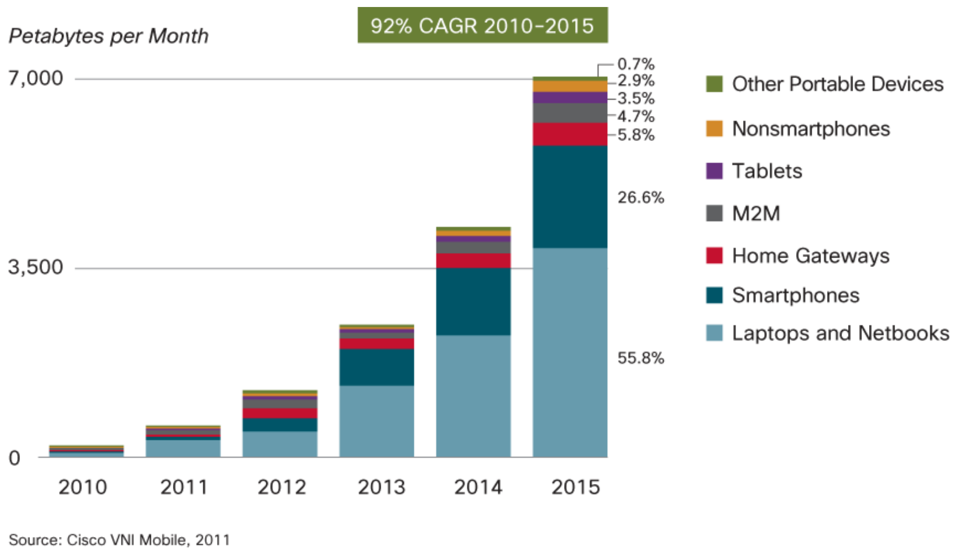
These growth rates show that users have considerably changed the way they use mobile services and they will continue over the next years to move from a fixed use of Internet to a mobile one. Furthermore, new devices and new services will continuously encourage people to consume more and more data with mobile devices. As mentioned earlier, data consumption on mobile networks started when the iPhone and other smartphones were released. These new phones brought to users a smart interface enabling them to easily use plenty of services out of their home. The nature of a device however strongly influences its data consumption. We can mention as an example a tablet like the iPad which has a screen resolution much higher than smart phones thus it consumes much more data in order to get all this additional information from the network.

To illustrate this, you can see below some estimations about data consumption for different kinds of devices.



Graph 2: Data Consumption of Various Wireless Devices compared to Basic Mobile Phone Data Traffic (Source: Cisco VNI Mobile, 2011)

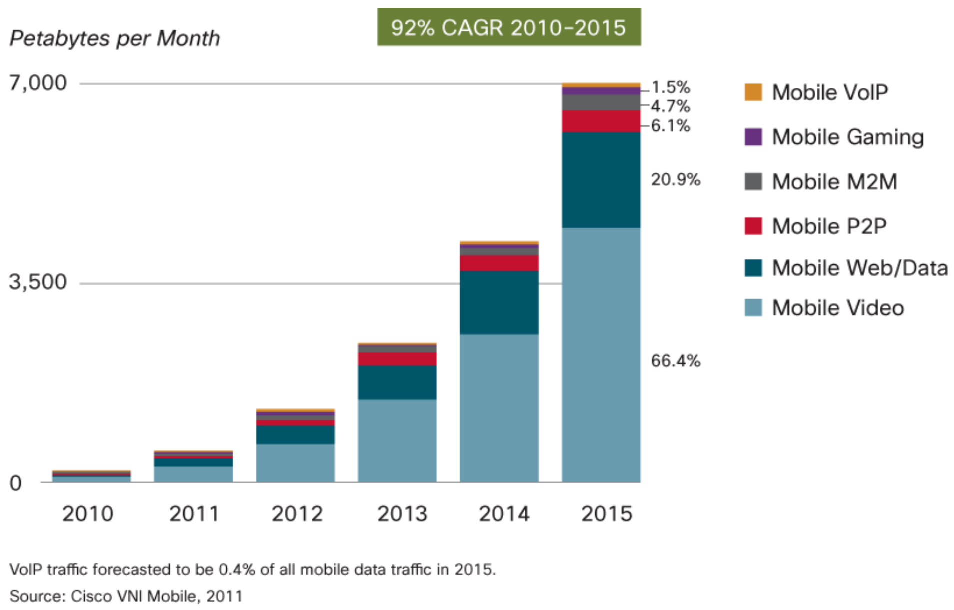
We can see below, how mobile data traffic is distributed amongst devices.



Graph 3: Mobile Data Traffic Distribution over Different Kinds of Devices (Source: Cisco VNI Mobile, 2011)

Another important criterion about data consumption is related to the kind of services concerned by data traffic. Indeed, real-time services require more than a high bit rate, they also require low transmission delays. This is crucial in order to guarantee interactivity for a call, for instance. Thus, it is essential for mobile operators to know how their customers use mobile networks and what their requirements in terms of quality are.

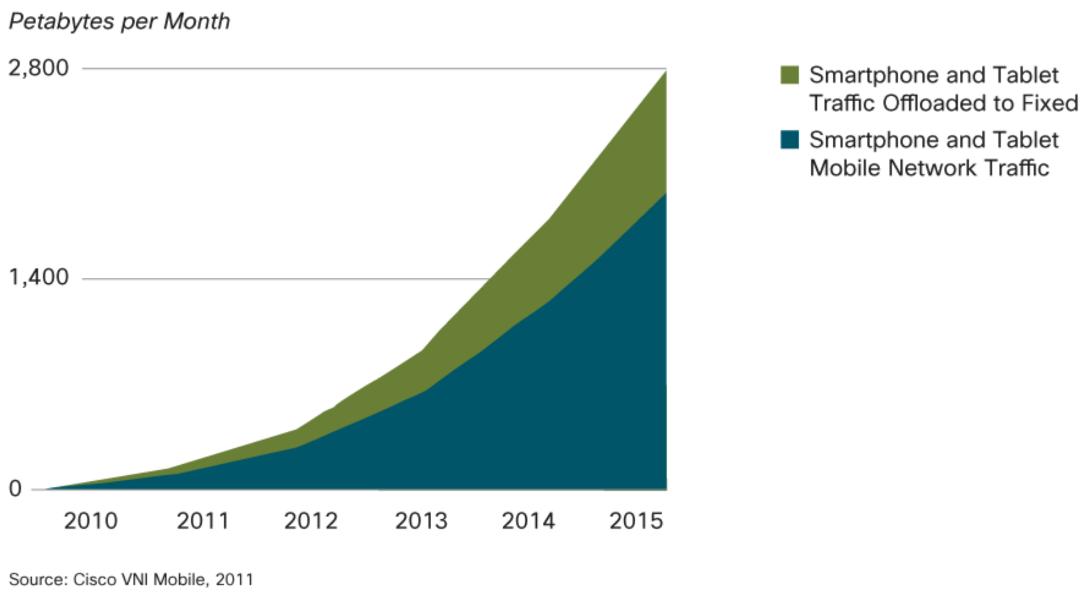
Below is presented a graph with services share and their expected evolutions over next years.



Graph 4: Mobile Traffic Distribution Forecasts by Type of Service (Source: Cisco VNI Mobile, 2011)

Real-time services have strict requirements and they cannot accept congestion. Capacity shortages on mobile networks are then unacceptable. Operators which want to provide such solutions have to take care of this aspect; allowing all services may be a risk and would require future investments in networks or to find alternative solutions.

According to Cisco's report, 39 percent of Smartphone and Tablet traffic will be offloaded by 2015.



Graph 5: Offloaded Traffic Forecasts for Smartphones and Tablets (Source: Cisco VNI Mobile, 2011)

2.2 Indoor/outdoor traffic

A survey conducted by Cisco's Internet Business Solutions Group[4] shows that approximately 40% of mobile data is used by people who are at home and 25% occurs when they are at work. So it means that about 65% of data is consumed by people who are indoors. This figure enables us to understand why it is so important and so efficient to offload mobile traffic which occurs inside buildings.

3 Offloading solutions

3.1 General Aspects

Mobile network offloading definition

“Offloading is the use of complementary network technologies to deliver data originally planned for transmission over cellular networks”[5].

Many mobile operators have started to implement a mobile data offloading strategy. Indeed, as we mentioned in the second chapter, mobile data traffic is expected to grow quickly in the following years. Operators have then to find solution to provide more capacity in urban areas which will be the first to need this capacity. For this, they are trying to find complementary technologies for delivering data originally targeted for outdoor macro-networks. At the same time, they would like to invest as little money as possible since benefits are not going to follow data trends.

The capacity to carry large volumes of traffic over radio waves is the most challenging aspect. It would be possible to increase the capacity for large mobile cells. However, costs, environmental aspects and especially radio interference issues will make this option less attractive. The idea is then to focus on indoor areas introducing small radio nodes to deliver the required capacity. These home nodes are characterized by transferring large volumes of data over a short distance and use fixed networks as backhaul.

Two technologies, WiFi and Femtocell have emerged and look today the most efficient way of offloading mobile traffic. A third technology, WiMax, is also emerging. However, it will not be tackled in this study. In this thesis, we focus on the WiFi offloading technology and femtocells. WiFi is presented with two different technical solutions; a classical mode comparable to how people currently use WiFi at home and the IWLAN architecture. The IWLAN standard proposes an integration of WiFi access networks with mobile operator networks. This approach is integrated with the 3G infrastructure and then enables seamless roaming between the mobile network and the WiFi network. Recent developments in Internet access at home have enabled many homes and apartments to be equipped with WiFi access points. These nodes represent a strong asset that could be easily used to offload traffic at low costs. We will see how to benefit from them. Then, we will describe femtocells which are specific cells for indoor areas. They use the same standards as mobile networks and are, for this reason, fully integrated. Femtocells are for the moment not widely-spread as a solution to increase capacity, they are used more to provide coverage in low density areas. However, they should experience a bright future with the new challenges of mobile networks.

In this thesis, we focus on mobile network offloading from mobile operator perspective. In this context, we will first try to figure out what offloading can bring to both players.

Non-technical offloading solutions

It is important to mention that we study in this thesis several offloading solutions which mainly differ from each other through specificities link to the technology they use. Comparison, analysis and outcomes are thus related to technological considerations.

However, before investing in expensive technical solutions, operators have still other ways to encourage users to change the way they consume data. Marketing is, for instance, an efficient means for operators to orient customers to one or another solution. It is thus easily imaginable to build new offers with block sized pricing or including incentives to convince customers to use WiFi networks operators in public areas. Solutions in this domain are as numerous as marketer ideas and we will not go deeper in this kind of considerations.

3.2 Benefits

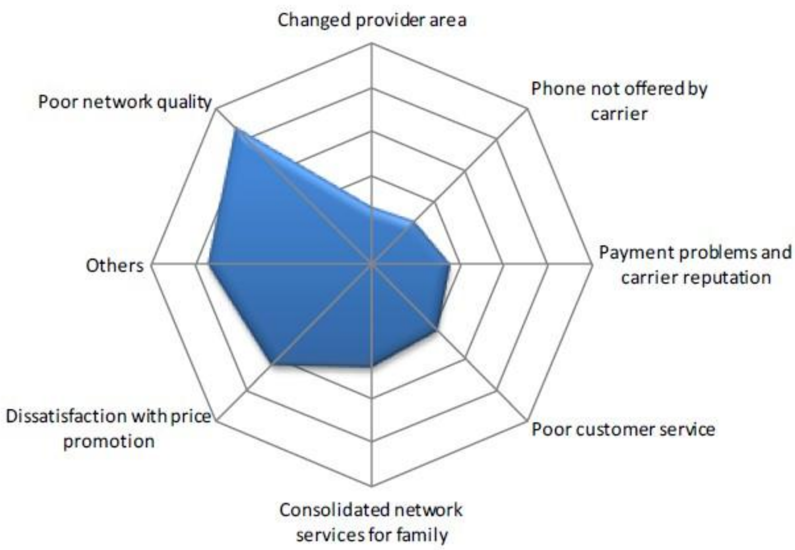
3.2.1 Mobile Operator Benefits

From the operator point of view offloading solutions have several benefits. First of all, they do not require heavy investments. Customers buy themselves devices required to deploy an offloading solution at home. Thus, only core network elements like femtocell gateways are supported by operators. This equipment can be deployed gradually and they do not require important up front investments that operators try to avoid in an unstable economic context like nowadays.

By using these alternative technologies to handle mobile traffic, operators reduce the amount of traffic on their network. It first enables them to save money. Indeed, the conventional macrocell deployment strategy with the installation of more dense cellular sites might solve the technical requirements, however such deployment is not a cost- and energy-efficient solution. It requires large number of base stations which are accompanied by expensive investment and operating costs. Furthermore, offloading by using home nodes implies that users support electricity provisioning of a part of the wireless access part of the network, and thus reduce the operator energy bill. Second it enables operators to avoid congestion troubles; a subject to which they also have to react. Congestion means quality deterioration and then unsatisfied customers. Two possibilities generally occur when customers are unsatisfied either: they consume less or they change their operator (see Graph 6 below). In both cases, it means a loss for the operator which does not take it into consideration but an opportunity for the other ones.

It will also enable operators to increase revenues. First, operators direct a part of the amount of data traffic to another network which is handled by a fixed operator (or ISP). They then move a part of costs out of their network but they may still continue to charge this depending on pricing method and the technology used. Second, fixed Internet access provides better quality of service than mobile broadband access which experiences delay and low bit rate. Operators are then able to provide better services thanks to higher bandwidth to those customers who use an offloading solution; who says better services, says generally more revenues for these services. So it is an opportunity for operators to increase their ARPU.

