KTH Royal Institute of Technology

IK2511 Project in Wireless Networks

Techno-economic study on capillary networks and cellular technologies for Machine-to-Machine communications

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Contents

List of Acronyms

ADP	Application Delivery Platform
AMR	Automatic Meter Reading
AP	Access Point
ARPU	Average Revenue per User
BAS	Building Automation System
CAGR	Compound Annual Growth Rate
CapEx	Capital Expenditure
CLH	Cluster Head
EPC	Evolved Packet Core
HVAC	Heating, Ventilation and Air Conditioning
H2H	Human-to-Human
IoT	Internet of Things
LTE	Long Term Evolution
MNO	Mobile Network Operator
MTC	Machine Type Communications
MVNO	Mobile Virtual Network Operators
M2M	Machine-to-Machine
OpEx	Operating Expense
RTU	Remote Terminal Unit
SG	Smart Grid
TCO	Total Cost of Ownership
UMTS	Universal Mobile Telecommunications System
WiFi	Wireless Fidelity
WSN	Wireless Sensor Network

Abstract

Machine-to-Machine (M2M) technology represents undoubtedly a promising field in the communications area nowadays. Moving from the traditional human-oriented connectivity to seamlessly integrating 'things', new market opportunities arise. M2M communications can be offered through different technologies. In the context of the project, emphasis is given on two particular solutions; the cellular architecture, where the M2M devices equipped with wireless cellular interfaces access directly the mobile network operator network and the capillary architecture, where the M2M devices are organised in a short-range network and access the backhaul network via a gateway. In the context of the project, a techno-economic study of the two solutions is performed. A quantitative analysis is carried out through the examination of two specific scenarios which refer to representative examples of M2M applications. Based on the outcomes, it is concluded that the preference of one solution or the other is strongly dependent on the specific deployment scenario that is considered. Moreover, the perspective (user/operator) under which each scenario is treated, affects the overall cost analysis.

Chapter 1

Introduction to M2M technology and the IoT

Machine-to-Machine (M2M) communications refer to an emerging type of communications where data is exchanged between smart devices or machines that communicate through a network with little or no human intervention at all [1]. Machines are more and more becoming an important participant in communication networks, from industry to smart homes.

M2M technology can be seen as a paradigm of data communication which involves mass-scale M2M networks consisting of a large number (e.g. hundreds to billions [25]) low-cost intelligent devices that do not necessarily need human intervention. A common M2M scenario begins with a smart device (sensor, meter) which captures an event or a series of events, or measures a particular variable of interest (temperature, supply level, etc.). The data about the event or measurement is then sent through a network (wireless, wired or a hybrid of the two depending mainly on the required QoS but also the cost) to an application (software program) running on a server operated by the service provider or network operator. Afterwards, commands from the servers may be sent back to the devices, instructing them to undertake certain actions, change the parameters of their operation, or go to sleep for a predefined period of time. The devices involved in a M2M application are called M2M devices. They need to have the required functionality, typically consisting of sending data automatically or upon request to the appropriate server, and responding to commands issued by the servers.

M2M represents a future where a large amount of everyday objects and the surrounding environment are connected and managed through a range of devices, communication networks, and cloud-based servers. Multiple connectivity options are available today to connect M2M devices to a server and each other. A typical M2M system architecture is illustrated in Figure 1.1.

As seen, hierarchical deployments that provide reliable, efficient interworking between multiple communication protocols (PAN/LAN/WAN) are needed in the case when many devices are limited in range due to cost/size/power constraints. The M2M devices can connect to the M2M server directly through a WAN connection (e.g., GSM, UMTS, LTE, LTE-A) or can formulate personal area networks that use short-range communications technology (e.g., ZigBee, BlueTooth, low power WiFi) and access the core M2M network via an M2M gateway (aggregation point). The gateway is a smart M2M device with enhanced capabilities (e.g. cellular interface) with respect to the other M2M devices. In particular, it collects and processes data from simpler M2M devices and manages their operation. Typically, connecting through a gateway is preferred