Finally, operators have to save the reputation of their network by continuing to provide enough capacity and good enough quality of service not to encourage customers to move to an alternative solution and not to encourage new entrants to find new ideas to meet customer demand for wireless services.



Graph 6: Main Reasons explaining churn (customers moving from one operator to another one)

Source: The evolution of Femtocells, Ubiquisys, world economic forum, technology pioneer 2009

This graph shows how far it is important for customers to have a reliable network when they use mobile services. It highlights the fact that operators which do not want to lose customers have to pay specific attention to congestion and the quality of their network in general. As seen above, offloading solutions bring an appropriate answer to this risk.

3.2.2 User Benefits

Offloading solutions use a fixed Internet access to provide mobile services. In fact, a femtocell is connected through the Internet to a gateway, called femto-gateway, which gives it access to the mobile network.

This fixed Internet access is usually more reliable than wireless access and provides better quality and less latency[6]. Thus, WiFi access points and femtocells provide good quality services with all the characteristics of the fixed connection they are linked to. As a result, users benefit from a better user experience.

Furthermore, by providing better coverage indoor, home nodes tend to reduce energy consumption of mobile devices. Indeed, buildings usually reduce signal power and to compensate this loss devices have to send out a more powerful signal and thus consume more energy which means reduced battery life.

Offloading solutions aim to free resources on mobile macro-networks, they should then contribute to improving mobile services quality for users on-the-move.

As a result, if mobile networks remain reliable and the favorite way of consuming wireless services for users, new services should continue to be created leading to competitive prices and attractive service packages.

3.2.3 Summary

Finally, mobile network offloading is a **win-win solution**. And this is the reason why it should not be difficult for operators to promote it. We then have every reason to believe that a bright future is promised for offloading solutions.

3.3 WiFi

3.3.1 General knowledge

The term Wi-Fi means Wireless Fidelity and it is a trademark of the Wi-Fi Alliance which provides the certification. The purpose of Wi-Fi is to connect through a wireless link a personal computer, a smartphone or digital audio player to the Internet. Access points which deliver the signal cover an area corresponding to a few rooms. However, this area can be expanded by using several access points and then reaching the size of a university or a city. Wi-Fi is currently used by 700 million people[7] and 750,000 hotspots are currently installed around the world – a hotspot is a public access point. Although, the first use of Wi-Fi remains a private or home access point. Today, the evolution of smartphones also enables users to turn their device into a Wi-Fi access point. The smartphone has however to be connected to a mobile network through 3G to provide an internet access.

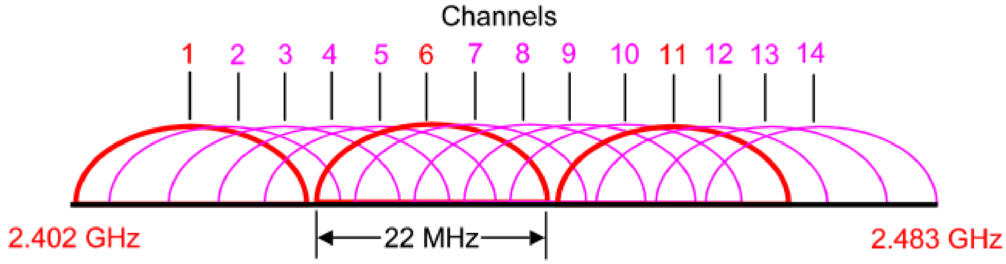
Concerning technological aspects, Wi-Fi builds on iEEE 802.11 standards. This set of standards is used to implement wireless local area networks (WLAN) in the 2.4, 3.6 and 5 GHz.

The two most common 802.11 norms today are 802.11g and 802.11n. In the following paragraphs we are going to give some details about them[8].

802.11g works in the 2.4 Ghz band. It uses an OFDM transmission scheme which was already used in a former norm 820.11b. The maximum physical layer bit rate observed in some specific conditions is about 54 Mbit/s and the average throughput is about 22 Mbit/s. Its spectral positioning exposes 802.11g to interferences from other devices signals which also occur on the 2.4GHz band.

802.11n improves 802.11 standards by using multiple-input multiple-output antennas called MIMO. It can operate on both bands 2.4GHz and 5 Ghz. It provides a significant increase of the bit rate compared to the earlier 802.11g. It grows from 54 Mbit/s to 600 Mbit/s with the use of four spatial streams at a channel width of 40 MHz. This maximum bit rate is reached using 64-QAM coding (Quadrature Amplitude Modulation) but other encodings are also used: n-QAM, QPSK, BPSK.

3.3.2 Spectrum management



Graph 7: Channel Allocation and Channel Overlap

Source: http://www.taurus2.co.uk/g0twn/wlan_diary, G0TWN, Bletchley, Milton Keynes, England.

As we can see on the above graphic, in 802.11 bands are divided into channels. For instance, the 2.4000 – 2.4835 GHz band is split into 13 channels. Each channel has a width of 22MHz whereas the space between each is only 5MHz. Channel is centered on 2.412 GHz and 13 on 2.472GHz. A consequence is that only every fourth or fifth channel can be used without overlap.

3.3.3 Advantages & Limitations

The first advantage of WiFi is to permit an easy deployment of Local Area Networks without wires. The effect is to reduce deployment costs and time.

WiFi uses the 2.4 GHz band in which it occupies 5 channels. No overlapping is observed when two channels use channel numbers which differ by five or more. The last norm 802.11n which is also the fastest one needs double the radio spectrum compared to former norms like 802.11a or 802.11g. The expected next norm of WiFi is 802.11ac and it will make all the other norms unusable if used on the same band. That is why the best solution would be to find another band and to allocate for instance UHF TV white space to this new Wi-Fi norm.

3.3.4 Security

Several encryptions are used to prevent unauthorized access to a WiFi network. The most used one was WEP but its widespread use tends to diminish since it has been proved that even if it is well-configured the code remains easily breakable. Other solutions are now provided and secure like WiFi Protected Access encryption (WPA and WPA2).

Concerning open WiFi networks, they usually do not benefit from any protection which means that all the traffic from connected devices is visible to anyone located in the given area. However, other ways exist to secure traffic and to avoid spreading personal data, like VPN or secure HyperTtext Tansfer Protocol (HTTPs) over Transport Layer Security (TLS).

In an area where the number of access points is really high, "WiFi pollution" might be observed. The consequences are interference between signals which is caused by overlapping in the 802.11b/g spectrum. This situation might appear in high-population areas like offices, conference halls or shared buildings. However, it is important to know that other equipment is present in the 2.4GHz band like cordless phones, microwave ovens, security cameras, etc.

3.4 Femtocells

3.4.1 General knowledge

Definition**: "Femtocells are low-power wireless access points that operate in a licensed spectrum to connect standard mobile devices to a mobile operator's network using residential DSL or cable broadband connections."** [9]

Femtocells are used in home or company buildings and they can support between 2 and 4 active mobile phones for domestic use and up to 16 for business users.

Femtocell characteristics. Not all of them will be useful for the next moment but it is important to keep them in mind.

- Low-power access points
- Using mobile technology
- In licensed spectrum
- Generating coverage and capacity
- Over internet-grade backhaul
- At low prices
- With full operator management
- Self-organizing / self-managing

A femtocell is a small device that mobile customers can buy from their operator. It is a small antenna which uses operator-licensed spectrum and is connected to the mobile network through a secured link over the Internet. A femtocell works from the customer point of view like a normal cell. It provides all the mobile services such as voice call, sms, mms. Mobile phones manage the handover between outdoor macrocells and femtocells.

3.4.2 Access management

As mentioned before, femtocells use as backhaul a private link, commonly a DSL link associated to a DSL subscription. This makes a femtocell a privileged access to a mobile network and offers guarantees in terms of capacity and coverage. In order to manage access rights, some solutions to restrict access have been implemented.

Amongst the range of restricted access, we can find three main families[10]:

- OSG which means Open Subscriber Group. In this situation, femtocell access is open to any customers of the femtocell provider (the mobile operator) which might be reached by the femtocell signal.

  This access management causes some issues linked to the fact that a personal DSL access may be disturbed by high data consumption of neighboring handsets. It may create some trouble with the DSL subscriber unless the femtocell provider is able to offer some discounts to share DSL access price.

  However, in terms of mobile offloading, this solution is the most efficient because a significant number of mobile users may be able to connect to femtocell inside buildings in case of an advanced femtocell deployment.

- CSG which means Close Subscriber Group. In this situation, only authorized handsets are able to connect to the femtocell. It is the most common access restriction. Indeed, in this case, femtocell is seen as a customer solution, it simply enables a subscriber to increase capacity and coverage in his/her private area.

  In terms of traffic offloading, CSG access restriction remains poor because only users who are at home can use it.

In the existing solutions, like the one provided by SFR in France, we can see that authorized handsets have to be declared to the mobile operator to get access rights. Indeed, even if a femtocell is deployed in a private area it still belongs to the spectrum owner; the mobile operator. (for more detail, see regulation part)

- Finally, it exists a last group of access restriction called Hybrid. This solution is a mix of the two previous ones. Indeed, in this case, all the customers of the femtocell provider can connect to the femtocell but only if none of the authorized handsets want to use it. It is a way to guarantee femtocell benefits to the DSL subscribers and also enables the mobile operator to offload traffic when the femtocell is not in use.

3.4.3 Interference management

One of the most important points in femtocell deployment is interference management. Indeed, when a mobile operator deploys a macro network it is concerned by the way frequencies are distributed and managed between different antennas to avoid interference. This interference is particularly disturbing because it entails a drop in both coverage and capacity and thus may represent wasted money wasting in the case of bad deployment planning.

By adding femtocells in its mobile network an operator may create interference[11]. This interference is due to the fact that a femtocell operates in the same spectrum band as macro cells. The stake for the operator is to take advantage of femtocells and not create a disadvantage by reducing the quality of the existing outdoor network.

In this part, some potential radio frequency (RF) interference issues related to femtocells deployment are presented.

- Desensitized Femtocell or Handset: Spectrum allocation allows an operator to use a given frequency band in its network. As a result handsets and base stations are calibrated to operate in a given dynamic range. However, it might happen that femtocells and handsets are close to each other. This creates high signal levels beyond the sensitivity range of the receiver[12]. The consequences are different for download link (DL) or upload link (UL) and that is why we distinguish the two situations. On the DL the handset receiver can be saturated and thus degrade demodulation performance. On the UL, a high noise (RoT) can be observed at the femtocell and this can make the system unstable.

- Interference between macro- and femtocells: Femtocells are deployed inside buildings and in this specific area they might interfere with the outdoor signal which goes through natural barriers such as walls and glass. In this case, femtocells may create interference on both DL and UL links. For instance, under certain conditions like a femtocell installed near a window, interference may be created outside and thus damage outdoor signals for users who are not served by the femtocell. On the UL the home handsets served by the femtocell can cause significant interference to the handsets served by the macro network.

- Interference between femtocells may also happen due to unplanned deployment. For instance, in a building with many apartments femtocells installed near a wall common to two apartments can cause significant interference to other apartments. In such a case, the femtocell which has the highest RF signal strength may not necessarily be the serving femtocell due to restricted access as explained earlier.

In order to avoid these issues in femtocells deployment, several solutions have been created. One of them is presented below to explain the principle:

- Femtocell DL Tx Power Selft Calibration

To avoid a femtocell creating coverage holes outside, a solution is to adjust signal power between the femtocell and the macro cell. The above mentioned cell uses an autonomous self-calibration. It means that femtocells make DL measurements from macrocells and other femtocells to calculate the required transmission power level.

3.4.4 Mobility

Femtocells have to stay transparent* to users; handsets have to be able to connect to them as they do with macrocells. However, femtocells have a limited coverage which implies that handsets will have to manage frequent transitions between femtocells and the macro network. As for classical handover, these transitions imply signaling procedure. This procedure may differ depending on the handset state; idle or active call.

In the idle state, the handset needs to register when it moves into and out of a femtocell to enable efficient paging. Frequent registrations have bad effects on the handset battery which tends to be drained by signaling procedures. This phenomenon can occur in an area where the density of femtocells is high; a handset would then almost continuously go from one femtocell to the next one.

In the active state, the challenge is here to identify the target femtocell. For classical handover from a source macrocell to a target macrocell, the target cell is identified by a unique combination of the pilot and the identity of the source macrocell. However the number of possible pilot sequences is limited and each femtocell will not be one unique sequence. As a result, the pilot transmitted by a femtocell is no longer unique.

*it means that femtocells have to run autonomously without user intervention.

3.4.5 Market offers

The first commercial deployment took place in the US in 2007 and gradually more and more operators have started to offer femtocell to their customers. For instance, SFR in France has launched a domestic femtocell called SFR Home 3G in 2009[13]. In all these cases, femtocell is however only seen as a customer solution which enables increased coverage and capacity in an apartment or a part of a house.

Today, as , femtocells are seen as a customer solutions but future stakes linked to mobile network offloading will turn them into an operator solution to continue to provide capacity and coverage customers ask for. In that scenario, we can already foresee some future challenges and future evolution for femtocells. Here are two of them.

Roaming support: In order to extend femtocells usefulness in an offloading way subscriber from another operator than the femtocell provider could be allowed to connect his/her handset. This evolution of femtocell use works in the three above mentioned modes OSG, CSG and Hybrid. The trickiest challenge linked to roaming support is to access the correct HLR and all the required information about users as well as updating them.

Temporary membership: This kind of restricted access could be implemented for some specific situation like in a hostel or for a conference. A handset would be allowed to access a femtocell during a given amount of time in a closed subscriber group mode.

3.4.6 Regulation

Regulatory benefits of femtocells

- Femtocells can help operators to meet regulator objectives in terms of coverage and capacity. It enables them to offer a good quality of service inside buildings and notably at home for consumer customers.

- Femtocells enable operators to provide coverage in hard-to-reach indoor environments instead of deploying large numbers of outdoor base stations.

- They enable operators to provide full services in rural area and satisfactory coverage in indoor area. Services which would be expensive for operators to provide on a large scale by outdoor means. Thus they enable remote areas or communities to get a chance to be as fully connected as an urban city may be.

- They can use empty spaces in the spectrum by scanning local signals and then choosing by themselves their band (within the operator spectrum). They can also use higher frequencies which might be limited for wide-area coverage. In the meantime, they can also operate in lower frequencies bands and thus reduce their transmitting power which can bring significant energy savings.

- They increase the value of services. Indeed, by providing good coverage and capacity they enable consumers to consume more services and they also increase the range of customers reachable for providers. Thus they increase the network value.

If we extend this idea, a more valuable network will attract more competitors which will result in more competition and then fair prices for customers, innovations and good quality services.

Regulatory issues associated with femtocells[14]

- Femtocells are an extension of a macro network. A certain number of rules have already been settled in order to guarantee good regulation for mobile services. This is the reason why femtocells which use the operator licensed spectrum do not require many additional rules. They mainly have to respect existing rules concerning network deployment.

- An important aspect of femtocell management is that a femtocell as a device using a licensed spectrum stays fully controlled by the operator. This is not the case for WiFi which is considered by regulators as belonging to the user and then each user can decide to manage access rights for instance by him/herself.

- Concerning human health, femtocells operate at low transmission powers (less than standard LAN access points). A non-negligible advantage of femtocell on this point is that it enables user devices to operate at low power and thus increase battery life.

- Concerning security aspects, it is important to know that femtocells are able to send their location to network controllers. Indeed, many different means can be used to identify a femtocell location: IP address of the DSL or cable modem, GPS, surrounding network cells.

Concerning configuration, a femtocell does not require anything from users, a self-configuration which operates through the Internet runs the admission process for each femtocell. During this process, the femtocell and the network authenticate mutually and securely. Then the femtocell becomes a trusted part of the mobile network, capable of reporting any troubles or hacking attempts.

3.4.7 Challenges

Some challenges are associated with femtocell deployment. The challenges are due to four factors of a femtocell.

- A femtocell is installed by a subscriber who does not have special training or knowledge regarding antenna placement and system configuration.

- Femtocell deployment is considered as random by operators. Indeed unlike a macro network, femtocells are deployed by customers without planning. It depends on customers who may decide to adopt this solution or not to increase capacity and coverage in their area. So no special consideration is given to traffic demand or interference with other cells as it would be for macro deployment.

- A femtocell uses a DSL connection or comparable technologies as a backhaul network. This link between the Internet and the private area is leased to a customer by his/her operator. As a consequence, not everyone can use a femtocell and access needs to be restricted. Usually only a few people linked to the subscriber of an Internet access lease are authorized (e.g. family members, hotel guests, employees).

- Owing to the diversity of mobile handsets available on the market, a femtocell has to be able to manage two kinds of devices: those which are femto-aware and those who are femto-unaware and represent the trickiest part. The role of a femtocell is to enable all of them to use existing access and core networks.

3.5 Deployment schemes for mobile network offloading

3.5.1 Offloading using WiFi

Two solutions using WiFi as an offloading means are used nowadays[15].

- A wireless device can be connected thanks to its wireless interface to a local WiFi network. Most of the time, this type of wireless access is chosen for laptops in public and private places. This WiFi network enables any device equipped with a WiFi interface to access the Internet. However in this basic configuration other services like voice or SMS remain on the mobile network. Usually, connecting a smart phone to these local WiFi networks require an authentication which is managed by the user.

- An improved configuration for mobile devices has been created. In this case, a mobile device can seamlessly roam between WiFi and mobile networks. WiFi is used for providing all mobile services to the phone. It means that voice and sms also go through the WiFi connection. A tunnel is actually created through the WiFi network between the phone and a gateway reachable over the Internet and operated by the mobile operator. Thanks to this gateway a mobile device can reach the mobile network without exchanging with the macro network. We will give some technical details about this solution in the following paragraph.

Technical aspects related to WiFi evolutions

Some evolutions have been developed for WiFi, notably to make it easier to use with all kinds of devices and for all kinds of services. As mentioned earlier, the most interesting advantage of WiFi is its ubiquitousness in indoor areas. Indeed, with the development of fixed Internet access at home and multiple-play solutions, fixed operators have provided their customers with WiFi access points and today a number of households in developed countries have their own WiFi network.

Operators see this existing network of WiFi access points as an opportunity[16] to use it as a second network and thus decrease the traffic which goes through the mobile network. In order to pursue this goal some solutions have been created. The most famous are UMA (Unlicensed Mobile Access) and IWLAN (Interworking-wireless LAN); IWLAN is in fact the evolution of UMA. The main purpose of each of these technologies is to provide mobile services through a WiFi network.

This specific choice of operators to deliver mobile services over wire line is generally called FMC for fixed-mobile convergence.

The 3GPP defines two FMC architectures regarding GSM networks[17]:

UMA (Unlicensed mobile access) – uses GSM signaling for voice services over the circuit-switched radio access network GERAN (GSM EDGE Radio Access Network) as well as the IP WiFi access network.

IWLAN (Inter-networking LAN) – uses GSM signaling for voice services over circuit-switched UTRAN (UMTS Terrestrial Radio Access Network) access but SIP signaling for voice services over WiFi access.

These technologies make use of fixed network backhaul since they use a fixed Internet access. However, we will here focus on IWLAN which is future-oriented compared to UMA which is now tending to disappear after several trials.

It is important to know that both UMA and IWLAN require a new network function: a security gateway that authenticates devices and terminates secured tunnels from the handsets when they are on a WiFi network.

IWLAN requires SIP and core IMS equipment investments and depends on a network function – the voice continuity server to enable roaming from and to WiFi and GSM access networks. We will now go through the technical considerations of IWLAN.

Remark: Another FMC architecture exists but is not tackled here: Access Network Discovery and Selection Function (ANDSF)

Architecture overview

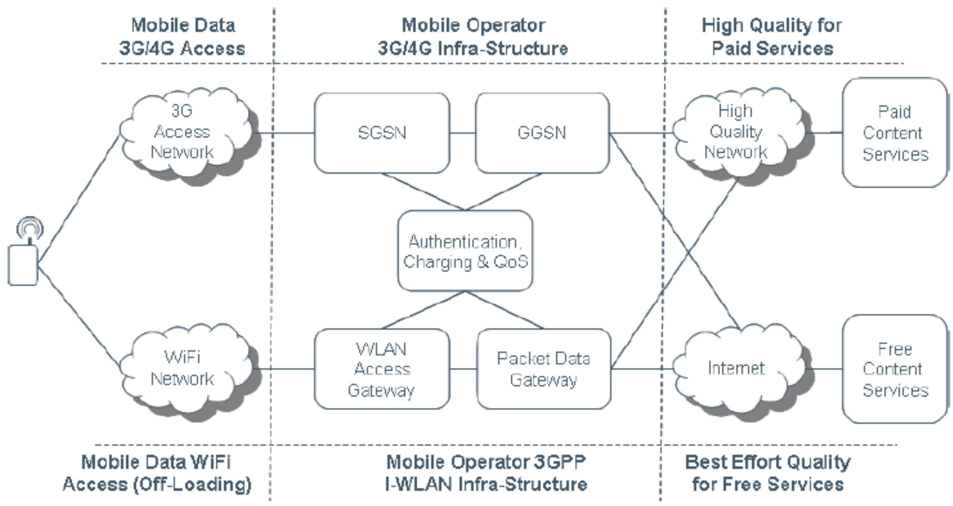
In IWLAN, a dual-mode device, which supports both SIP and GSM signaling, access to the UTRAN or WiFi network depends on the radio signal strength. Both voice and data services are delivered through the same access network (mobile network or WiFi network).

When services are delivered through the UTRAN, voice is circuit-switched and it uses traditional MSCs. Data services are delivered via the IP portion of the UTRAN and are served by the existing SGSNs (Serving GPRS Support Node) and GGSNs (Gateway GPRS Support Node)

When services are delivered via WiFi network, all voice and data services are encapsulated in an IPsec tunnel and go through a fixed Internet access such as a DSL line. IP data services and IP address management are controlled by the SGSN and GGSN. A VCC application server enables handover and roaming between the circuit-switched GSM voice and the IP-based SIP voice. The new function which is defined in IWLAN is the TTG (Tunnel Termination Gateway). The TTG authenticates devices via AAA queries, decrypts sessions from mobile handsets, allocates IP addresses and protects the layer 3 and key exchange infrastructure from denial-of-service attacks.

The following figure provides a simplified view of networks and nodes that play key roles in handling mobile data traffic using traditional 3G communication and the WiFi access network to off-load traffic from the 3G access network.

In addition to network equipment, mobile devices have to be configured and some software added in order to be able to initiate secured sessions and to communicate with the specific equipment.



Graph 8: 3GPP I-WLAN architecture

Source: Mobile Data Traffic & Wifi Offloading

We can see two key elements in the illustration: the WLAN Access Gateway and the Packet Gateway. We describe below the role of this equipment.

➔ WLAN Access Gateway

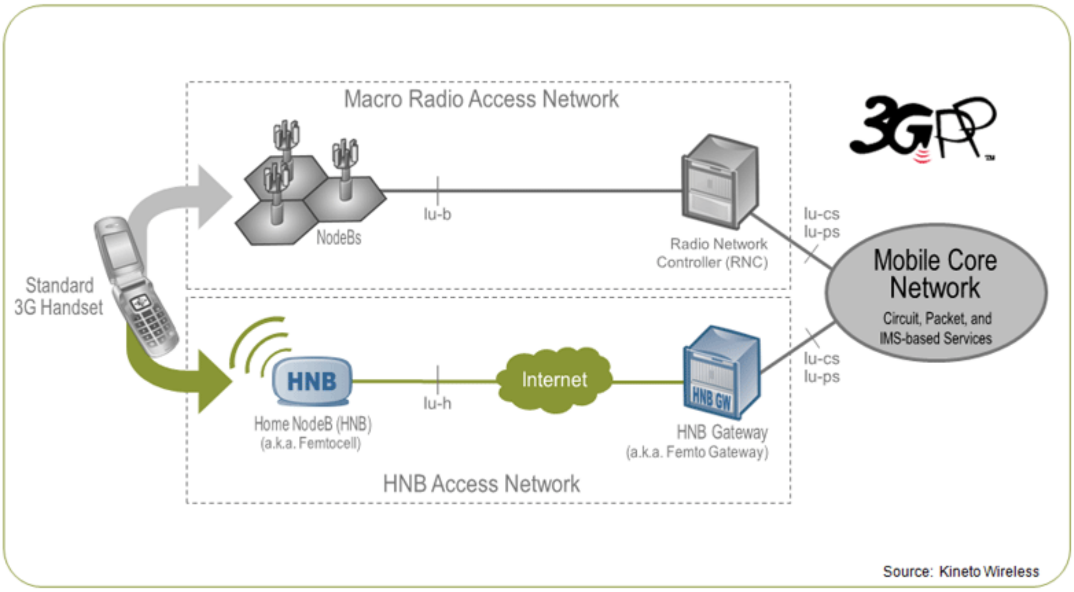
The WLAN Access Gateway is responsible for routing the data to/from the WLAN Access Network and the Packet Data Gateway. It is the first node that exchanges with the WiFi network. The most important functions of the Access Gateway are presented here.

- Supports QoS mechanism
- Discards data packets that will not be forwarded to the PDG.

➔ Packet Data Gateway (PDG)

- Responsible for the authentication of a mobile device.
- Resolves and assigns an IP address for the mobile device.
- Maintains routing information for the mobile device.
- Generates charging information related to the user data traffic.
- Applies QoS mechanisms
- Routes traffic to/from packet data networks.

3.5.2 Offloading using femtocells



Graph 9: Femtocell Network Architecture - Source: Kineto Wireless.

On this picture, we can see how a femtocell is linked to the mobile core network. Typically, a femtocell is installed in a private place and connected to the Internet through a basic DSL or cable Internet access. The femtocell creates a secured tunnel (IPsec, VPN) between the femtocell and the Femto Gateway in order to guarantee user's privacy[18]. This process is triggered when a femtocell is connected for the first time. An authentication is initiated by the femtocell to the femto gateway.

A femtocell is connected to the Internet through an internet access link. Depending on the country and the area, this link may be a DSL link, an optical fiber link or a cable link. Once connected to the Internet, a femtocell is able to reach a gateway called femto-GW which enables femtocell traffic to reach a mobile network. See above.

Some issues are related to the fixed network: Lack of security, Lack of QoS (Quality of Service) and Limited bandwidth. In the following paragraphs we will present key elements of each of these topics.

Lack of Security

Femtocells and femtocell gateways communicate over the Internet which means an infrastructure shared by many actors contrary to operator-controlled network. As a result, any communication between femtocells and gateways must be secured in order to guarantee confidentiality and integrity. IPsec and VPN are usually used for this purpose.