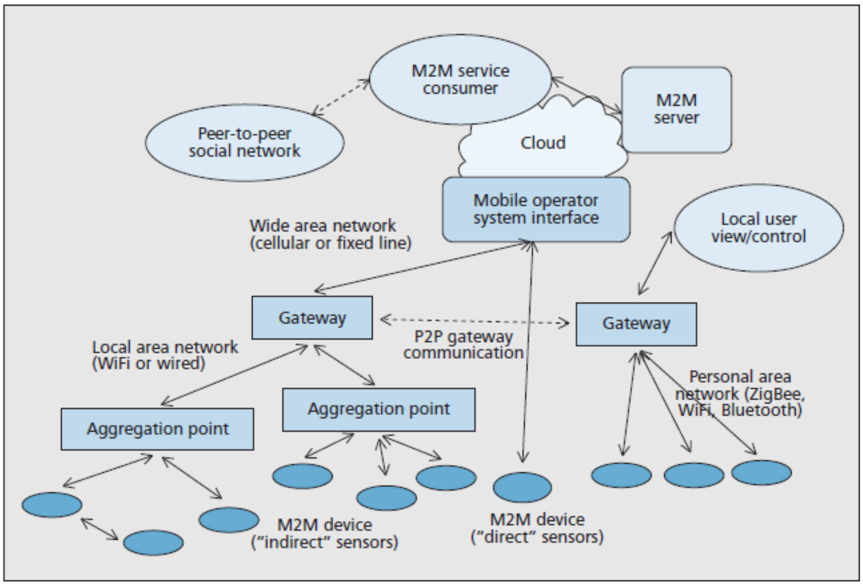

Figure 1.1 An M2M system architecture [1]

when devices are sensitive to cost, power, or location. There are several lower-cost radio protocols, such as IEEE 802.11, IEEE 802.15, and power line communications, through which these devices can communicate. These two approaches are called cellular M2M and capillary M2M respectively and the preference of one or the other is strictly dependent on the application scenario that is considered. Another connection method is the wired (cable, xDSL, optical) whereas in the context of the project the emphasis will be given on the two previously mentioned solutions. Figure 1.2 illustrates four different methods for ensuring access to the core M2M network considering the scenario of deploying several smart meters in the water pipes of a five-floor building.

1.1 Motivation and Background

By enabling smart devices to communicate directly with one another, M2M communications technology has the potential to radically change the world around us and the way that we interact with objects, as the communication devices can be implanted in different environments such as cars, appliances, smart homes, vending machines, and other objects we encounter in our daily lives.

The growth of this area is not only restricted to the diversity and number of future M2M devices, but also the mobile data traffic is expected to grow significantly in future communications. Mobile data traffic is expected to grow at a compound annual growth rate (CAGR) of 66% from 2012 to 2017 with M2M nodes starting to account for a more significant portion of the traffic by 2017 [4] as shown in Table 1.1.

While the mobile global M2M modules are going to grow 4.6-fold, a CAGR of 36 percent, from 369 million in 2012 to 1.7 billion in 2017, globally, M2M traffic will grow 24-fold from 2012 to 2017, a compound annual growth rate of 89 percent, with M2M traffic reaching 563 petabytes per month in 2017. M2M will account for 5 percent of total mobile data traffic in 2017, compared to 3 percent at the end of 2012. The average M2M module will generate 330 megabytes of mobile data traffic per month in 2017, up from 64 megabytes per month in 2012 [4].

Cellular communication between objects, machines, or sensors has led to the growth

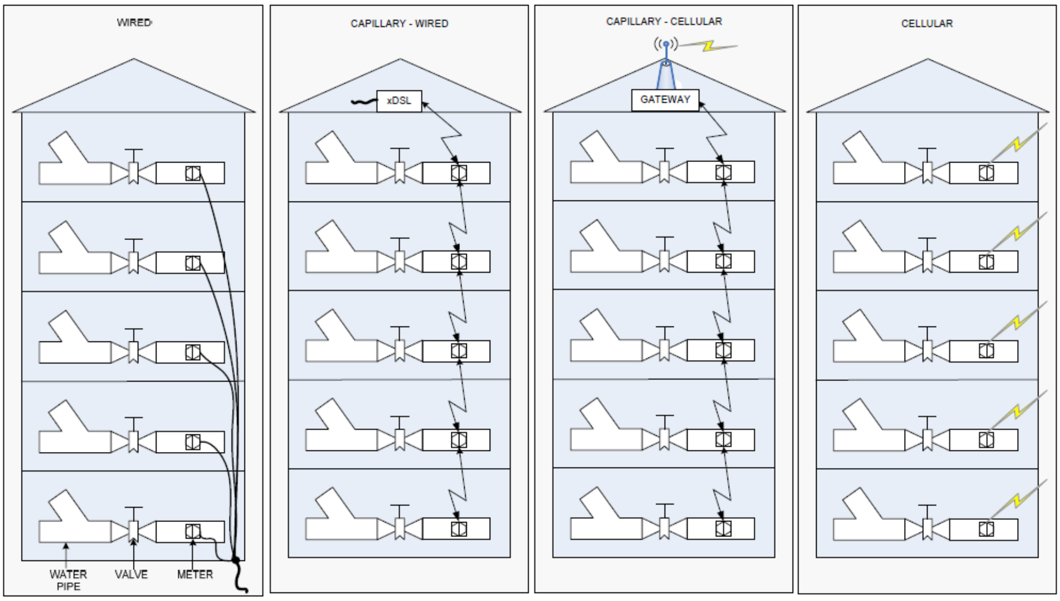

Figure 1.2 Connecting smart meters through four access methods [3]