Quality of Service

Femtocell traffic like all the Internet traffic may experience some troubles: packet loss delay and jitter. These inconveniences can vary and depend on network, location and time. They affect notably real-time communication like voice calls. In order to address these issues, femtocells and femtocell gateways may use Differentiated Services Code Point (DSCP). This differentiation in service categories appears in packet headers, and routers on the Internet are able to allocate required priority in order to offer an acceptable quality of service.

Limited bandwidth

Knowing that the most used internet access technology is DSL link and the fact that bit rates can greatly vary with this type of Internet access it is predictable that in some cases additional traffic from a femtocell could not be handled. As a result, it is important for mobile operators not to provide femtocells to all customers and to create some guidelines about their Internet access to be sure to be able to provide adequate service over a femtocell.

For instance, for some people who live in a rural area with a bad coverage, installing a femtocell may not be a solution because their Internet access might not be insufficient to provide minimal requirements.

3.6 Comparison

In this part, we will quickly go through the advantages and drawbacks of each technology, femtocell and WiFi. The point is to find key parameters and confront them with real life situations in order to provide an answer to “which offloading should be deployed where?”

3.6.1 Femtocell use

Femtocell remains today a brand-new device: only a few operators in the world have decided to offer them to their customers. Purchase price is still quite high and many users do not see the benefits. Indeed, in urban areas, where most people live, coverage and capacity are sufficient for users’ needs. This situation should change in the future with more people using smartphones. At this point, femtocell benefits will be clearer and users will probably be more interested in acquiring a femtocell.

- **Femtocell advantages**

Femtocell has one strong asset: it uses the same technology as macro cells. It enables all mobile devices using mobile technologies to connect to a femtocell. Of course, some limitations inherent to mobile technologies exist, like the fact that mobile devices and femtocell have to use the same license spectrum and they have to respect the same standards (which might require some adpatations depending on the region).

To sum up, no additional software is required on mobile devices. As long as they are able to connect to the macro network they will be able to use femtocell to provide mobile services.

- **Femtocell drawbacks**

Even if femtocell is a practical technology, it has some drawbacks. The first of those is the fact that femtocells are not provided by all operators, they are still expensive thus existing infrastructure is poor.
Furthermore, femtocells use the same licensed spectrum as outdoor macro cells. They might create interference and thus decrease capacity and coverage.
On the operator side, in order to manage femtocells operators have to invest in access point management systems which are expensive. The femto gateway is a part of this system.

3.6.2 WiFi use

Mobile devices users are familiar with WiFi. This technology has however both advantages and drawbacks. We go through them here in order to understand WiFi potential as an offloading solution for mobile networks.

- **WiFi advantages**

The first advantage of WiFi is its maturity and the fact that users are familiar with the technology, and already use it at home for many of them. In urban areas, existing WiFi infrastructure is widely spread; access points exist basically everywhere.
Concerning spectrum, WiFi uses an unlicensed spectrum which guarantees that it does not interfere with the macro network. Even if unlicensed spectrum are disturbed by other devices or machines which use the same frequency band, that is not really harmful since in our case, if WiFi is deficient the macro network is still usable (offloading is an additional solution not a primary one).
WiFi products are also inexpensive and they equip most wireless devices today.

- **WiFi drawbacks**

As we have seen in the WiFi part previously, technologies like IWLAN require implementing additional software on mobile devices. It remains rare today and many efforts should be made in this area if we would like to use it massively to offload mobile networks.
This software requires investment and then costs for operators and vendors.
WiFi has another drawback which is to add an additional wireless interface. It may have some bad effects on batteries.

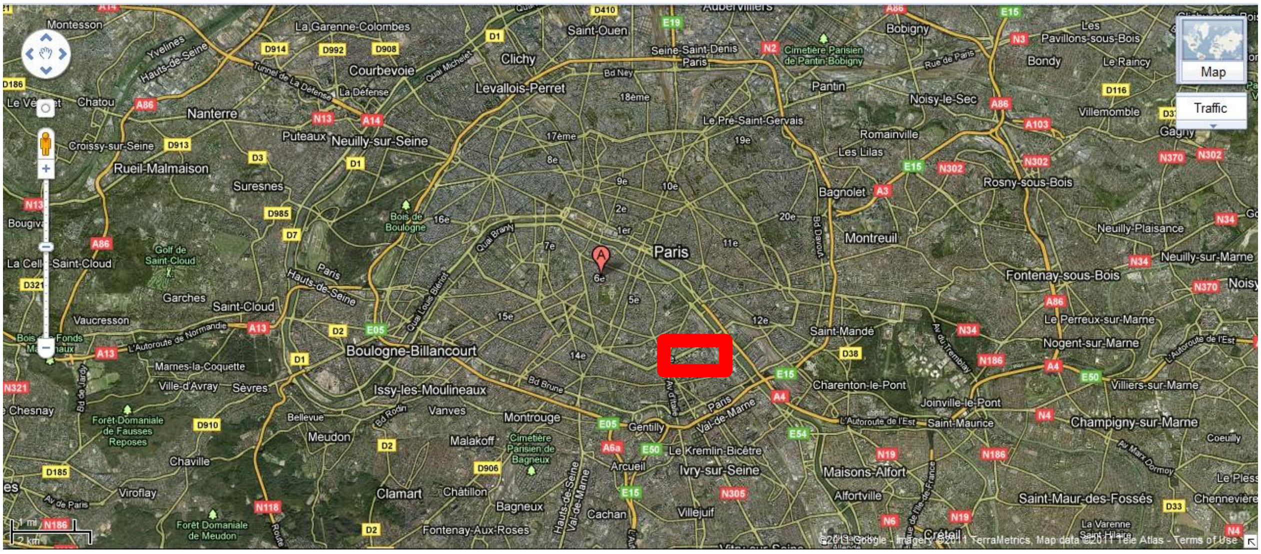
3.6.3 Summary

After this analysis, we have a better understanding of these two offloading solutions. We can then realize that they are not exactly the same, they do not meet the same requirements. Furthermore, depending on the local context, these advantages and drawbacks might change. Through the following example, we present a deployment strategy which takes into consideration femtocell and WiFi characteristics to understand what could be a relevant deployment scheme.

Selected operator: SFR (French fixed operator)[19]

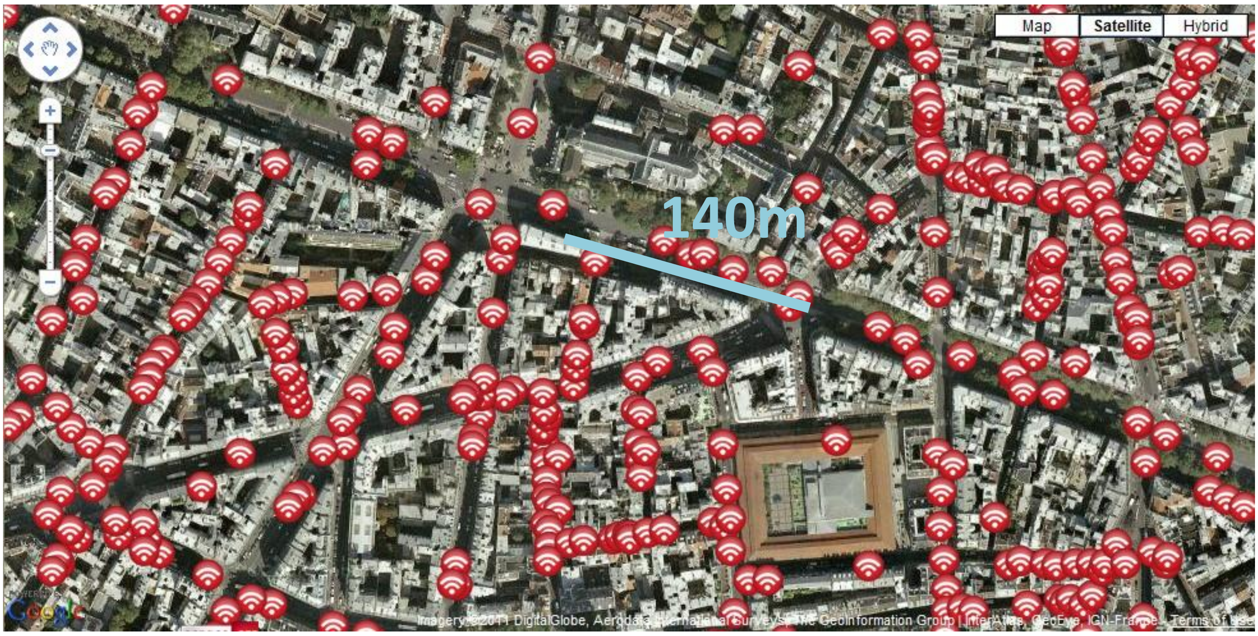
- Mobile operator and ISP.
- Second biggest ISP in France, 4,952 million customers (23,61 %).
- 3 million hot-spots through customers' boxes, shops, public areas.

The first point we have mentioned for WiFi is a strong existing infrastructure. The picture below shows this. Indeed, we realize here that in a dense area of Paris, SFR WiFi access points are ubiquitous.



Graph 10: Map of Paris – Chosen Residential Area in Red

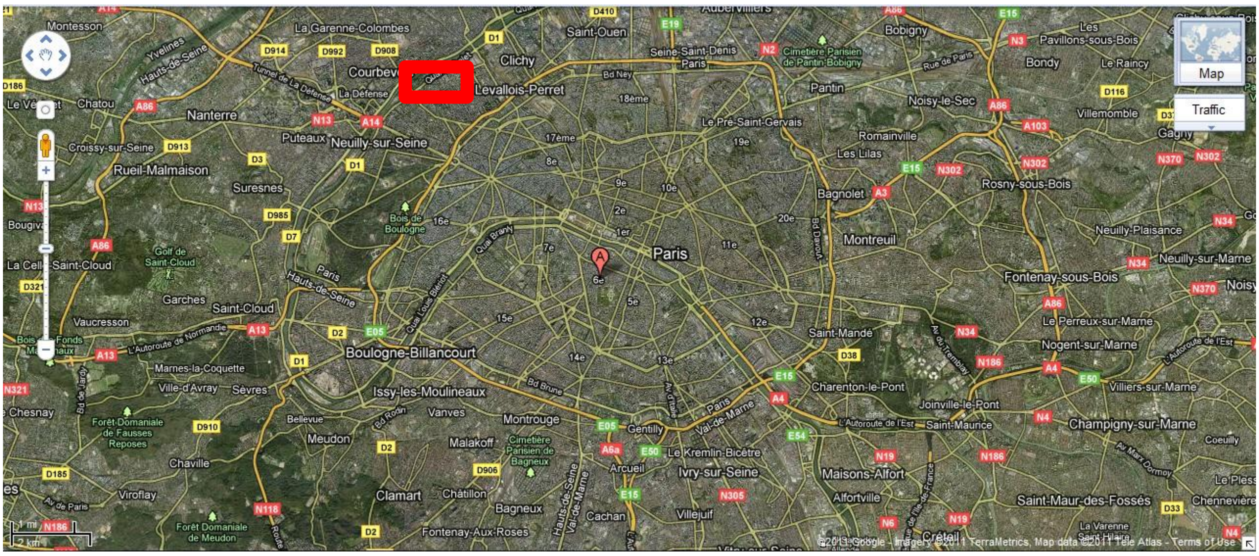
Source: Google Maps



Graph 11: SFR WiFi Access Points in a Residential Area of Paris

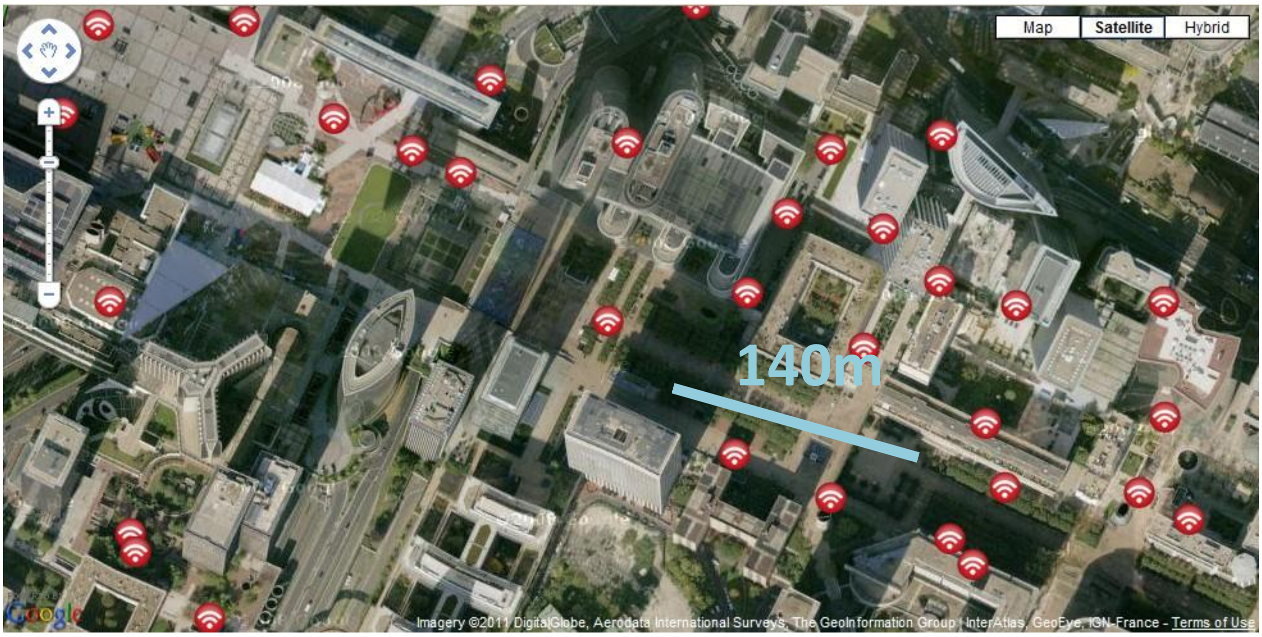
Source: www.sfrwifi.com

In business areas, the situation is however different



Graph 12: Map of Paris - Chosen Business Area in Red

Source: Google Maps



Graph 13: SFR WiFi Access Points in a Business Area of Paris

Source: www.sfrwifi.com

However, we cannot consider that all WiFi access points in business areas belong to SFR. Companies may have their own access points. But some studies show that companies prefer not to use WiFi for security reasons[20]. So even if a bit more WiFi access points than shown here can be found in real life, they are still much less numerous in business areas.

So, we can conclude that existing WiFi infrastructure is stronger in residential areas than in business areas. WiFi loses then its main advantage in business areas. Furthermore, the fact that companies do not really trust WiFi technology for security reasons may represent a non-negligible drawback for operators who would like to promote it to their business customers in order to provide offloading solutions.

Otherwise, femtocells are able to provide as much safety as classical mobile networks, which makes a strong argument for this technology in business areas. Furthermore, for business customers, operators are generally in charge of maintenance and then would be allowed to manage themselves both femtocells and potential interferences even inside buildings. Finally, thanks to the previous example, we have realized that existing infrastructure is weak in offices.

We can then consider that WiFi will probably be chosen for residential area thanks to its ubiquitous presence, low prices, no quality of service requirements,… and on the other hand, femtocells will probably be preferred for business customers who ask for more guarantees and security. They are also more likely to spend more money for services than consumer customers.

The last argument which sustains this deployment scheme is that femtocells restricted access management is not the same for business customers and consumer customers. Indeed, even if it changes in the future, currently femtocells use Open Subscriber Group method for business customers and Closed Subscriber Group for consumer customers. This makes them even more useful in order to offload mobile networks in business areas.

4 Game theory

4.1 General information

A definition commonly accepted for game theory is: “A discipline aimed at modeling situations in which decision makers have to take specific actions that have mutual, possibly conflicting consequences”[21].

The purpose is to model strategic situations where the success of a player depends on his choices but also on competitor choices. In this context, decision outcomes take into account the effects of interaction between different actors.

Interactions between two players are made of cooperation or competition. In this study, we will consider a non-cooperative game; cooperation is then not allowed. We however detail more this choice in 4.2.1. Players then compete to maximize their own benefit without any agreement between them.

The purpose of the following game is to determine when it becomes profitable for an operator to start deploying offloading solutions. It includes financial and strategic aspects. In the game, we use two main parameters: costs and benefits. They represent respectively what a player may lose or gain by deciding to adopt one strategy or another. Player strategies are either deploying or not deploying and each offloading solution is studied independently. Each year, players then decide to deploy or not. The game–theoretic analysis by combining own-decision and other players outcomes provide an answer which takes into account competition effects. By repeating this analysis with every technology, it becomes possible to figure out what is the right time to start deploying each offloading solution.

As we will base our game on forecasts, we have chosen to use qualitative parameters to calculate payoffs.

4.2 Context of the game

In this game, we will consider a situation with two mobile operators who do not provide fixed services and who do not own a fixed network. Their activities are then only linked to mobile services through their mobile network. However, it is important to understand the fact that even if an operator is present on both mobile services and fixed ones, these two parts are easily separable since usually operators do not consider them together in their organization. So, by this assumption, we do not narrow the game to some specific cases but we keep it general.

Some parameters are linked to local environment. Mobile network offloading will occur in areas where mobile operators experience congestion troubles. It concerns dense urban areas. In these areas, mobile networks are considered reliable and use the newest mobile technologies. As a consequence, no lack of coverage is observed and offloading solutions are then considered as capacity increasing solutions and not coverage increasing solutions.

Concerning WiFi access points, we consider that these are widely spread. It means that an important part of households have their own WiFi access points at home usually through a box provided by their internet service provider. At the same time, mobile operators also have their own WiFi access points in public areas like railway station or famous places. Other actors may also provide free WiFi, like bars and restaurants.

Concerning the timeline, the game takes place over five years. It has been chosen to not exceed five years, given the fact that forecasts for more than five years are not reliable. Furthermore, five years gives already a wide view for deployment projects. Years are numbered from 1 to 5; year 1 corresponding to the middle of 2011.

4.2.1 Characteristics of the game

The game which is going to be presented later is non-cooperative and simultaneous.

A non-cooperative game is a game where players are not able or allowed to form binding commitments. Non-cooperative games are commonly able to model situations and produce accurate results.

A simultaneous game is a game where players move or make a decision simultaneously or in an equivalent way the later players are not aware of the earlier player actions.

Concerning the market, we consider churn effects (when customers move from one operator to another one) only between competitors. Furthermore, we have not taken into account the impact on general price levels in the total market. Demand is supposed to grow depending on user needs and usages.

We have made the choice to keep the game static, which means that only one decision is made at the beginning of each year, since the time period which has been chosen is one year.

a. COSTS

Costs are divided into three types: Marketing and Sales, Network Upgrades, Operation and Maintenance.

➔ *Marketing and Sales*

Marketing costs: when an operator decides to encourage users to adopt a technology or a service, it uses some sales campaigns or incentives. It is particularly the case when they practice bundling (operator offers the device and users pay it back in their monthly payment) or subsidizing (more costly and aggressive incentives). Operators have also the power to teach customers how to use their telecom equipment. They can make campaigns to influence their customers through advertisements documentation or demonstration. These initiatives cost money to the operators. Their purpose is however to enable more users to access more easily to mobile services.

Concerning devices, we will talk about different types of them. In this study, they can be smartphones, tablets and laptops. Laptops may be originally equipped with a 3G wireless interface or added thanks to a USB stick antenna. When we talk about bundling, it may concern all of them.

Otherwise, bundling and subsidies can also be provided on Femtocells or WiFi access points: later, in the game, we will consider a specific case for subsidized femtocells. Comparable things can be done with WiFi, by providing home access points (not internet access).

To go further operators can also bundle a mobile subscription with a fixed internet access, this kind of offer is called multiple play. In our case, it requires an agreement between mobile operator and fixed operator. However, it may encourage users to use WiFi at home with their wireless devices and then offload mobile traffic.

➔ *Network Upgrades*

Upgrades and implementation costs are linked to additional network deployment or upgrades. It may represent gateways, servers or network deployment. In this section, we talk about efforts which have to be handled by an operator which decides to deploy a new solution.

Technological maturity: the maturity of a product has an impact on CAPEX. A young product recently released and using brand-new technologies is expensive. Low competition between suppliers and high spending in research and development tend to keep prices high. In the game, we take into account this effect and this is the reason why a low-maturity product costs more to operators; buying devices and network equipment will be more expensive than for an old and well-tried technology.
Otherwise, when an operator chooses to develop or implement new technologies, it requires research and development investments since everything is not done yet and some improvements or customizations are necessary. This will entail costs which are going to be inversely proportional to the maturity of a technology; low costs for a mature technology and high for a non-mature one. Not all operators do have their own research and development labs so these costs can be supported by a supplier but will be finally billed to the operator. Thus we can consider these two cases as equivalent.

"Technological maturity" and "Upgrades and implementation costs" are not totally independent. That is why, it is important to keep in mind that "Upgrades and implementation costs" is an effort operated in the network required by a will to extend services and "technological maturity" is a way to take into account the negative effects on cost of a new technology.

➔ ***Operation and Maintenance***

- Energy consumption: additional equipment consumes electricity. This will only take into account the network side since the costs related to equipment deployed on the user's side are supported by users themselves.

- Network maintenance: routine operations in telecom networks. More and more services go however through servers and gateways. Updating and maintaining costs of this equipment are also taken into account.

b. BENEFITS

In this study, we make the decision to consider benefits as an aggregation of two elements: savings and congestion. Indeed, offloading is a solution to increase mobile network overall capacity in urban areas that is to say avoid congestion. In addition, it is also a way to continue to provide services without spending a lot of money on network equipment and upgrades that is to say save money.

We make here the assumption that offloading solutions will not be the reason why revenues increase; mobile offloading will be a facilitator which will make operators able to harness customers growing demand (see part 1).

➔ ***Savings***

Several kinds of savings are associated with mobile network offloading:

- In order to handle growing traffic on mobile networks, operators have to invest more and more money to upgrade them; using new technologies, adding base stations. Offloading means that a part of this traffic will not be handled by outdoor stations anymore but rather by indoor solutions. The result is less* traffic and then less needs for outdoor mobile networks. Finally, operators need to spend less money; they save money[22].

*compared to what it would have been without offloading.

- An important part of operators' costs are OPEX. These costs are more and more important because of energy consumption of the wireless access part of mobile networks. By offloading, operators transfer a part of these costs to users since they maintain offloading solutions by their own means; home WiFi access points, femtocell.

For both types of savings, their benefits are linked to user adoption and how much traffic is going to pass through them instead of using outdoor networks; adoption rate is the key factor here.

➔ ***Congestion***

Congestion is a big issue in telecommunication networks. Indeed, it may trigger numerous problems making some services impossible to use and customers angry. In a context, where operators want to provide always more and more services to increase their ARPU, it is crucial for them to avoid congestion.

Here are key elements which show how congestion avoidance may result in benefits for operators.

- If congestion happens in network, services provided by operators or some partners may be disturbed and then customers will not use them. As well as consuming traffic, it results in a loss of revenue for operators.

- Congestion in a network means unsatisfied users and thus a high churn rate.

- Mobile networks appear reliable today and this is one reason why people and companies extend their services using abundant mobile technologies. However, congestion could change this and make mobile networks less interesting which would have the effect of encouraging substitution that is to say finding comparable technologies away from mobile operators.

Later, we will apply competition effects on benefits. They may become negative under certain conditions. It is however important to keep in mind that negative benefits are not linked to congestion avoidance and savings but are only effects resulting of competitive advantages and market opportunity losses.

4.2.2 Assumptions

In order to apply game theory, we have to build a model. This model has to be simple and remain suitable for most real life situations. In this context, some assumptions are necessary. They are explained in the following paragraphs.

a. DEMAND

Demand forecasts may differ quite a lot. For this reason, we focus more on trends than exact values. To keep the game as independent as possible of demand evolution, we have made the choice to not link payoffs to exact figures and to use instead qualitative methods. Thus, benefits and costs we use in the game will fit with many other demand forecasts as long as trends are the same.

As we will discover later, the qualitative evaluation system uses signs like "minus" and "plus" to build a model from complex real life observations. For instance, expensive operational costs will be represented by "- -" that is to say two minus signs. We realize here the benefits of this system which enables this study to remain true in most real life situations and not linked to some specific demand forecasts.

b. PRICING

Concerning operators' pricing strategy, the game will not choose one specific method and we will assume that all the players have the same pricing method. This parameter is really important because, depending on the chosen pricing strategy, it may have an impact on user demand and then on costs and benefits. However, if we consider that all players have the same pricing strategy, we can then assume that these effects on costs and benefits are relatively the same, that is to say, all offloading solutions share the benefits and the costs of a pricing method.

For instance, if a pricing method involves a significant modification concerning traffic demand it will entail some costs and benefits for the operator with a given offloading solution but with another solution these effects will also be observed and will have a comparable impact. Then we can consider this study independent of the pricing method, and we will not propose one in order to remain general.

c. COMPETITION

About competition, it is important to know that any game requires taking into consideration competition effects. This enables us to differentiate situations where players act together and where they act alone. In this game, we assume that competition effects on costs and benefits are the same, that is to say, competition has same effects on costs and benefits and will be represented by a common ratio.

d. OFFLOADING SOLUTIONS SPECIFICITIES

When we talk about mobile network offloading it means redirecting mobile traffic from mobile devices to another network than the outdoor macro network. By devices, we mean phones, smartphones, tablets and laptops. All these devices tend to consume more and more data and to be adopted by more and more users and then contribute to mobile network congestion. Among the offloading solutions selected for the game, some of them provide all network services, some only provide an alternative for accessing the Internet. Data consumption of mobile devices is the main reason for congestion troubles in mobile network[23], we will then consider that offloading consists of taking care of data traffic with the Internet and not voice, sms or mms. We will not evaluate the relevance of an offloading solution depending on its capacity to handle these services but only depending on the amount of data which is going to be kept out of the mobile network.

e. PLAYERS' STRATEGIES

Players' strategies are simple. They can decide to deploy or not; one decision per year.

4.2.3 Purpose of the game

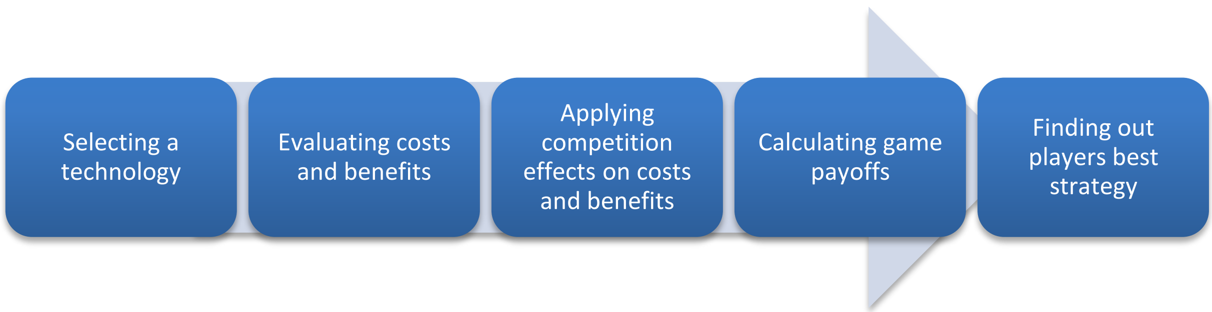
The main purpose of the game is to consider four offloading solutions and to determine for each of them when it should be deployed by operators given some inputs: cost and benefits analysis, interaction with other actors. Typically, for an offloading solution, we will be able to say over five years what should be the operators' decision in terms of deployment; one decision for each year. The game which has been chosen does not take into account previous years' decisions. So, for instance, if the result of the game is "deploy" in year y for the technology x, this decision does not depend on y-1, y-2… or on other studied technologies. Each decision is made for a selected technology in a selected year. Thus, we will obtain for each year, for each offloading solution the decision "deploy", "not deploy" or "uncertainty" which will provide what should be the operator's choice in this context.

How exactly will we find out this decision?

It is exactly this process which requires game theory. We will use some inputs. We will divide them into two categories: cost and benefits as explained before. Cost and benefits will then be faced with competition effects (detailed later) and finally we will be able to calculate game payoffs depending on the following competitive situation: alone to deploy or not, both deploy.

And, through a game theoretical analysis, we will be able to provide a result which will be either a prisoner dilemma (one Nash equilibrium) or an uncertain situation (several Nash equilibriums). In this second situation, even though a Nash equilibrium can be generally preferred by comparing payoffs we will keep the uncertain situation as a result; keeping as major information the fact that the situation cannot be totally clear.

To explain schematically the whole procedure, we can look at the picture below.



Graph 14: Analysis Process for Game Modeling

4.3 Initialization

We refer to the four offloading solutions presented in the previous part (part 3). This initialization part consists of evaluating costs and benefits for each studied offloading solution.

4.3.1 Costs

Femtocell 1

This first offloading solution that we consider here is simple. It consists of a femtocell sold by a mobile operator. Customers who want to increase coverage or capacity at home can buy the product. In this study, we do not deal with coverage aspects however since we have assumed at the beginning the fact that in dense urban areas no coverage issues are observed[24]. For us, the femtocell is a way for customers to increase available capacity and then use their mobile devices in perfect conditions.

Purchase costs are here completely paid by the customer. The operator has to deploy and maintain specific equipment in order to control its customer femtocells. All these costs are quite high at the beginning since the technology is not widely spread but they are expected to decrease in the future.

At the beginning of the game in year 1, the current demand does not require such equipment but future rates may make it necessary. Of course, when traffic on femtocell increases it means less traffic is handled by outdoor networks and thus savings. All these things are linked and proportional.

We then evaluate costs through a qualitative method, using "- -" for high costs, "-" for quite high costs, "0" for low costs.

Costs	Femtocell 1				
	Year 1	Year 2	Year 3	Year 4	Year 5
Network Upgrades	--	-	-	0	0
Marketing and Sales	--	--	-	-	0
Operation and Maintenance	--	-	-	-	-

Table 3: Qualitative Cost Analysis – Femtocell 1

And then we transpose signs into figures.

Costs	Femtocell 1				
	Year 1	Year 2	Year 3	Year 4	Year 5
Network Upgrades	2	1	1	0	0
Marketing and Sales	2	2	1	1	0
Operation and Maintenance	2	1	1	1	1

Table 4: Mathematical Transcription of the Qualitative Cost Analysis – Femtocell 1

Femtocell 2

This solution is inspired by femtocell 1. The difference here is that we consider that part of customer purchase costs are paid by the operator. It has a slightly different effect. Reducing adoption barriers for users increases costs for operators; the effect on benefits will be different.

Costs	Femtocell 2				
	Year 1	Year 2	Year 3	Year 4	Year 5
Network Upgrades	1	0	0	0	0
Marketing and Sales	2	2	1	0	0
Operation and Maintenance	2	2	2	2	1
Total costs	5	4	3	2	1

Table 5: Mathematical Transcription of the Qualitative Cost Analysis – Femtocell 2

WiFi 1

A majority of households has today an Internet access at home. Commonly a WiFi access point is provided with Internet access. Devices connected to this WiFi access point require a specific configuration which has to be done by the user.

Apart from buying a device equipped with a WiFi interface, which is common nowadays, no additional purchase cost has supported by the user.

On the other hand, the operator can encourage users to put WiFi access points in their home or apartment. Those access points may be provided by the operator or subsidized. Otherwise operators can promote this solution with advertising campaigns or through training. Finally, they can also invest money in research and development in order to find easier ways to connect home WiFi access points to wireless devices.

In this case, WiFi 1, basic mobile services like voice calls, sms or mms are not offloaded. They stay in the mobile network, only the Internet access goes on the WiFi network. Then no specific gateway is required for the operator.

We collect this information in this table.

Costs	WiFi 1				
	Year 1	Year 2	Year 3	Year 4	Year 5
Network Upgrades	1	0	0	0	0
Marketing and Sales	2	2	2	1	1
Operation and Maintenance	1	1	0	0	0
Total costs	4	3	2	1	1

Table 6: Mathematical Transcription of the Qualitative Cost Analysis – WiFi 1

WiFi 2

It consists of using a new technology which is not yet mature. In WiFi 2, mobile devices would be equipped with specific software which enables them to roam seamlessly on WiFi networks to access a specific gateway and link them to the mobile network. To reach this gateway a simple Internet access is required.

We take into consideration developments for enabling mobile devices to roam seamlessly on WiFi networks and be able to provide all the mobile services through it. It does not include laptops but most smartphones and maybe tablets on which it is possible to deploy additional software in order to provide voice call, sms, mms and internet access through WiFi. Some techniques mentioned earlier are UMA or IWLAN.

In this case, the operator has to promote devices with WiFi interfaces and has to buy and develop specific equipment like gateways in order to provide mobile services through WiFi access[25]; through an Internet access.

It is important to notice that in this case, all mobile services go through the Internet; no interaction with the mobile network exists.

No specific costs for users except having an Internet access at home and a WiFi access point. Operators can encourage their customers through marketing and advertising as in WiFi1.

Costs	WiFi 2				
	Year 1	Year 2	Year 3	Year 4	Year 5
Network Upgrades	2	2	1	0	0
Marketing and Sales	2	1	0	0	0
Operation and Maintenance	2	1	0	0	0
Total costs	6	4	1	0	0

Table 7: Mathematical Transcription of the Qualitative Cost Analysis – WiFi 2

4.3.2 Benefits

As said before, benefits are evaluated in terms of savings and congestion. We will then give grades to each offloading solution as we did for costs. Grades are here a bit different than for costs. Indeed, in order to have two equivalent way to take into consideration costs and benefits, we use four different grades for benefits {+++;++;+;0}. In order to save some space, we will go directly to the mathematical transcription of the qualitative table. Here {+++;++;+;0} = {3;2;1;0}. .

Femtocell 1

Femtocell is an efficient way of offloading. The most interesting advantage of femtocells is the fact that they are fully integrated in the network, all mobile devices can directly use them without any configuration by the user.

At the beginning of the game in year 1 and 2, congestion is not really an issue on mobile networks and thus femtocell impact is not yet observable. However, it already has an effect on network deployment since operators start to deploy femtocells as indoor cells, they then offload a part of the macro network traffic.

Decreasing prices and a technology which will become more familiar for users will increase the adoption rate in the future and we can expect really good benefits after several years. However, the adoption rate may not be high enough to get strong benefits in year 3 and 4.

Benefits	Femtocell 1				
	Year 1	Year 2	Year 3	Year 4	Year 5
Savings	1	1	1	1	3
Congestion	0	0	2	2	3
Total benefits	1	1	3	3	6

Table 8: Mathematical Transcription of the Qualitative Benefits Analysis – Femtocell 1

Femtocell 2

In this case, we keep all the benefits of a femtocell as described in femtocell 1. We only try to improve the adoption rate by offering some incentives which will encourage and help users to adopt femtocells faster. Of course this has a cost for the operator. This cost has been evaluated in the part related to this issue previously. We will here focus on benefits. And what we can quickly say is that femtocell 2 will be femtocell 1 with more benefits in years 2, 3 and 4 which is exactly the impact of more users using the offloading solution.

Benefits	Femtocell 2				
	Year 1	Year 2	Year 3	Year 4	Year 5
Savings	0	1	2	3	3
Congestion	1	1	2	3	3
Total benefits	1	2	4	6	6

Table 9: Mathematical Transcription of the Qualitative Benefits Analysis – Femtocell 2

WiFi 1

With WiFi 1 only the Internet traffic is offloaded, classical mobile services stay on the macro network. However, asdata traffic is mostly represented by Internet traffic, this solution is considered quite efficient. The limits of WiFi 1 are linked more to complex configuration which requires user intervention. Indeed, in this case, the user has to set the connection between his/her own WiFi access points and his/her mobile device. Even if the procedure is quite simple it still requires establishing an authentication from the device and this procedure is likely to discourage users: only about 30% of users do this.

In the future, this part should grow through different processes. First, operators can encourage their customers to configure their mobile devices by explaining to them how to do it. Second they can also develop new authentication procedures easier for users. Third, they can insist on user experience which is increased by using fixed Internet access (see offloading a win-win situation). However, it should not reach 100% and thus is not the most sustainable.

Benefits will then be observed gradually. First, in terms of new deployment savings because congestion is simply absent during year 1. However the effect on data traffic will start from year 1 and then will enable operators to invest less in their mobile network.

Despite immediate benefits, this solution is not the best one because of an unpredictable adoption rate which will not enable operators to rely only on this technology. That is why, it will help to avoid some congestion troubles in the future but will not replace network investment since it does not solve the entire problem of offloading.

Benefits	WiFi 1				
	Year 1	Year 2	Year 3	Year 4	Year 5
Savings	2	2	1	1	1
Congestion	0	0	1	2	2
Total benefits	2	2	2	3	3

Table 10: Mathematical Transcription of the Qualitative Benefits Analysis – WiFi 1

WiFi 2

In this case, configuration is not a problem anymore. Roaming between WiFi network and the mobile network is done automatically. Furthermore, all mobile services go here through the local network.

The adoption rate will be determined by the number of devices capable of roaming seamlessly that is to say the number of devices where such software is implemented. This ratio is zero during the first year but will grow over the next years. And if it is needed, operators will be able to reach high adoption rates as they currently do with 3G devices.

This solution is then more efficient than WiFi 1 and it is really capable of replacing network deployment and avoiding congestion troubles.

Benefits	WiFi 2				
	Year 1	Year 2	Year 3	Year 4	Year 5
Savings	0	0	1	3	3
Congestion	1	1	2	3	3
Total benefits	1	1	3	6	6

Table 11: Mathematical Transcription of the Qualitative Benefits Analysis – WiFI 2

4.3.3 Payoffs

At this step, we have costs and benefits for each offloading solution and we want to apply to them competition effects:

- Monopolistic situation: Micro-economy proves that every monopolistic situation tends to increase benefits[26] for the firm thus this effect will be reflected in the game thanks to the parameter t.
- Effects on costs: We assume that when more players (that is to say operators) choose a technology it has the effect of decreasing costs by attracting more suppliers to a market that is to say increasing competition between suppliers*. It is really tricky to evaluate and to compare these two effects; the effects of competition on costs and benefits, that is why for simplicity reasons we will consider they are the same. So the effect of competition on costs and benefits is the same and then to obtain costs and benefits in a competitive situation it is only necessary to apply a multiplier to those in a non-competitive situation. This factor is then also t (as for monopolistic situation).

* competition between suppliers decreases network equipment prices, network upgrades and reduces the negative effect on maturity by committing more task forces to deployment…

Concerning situations where an operator deploys alone, we consider this effect is the opposite of what the competitor wins. In case where neither of them deploy, they take the opposite of what they would have got by both deploying.

Inputs	Costs		Benefits			
	Only one deploys	Both deploy	Alone to deploy	Both deploy	Alone to not deploy	No deployment
Year 1	c[year1]	t* c[year1]	b[year1]	t* b[year1]	-b[year1]	t*-b[year1]
Year 2	c[year2]	t* c[year2]	b[year2]	t* b[year2]	-b[year2]	t*-b[year2]
Year 3	c[year3]	t* c[year3]	b[year3]	t* b[year3]	-b[year3]	t*-b[year3]
Year 4	c[year4]	t* c[year4]	b[year4]	t* b[year4]	-b[year4]	t*-b[year4]
Year 5	c[year5]	t* c[year5]	b[year5]	t* b[year5]	-b[year5]	t*-b[year5]

Table 12: Competition Effects on Costs and Benefits – Variables

With an example (Femtocell 1), we obtain results of Table 13.

t=0.7, costs are given in part costs.

Inputs	Costs		Benefits			
	Alone to deploy	Both deploy	Alone to deploy	Both deploy	Alone to not deploy	No deployment
Year 1	6	4	1	1	-1	-1
Year 2	4	3	1	1	-1	-1
Year 3	3	2	3	2	-3	-3
Year 4	2	1	4	3	-4	-4
Year 5	1	1	6	4	-6	-6

Table 13: Competition Effects on Costs and Benefits – Example

4.4 The game

We keep the situation of the previous example (Femtocell 1).

Payoffs are calculated by summing costs and benefits corresponding to each situation from the table 13. Costs are subtracted and benefits added.

When an operator chooses not to deploy, costs are equal to zero but effects may be observed on benefits.

So for example, in year 1, in the case where A decides to deploy and B decides not to deploy:

- payoff(A)= -6 (costs for A which is alone to deploy) + 1 (benefits for A which is alone to deploy) = -5
- payoff(B)= 0 (no cost because nothing deployed) + (-1)(alone to not deploy) = -1

We then put all the payoffs in the following table. In each cell, the first figure corresponds to A's payoff and the second to B's payoff.

So for instance, on the first line, second column, where A is not deploying and B is deploying. A's payoff is then -1 and B's payoff is -5.

<table>
<tr><td></td><td></td><td colspan="4">B</td></tr>
<tr><td></td><td></td><td colspan="2">not deploying</td><td colspan="2">deploying</td></tr>
<tr><td rowspan="2">A</td><td>not deploying</td><td>-1</td><td>-1</td><td>-1</td><td>-5</td></tr>
<tr><td>deploying</td><td>-5</td><td>-1</td><td>-3</td><td>-3</td></tr>
</table>

Table 14: Game Payoffs – Femtocell 1 – Year 1

How to read results of the game:

We assume that mobile operators are rational players and they don't play strictly dominated strategies. Applying iterated elimination of strictly dominated strategies we can conclude to a pair of strategies which is a Nash equilibrium. If player A plays "not deploying", then the best response for player B is "not deploying" with payoff -1 instead of playing "deploying" with payoff of -5. If player A plays "deploying", then the best response for player B is again "not deploying". Hence, player B's strategy to deploy is dominated by each strategy followed by player A. Player A knows that player B will follow the strategy of not deploying and choose the strategy with the higher payoff for him which is "not deploying". Therefore the strategy of "not deploying" for both players is a Nash equilibrium.

Other situations may also be observed. It's possible for some games to result in more Nash equilibriums. In this case, uncertainty remains and the strategy that each player will follow cannot be clearly determined.

In year 3 still with femtocell 1, we observe a different situation from the one observed in year 1.

		B			
		not deploying		deploying	
A	not deploying	-3	-3	-3	0
	deploying	0	-3	0	0

Table 15: Game Payoffs – Femtocell 1 – Year 3

We have this time a prisoner dilemma but the result is deploying.

Sometimes, a hybrid conclusion may happen like with WiFi 1 in year 1.

		B			
		not deploying		deploying	
A	not deploying	-2	-2	-2	-2
	deploying	-2	-2	-2	-2

Table 16: Game Payoffs – WiFi 1 – Year 1

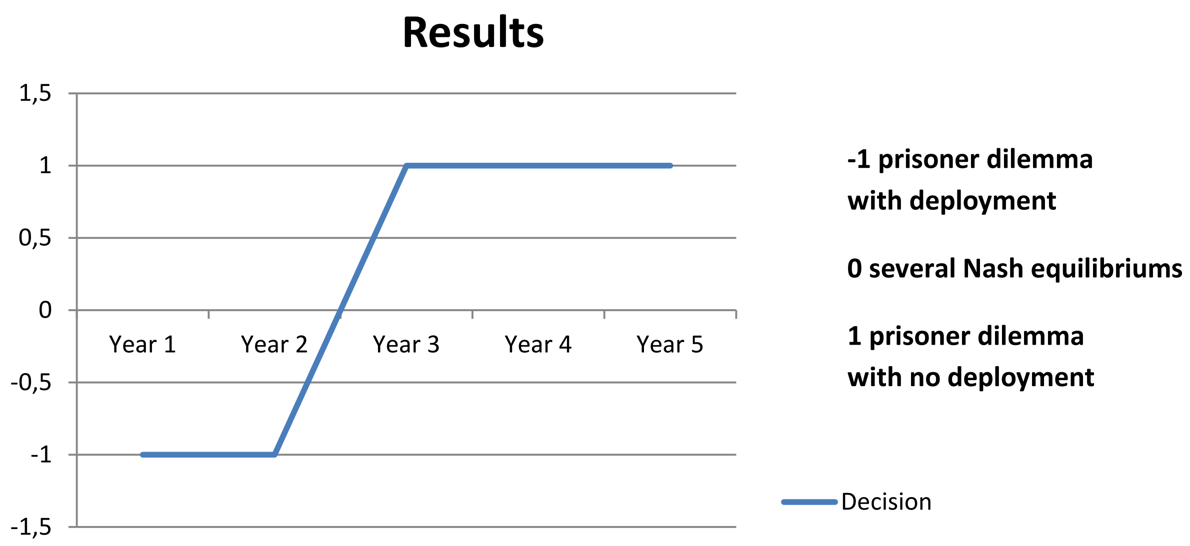
We have here four Nash equilibriums and the situation is unpredictable since all payoffs are the same.

All the results are in the annexes, however they are presented on graphs in the next paragraph. It is then easy to read conclusions from each situation depending on the offloading technology and the year.

4.5 Analysis of Games

All the results presented are visible on the following graphs.

Femtocell 1



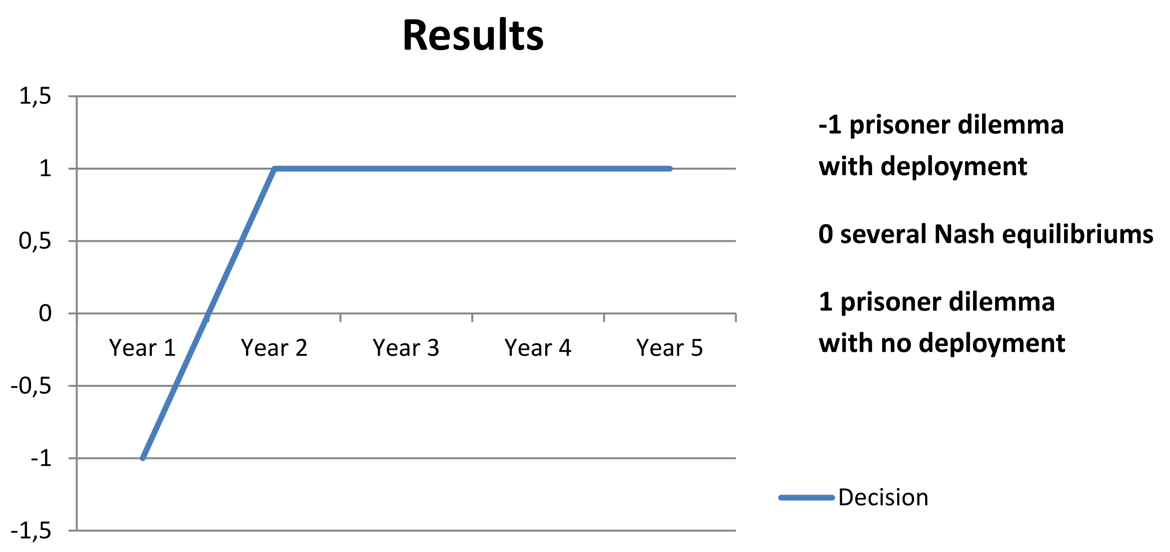
Graph 15: Results Graph – Femtocell 1

We realize thanks to this graph, that a deployment is not something to plan during the first years (year 1 and year 2). Then, femtocell 1 becomes a good offloading solution and the competitive context predicts that operators should make the decision to deploy from year 3.

Some characteristics have a significant impact on observed results:

- Purchase price is high at the beginning and discourages users from acquiring a femtocell.
- Femtocell remains a new technology for users. The product is not common and sold only by operators. As a result, they do not necessarily understand the usefulness of a femtocell.
- However, a femtocell is easy to set and to use. In terms of efficiency as an offloading solution, femtocell is good and we can see on the graph that after a few years femtocell should be proposed by operators to their customers.

Femtocell 2



Graph 16: Results Graph – Femtocell 2

In femtocell 2, operators offer some incentives to encourage users to adopt femtocells (bundling and subsidizing). They reduce adoption costs by decreasing purchase cost for customers. Femtocell then becomes easier to get for customers who adopt it fast.

In the win-win solution of offloading, this strategy puts more effort on the operator side, users understand better what they get in terms of user experience, they then adopt femtocells easily.

WiFi 1

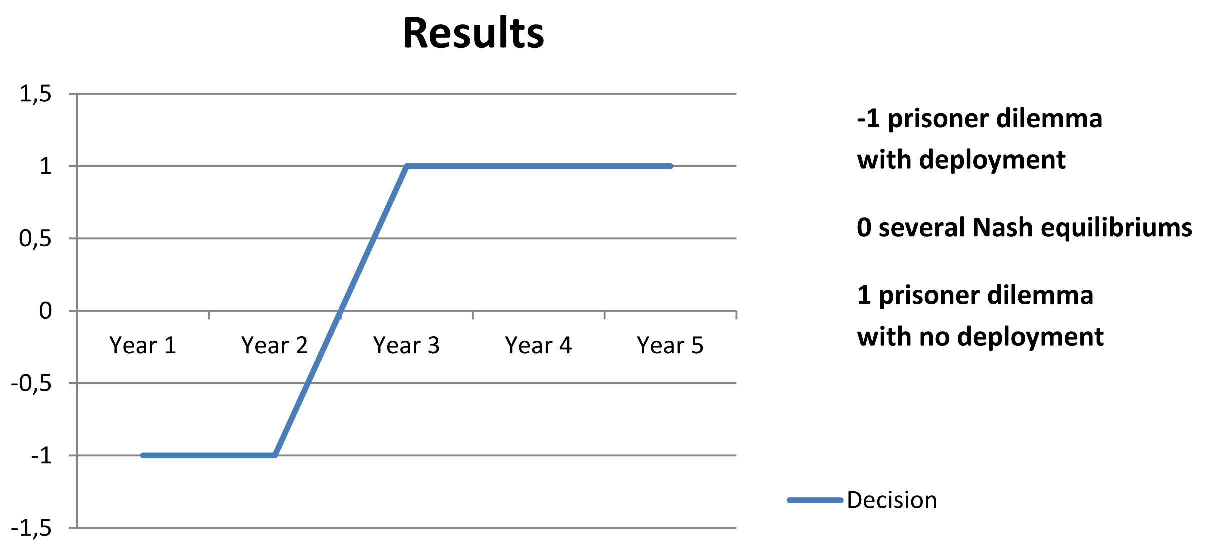
Graph 17: Results Graph – WiFi 1

The most interesting advantage of WiFi 1 is the fact that this solution is already deployed. Many users own their own WiFi access point at home. Furthermore, WiFi is really cheap which enables almost all wireless devices to be equipped with such an interface. And thus they can fully get the benefits of a home access point to the network.

These points explain why WiFi should be deployed from the beginning. The only drawback is the adoption rate. Indeed, the complexity of the configuration procedure tends to discourage users from doing it. Current studies show that about 30% of smartphone users, for instance, configure their phone to use local WiFi in their private place.

This argument about a low adoption rate tends to reduce the capability of WiFi as a complete solution for mobile offloading however it has the advantage of immediately providing an operational solution.

WiFi 2



Graph 18: Results Graph – WiFi 2

WiFi 2 is not a mature technology in year 1. It is thus difficult for operators to start deploying it. They might face numerous costs linked to the deployment of an early technology. Waiting is probably a good decision in a first time but then it is likely to be one of the most profitable solutions thanks to the ubiquity of WiFi networks in dense urban areas. It is thus possible to offload for low costs and to not disturb users who still manipulate technologies they know.

Another important aspect of WiFi 2 which tends to slow deployment is the fact that both devices and mobile operators, have to be updated; mobile devices need additional software which is currently not installed on phones and operators need specific management systems. This situation might change in the future but it will require strong commitment from operators to influence mobile devices vendors and to trigger non-negligible investments in network equipment.

As it is with femtocells, WiFi 2 is transparent for the user, it makes it a valuable solution for operators which would like to offload. This offloading scheme is then a solution to follow in the future thanks to its strong arguments.

4.6 Discussions

4.6.1 Analysis outcomes

This game-theoretic analysis has enabled us to confront offloading solutions with a real life competitive situation. Indeed, by using game theory, we have modeled interactions which occur between operators in a competitive market to the case of mobile network offloading. Modeling has been the trickiest part since it is impossible to perfectly match a model with a real situation. However, the strong analysis of offloading solutions made previously in chapter 3 has enabled us to evaluate with good accuracy potential gains and losses associated to a new deployment. In this evaluation, we chose to use a qualitative method in order to not link too much the relevance of this study to traffic demand forecasts which remain unsure. Then, we have applied competitive effects to our qualitative analysis. We made the choice at this point to use a simple model which only made the difference between a monopolistic situation and an oligopolistic situation. Effects were observed on potential gains and losses and it provided relevant results. It finally enabled us to calculate game payoffs and then to obtain game results. These results have been conclusive. We got clear decisions from the game; well-known game theoretic cases like prisoner dilemma appeared automatically. These decisions were put into graphs in order to represent the evolution over the five years we chose as the time-line. This way of showing results enables the reader to have a quick view over the offloading solutions studied, their maturity, their future and the way they will probably penetrate the market which was our purpose*.

*When should each of these offloading solutions be deployed?

4.6.2 Scope of the analysis

In 4.2.2, we already discussed assumptions we made in order to build the model used in the game. We will not now come back to those assumptions but focus more on the limitations of the game in itself.

The qualitative analysis which has been made before the game in order to calculate the game payoffs remains general and linked as little possible to other studies or forecasts which might be proved wrong in the future. However, this qualitative approach does not provide precise results, it only gives a rough analysis about key parameters in the telecom field. It is then important to keep in mind these evaluations when we talk about the exactness of the results.

Concerning competitive effects, even if we already talked about them in the assumptions part, it is important to notice that the competition model for this study is basic and simply multiplies by a given ratio (we took 0.7) costs and benefits to go from a monopolistic situation to a oligopolistic. This method may not represent real life precisely.

Finally, game theory is not a perfect science, it is a way of reasoning based on some gains, losses and rational choices where players always want to maximize their profit. It is usually a relevant way of thinking and it provides satisfactory results. However it remains imperfect and leads more to indications than exact outcomes.

5 Conclusion

5.1 Results

In this thesis, we started with a thorough analysis of the mobile traffic nature which enabled us to realize that a big part of the traffic come from indoors. Several mobile network offloading solutions based on two different technologies, femtocells and WiFi, have been then studied. These two technologies are specifically designed for indoor areas and can bring an alternative to classical mobile outdoor cells. Indeed, they can be used in the access network to handle a part of the traffic. However, even if femtocell and WiFi are able to provide the same services, they do not have exactly the same characteristics.

On one hand, Femtocells are more likely to be deployed in business areas since they guarantee a better quality of service, they meet higher security requirements and remain more manageable by operators. On the other hand, WiFi networks already exist in most residential areas and consumer customers are familiar with the technology. It is thus easy for operators to use this existing infrastructure to redirect a part of the mobile traffic. This analysis taking into account technical parameters as well as business and strategic ones enabled to understand where each offloading solution is more likely to be deployed.

After focusing on each solution specificities to figure out where they may be deployed, we went to a more theoretical part using a mathematical model in order to predict when these different offloading solutions will be deployed. This analysis was based on game theory; a method which enabled us to take into account competition effects on mobile network deployment schemes. Most mobile markets are oligopolies and thus interaction between actors plays an important role; one operator’s decision can have consequences on the whole market. This game-theoretic approach of mobile network offloading required two modeling tasks: First we built a model which implied to make some assumptions and to make a qualitative assessment of the different cases studied. Second, based on this mathematical model, we defined a payoff function which determines from given inputs, set by the context, what will be the player payoffs. Then, the game is implemented and provides an insight of the most likely deployment period for each offloading solution.

We actually presented game results through several graphs which showed that WiFi and femtocell can meet operators’ needs in terms of offloading means. We also realized that the current stake, from the operators point of view, is to decide how much they should get involved in the deployment of offloading solutions; by investing or incenting customers to use offloading solutions. According to our results, although operators should integrate offloading solutions to their offer from now, they should probably not start to spend money to encourage their adoption. This will surely come later and will mostly depend on the demand evolution.

Finally, all the offloading solutions studied in this thesis have the prerequisites to be profitable in the future and to face an expected data traffic explosion on mobile networks, their role will however be determined by capacity needs in mobile access networks and operator strategies.

5.2 Assessment of results

In the qualitative analysis, in which we have pointed out strengths and weaknesses of several offloading solutions, our criteria have been chosen and evaluated through a subjective approach which may be inexact. Indeed, this analysis relies on various sources like papers, white papers and figures provided by companies which might be not fully objective because of the own implication of people who wrote these documents; femtocell actors have their own business to support. By crossing diversified sources, we tended to downplay this impact however our analysis may have been oriented towards one technology or another due to a lack of sources or a lack of diverging opinions.

In the game theoretical analysis, we built a mathematical model which set the rules between players and enabled us to calculate payoffs. This model is the central point of any game in game theory and the relevance of the results depends on it. An accurate mathematical model in game theory has to fill mainly two objectives: it has to match with real life, this means representing as well as possible the context studied, and it also has to remain simple that is to say ignoring useless parameters and pushing forward key elements. The second most important thing in game theory is the payoff function. This function determines the final results of the game; in our case “Nash equilibrium” or “prisoner dilemma”. Both the model and the payoff function are built to match to a specific situation.

Imperfections in our game, which may create inaccuracy in our outcomes, may come from these two elements, the model and the payoff function. First of all, our model pushes forward key elements which are integrated as inputs in the payoff function. When we chose to select or not a certain parameter or to affect or not to this parameter a weighting, it has a direct impact on our conclusions; we for instance, apply similar multiplier on costs and benefits to represent competition effects. Furthermore, we made some assumptions concerning the demand and its evolution, the pricing method, the type of competition in order to simplify the context. The payoff function results depend directly on these assumptions. Indeed, costs and benefits are the only two inputs of the payoff function one more time for simplicity reasons. Of course, that does not mean that only costs and benefits are taken into account, for instance competition effects have been applied by an indirect way on the inputs, it still affects considerably our way of addressing this issue. Moreover, we decided to evaluate payoffs from a mobile operator point of view considering thus mobile offloading as an operator issue and not, for instance, as a user one. This choice may influence our conclusions since we agreed in the thesis that mobile offloading is a win-win solution and customers may play a more important role than what we have considered. Their role is nevertheless completely forgotten and as well as competitive effects, they appear in costs and benefits. Amongst our considerations and assumptions, some elements may be more important than actually thought; their impact in the future may also evolve. Knowing that only one modification on a key parameter can provide totally different final results, it is important to pay attention to the context of a game theoretical study before interpreting the results, using them or trying to paste them on another situation.

5.3 Exploitation of results

From an academic viewpoint, this thesis brings a quaint way of tackling technology-driven choices. Technology is today ubiquitous and the success or the failure of a strategy becomes more and more a matter of technological choice. By an approach different, we had in this thesis the opportunity to provide other types of recommendation and make other predictions for the coming years. Game theory is today more and more used in the industry to explain and to foresee decisions in competitive contexts, it would also probably be an interesting tool for academics. Furthermore, building a model and a payoff function in game theory is an efficient way of tackling a techno-economic problem. This work enables a deep understanding by identifying essential parameters and their respective influence on payoffs.

For business and industrial purposes, this thesis shows in a first part a wide overview of the advantages and disadvantages of each offloading solution currently studied for mobile networks. This analysis enables the reader to make his/her own opinion clearer and to understand the impact of strengths and weaknesses on business performances. The second part brings interesting information and mainly gives a new approach of decision issue notably in a technological choice context. Maybe the method is here even more interesting for business purposes that results in themselves.

5.4 Future Research

As a future task, it would probably be useful to make a quantitative analysis of the different offloading solutions in order to calculate game payoffs with a higher accuracy. This work is quite tricky because it has to be precise on one hand and based on forecasts that is to say estimations on the other hand. If this were done, it would certainly be possible to reduce the time slot to less than one year and then to know almost exactly when an offloading solution is ready to go to the market.

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Appendix 1: Result details

Femtocell 1

Inputs	Costs		Benefits			
	Alone to deploy	Both deploy	Alone to deploy	Both deploy	Alone to not deploy	No deployment
Year 1	6	4	1	1	-1	-1
Year 2	4	3	1	1	-1	-1
Year 3	3	2	3	2	-3	-3
Year 4	2	1	4	3	-4	-4
Year 5	1	1	6	4	-6	-6

Table 17: Competition Effects on Costs and Benefits – Femtocell 1

		B			
		not deploying		deploying	
A	not deploying	-1	-1	-1	-5
	deploying	-5	-1	-3	-3

Table 18: Game Payoffs – Femtocell 1 – Year 1

		B			
		not deploying		deploying	
A	not deploying	-1	-1	-1	-3
	deploying	-3	-1	-2	-2

Table 19: Game Payoffs – Femtocell 1 – Year 2

		B			
		not deploying		deploying	
A	not deploying	-3	-3	-3	0
	deploying	0	-3	0	0

Table 20: Game Payoffs – Femtocell 1 – Year 3

		B			
		not deploying		deploying	
A	not deploying	-4	-4	-4	2
	deploying	2	-4	2	2

Table 21: Game Payoffs – Femtocell 1 – Year 4

		B			
		not deploying		deploying	
A	not deploying	-6	-6	-6	5
	deploying	5	-6	3	3

Table 22: Game Payoffs – Femtocell 1 – Year 5

Femtocell 2

Inputs	Costs		Benefits			
	Alone to deploy	Both deploy	Alone to deploy	Both deploy	Alone to not deploy	No deployment
Year 1	5	4	1	1	-1	-1
Year 2	4	3	3	2	-3	-3
Year 3	3	2	4	3	-4	-4
Year 4	2	1	6	4	-6	-6
Year 5	1	1	6	4	-6	-6

Table 23: Competition Effects on Costs and Benefits – Femtocell 2

		B			
		not deploying		deploying	
A	not deploying	-1	-1	-1	-4
	deploying	-4	-1	-3	-3

Table 24: Game Payoffs – Femtocell 2 – Year 1

		B			
		not deploying		deploying	
A	not deploying	-3	-3	-3	-1
	deploying	-1	-3	-1	-1

Table 25: Game Payoffs Femtocell 2 – Year 2

		B			
		not deploying		deploying	
A	not deploying	-4	-4	-4	1
	deploying	1	-4	1	1

Table 26: Game Payoffs – Femtocell 2 – Year 3

<table>
<tr><td></td><td></td><td colspan="4">B</td></tr>
<tr><td></td><td></td><td colspan="2">not deploying</td><td colspan="2">deploying</td></tr>
<tr><td rowspan="2">A</td><td>not deploying</td><td>-6</td><td>-6</td><td>-6</td><td>4</td></tr>
<tr><td>deploying</td><td>4</td><td>-6</td><td>3</td><td>3</td></tr>
</table>

Table 27: Game Payoffs – Femtocell 2 – Year 4

<table>
<tr><td></td><td></td><td colspan="4">B</td></tr>
<tr><td></td><td></td><td colspan="2">not deploying</td><td colspan="2">deploying</td></tr>
<tr><td rowspan="2">A</td><td>not deploying</td><td>-6</td><td>-6</td><td>-6</td><td>5</td></tr>
<tr><td>deploying</td><td>5</td><td>-6</td><td>3</td><td>3</td></tr>
</table>

Table 28: Game Payoffs – Femtocell 2 – Year 5

WiFi 1

Inputs	Costs		Benefits			
	Alone to deploy	Both deploy	Alone to deploy	Both deploy	Alone to not deploy	No deployment
Year 1	4	3	2	1	-2	-2
Year 2	3	2	2	1	-2	-2
Year 3	2	1	2	1	-2	-2
Year 4	1	1	3	2	-3	-3
Year 5	1	1	3	2	-3	-3

Table 29: Competition Effects on Costs and Benefits – WiFi 1

		B			
		not deploying		deploying	
A	not deploying	-2	-2	-2	-2
	deploying	-2	-2	-2	-2

Table 30: Game Payoffs – WiFi 1 – Year 1

		B			
		not deploying		deploying	
A	not dploying	-2	-2	-2	-1
	deploying	-1	-2	-1	-1

Table 31: Game Payoffs – WiFi 1 – Year 2

		B			
		not deploying		deploying	
A	not deploying	-2	-2	-2	0
	deploying	0	-2	0	0

Table 32: Game Payoffs – WiFi 1 – Year 3

		B			
		not deploying		deploying	
A	not deploying	-3	-3	-3	2
	deploying	2	-3	1	1

Table 33: Game Payoffs – WiFi 1 – Year 4

		B			
		not deploying		deploying	
A	not deploying	-3	-3	-3	2
	deploying	2	-3	1	1

Table 34: Game Payoffs – WiFi 1 – Year 5

WiFi 2

Inputs	Costs		Benefits			
	Alone to deploy	Both deploy	Alone to deploy	Both deploy	Alone to not deploy	No deployment
Year 1	6	4	1	1	-1	-1
Year 2	4	3	1	1	-1	-1
Year 3	1	1	3	2	-3	-3
Year 4	0	0	6	4	-6	-6
Year 5	0	0	6	4	-6	-6

Table 35: Competition Effects on Costs and Benefits – WiFi 2

		B			
		not deploying		deploying	
A	not deploying	-1	-1	-1	-5
	deploying	-5	-1	-3	-3

Table 36: Game Payoffs – WiFi 2 – Year 1

		B			
		not deploying		deploying	
A	not deploying	-1	-1	-1	-3
	deploying	-3	-1	-2	-2

Table 37: Game Payoffs – WiFi 2 – Year 2

		B			
		not deploying		deploying	
A	not deploying	-3	-3	-3	2
	deploying	2	-3	1	1

Table 38: Game Payoffs – WiFi 2 – Year 3

		B			
		not deploying		deploying	
A	not deploying	-6	-6	-6	6
	deploying	6	-6	4	4

Table 39: Game Payoffs – WiFi 2 – Year 4

		B			
		not deploying		deploying	
A	not deploying	-6	-6	-6	6
	deploying	6	-6	4	4

Table 40: Game Payoffs – WiFi 2 – Year 5

Appendix 2: Result overview

	Femtocell 1	Femtocell 2	WiFi 1	wiFi 2
Year 1	-	-	=	-
Year 2	-	+	+	-
Year 3	+	+	+	+
Year 4	+	+	+	+
Year 5	+	+	+	+

+ : Prisoner dilemma - deploying
- : Prisoner dilemma - not deploying
= : Nash equilibrium(s)

Table 41: Game Payoffs – Result Overview