Device Type	Growth in Devices, 2012-2017 CAGR	Growth in Mobile Data Traffic, 2012-2017 CAGR
Smartphone	20%	81%
Tablet	46%	113%
Laptop	11%	31%
M2M Module	36%	89%

Table 1.1 Comparison of Global Device Unit Growth and Global Mobile Data Traffic Growth. Source: Cisco VNI Mobile Forecast, 2013 [4]

of M2M connections. These connections are in the form of home and office security and automation, smart metering and utilities, maintenance, building automation, healthcare and consumer electronics etc. Globally, M2M connections are expected to grow three-fold from two billion in 2012 to six billion by 2017 [4].

M2M technologies are being used across a broad spectrum of industries. There are many applications that can benefit from M2M communications, such as transportation, health care, smart energy production, transmission, and distribution, city automation and manufacturing, security and safety, and others. As real-time information monitoring is helping companies to deploy new video-based security systems and hospitals to remotely monitor the progress of their patients, bandwidth-intensive M2M connections become more prevalent. Among various verticals healthcare M2M segment is going to experience the highest CAGR at 74% from 2012 to 2017, followed by automotive industry at 42 percent CAGR [4].

M2M technology makes the Internet of Things (IoT) realisable. As defined by technology analysts and visionaries, the Internet of Things (IoT) is the network of physical objects accessed through the Internet where these objects contain embedded technology to interact with internal states or the external environment [4]. IoT is the key to gaining real business value from M2M services. The authors of [5] anticipate that the IoT would extend the existing Internet with a large variety of connected devices. The proliferation of intelligent devices introduces a market for entirely new solutions based on Machine-to-Machine (M2M) technology and enterprises need more innovative ways to harness ever-increasing amounts of data and use it to drive smarter decisions, enable new services and business models, and reduce costs. Furthermore, IoT is expected to make a tremendous impact not only on how businesses operate, but also on how individuals live their lives each day.

Chapter 2

The techno-economic perspective on M2M

Besides the technological motivations for M2M that come from the advancements in semiconductor technology and improved coverage of wireless networks, there are also economic motivations for the wireless industry to pursue M2M and invest towards this technology [1].

As seen in Figure 2.1, the costs of cellular services experienced dramatic decrease and cellular broadband connectivity became ubiquitous. The decrease in the costs and sizes, and the increase of power capabilities of devices with integrated sensors, network interfaces, etc. has paved the way for manufacturers to offer diverse applications and services.

During the recent years, the traditional M2M market especially in the business field has been increased. That means that M2M service providers will continue to see an increase in the number of devices that are connected in their networks. Until today, a large portion of M2M market is related to specialised and large-scale applications whereas it is not until recently when the largest Mobile Network Operators (MNO) started adopting M2M services that are widely consumable. M2M market has received a lot of attention over the last recent years as an opportunity for substantial growth by the mobile operators. As voice revenue continues to deteriorate, operators are striving for introducing new services that will fill this revenue gap. The rise of M2M comes at a time when the traditional cellphone-based mobile services market is becoming increasingly mature and saturated, with growth slowing particularly in the developed markets like the United States and Western Europe [8]. MNOs are now realising the rising opportunities for investing towards new M2M services that can be feasible using the already existing infrastructure. As they observe an increasing saturation of wireless and wireline voice services, they now focus on data connectivity as the long term growth engine.

Under this perspective, several challenges arise. In specific, since MNOs are mostly oriented in human-to-human (H2H) connectivity and present a lack of M2M experience, a mental shift is required to a new promising market. Consequently, the high operational costs need to be reduced and the network has to be dimensioned for a number of devices that transmit data in a sporadic manner. These new market opportunities have already enhanced the cellular M2M standardization activities [2]. Due to potentially heavy use of M2M devices and thus high loads onto networks, interest and several efforts have been made from 3GPP, ETSI TC M2M, IEEE 802.16 and recently from oneM2M Partnership Project [3,26].

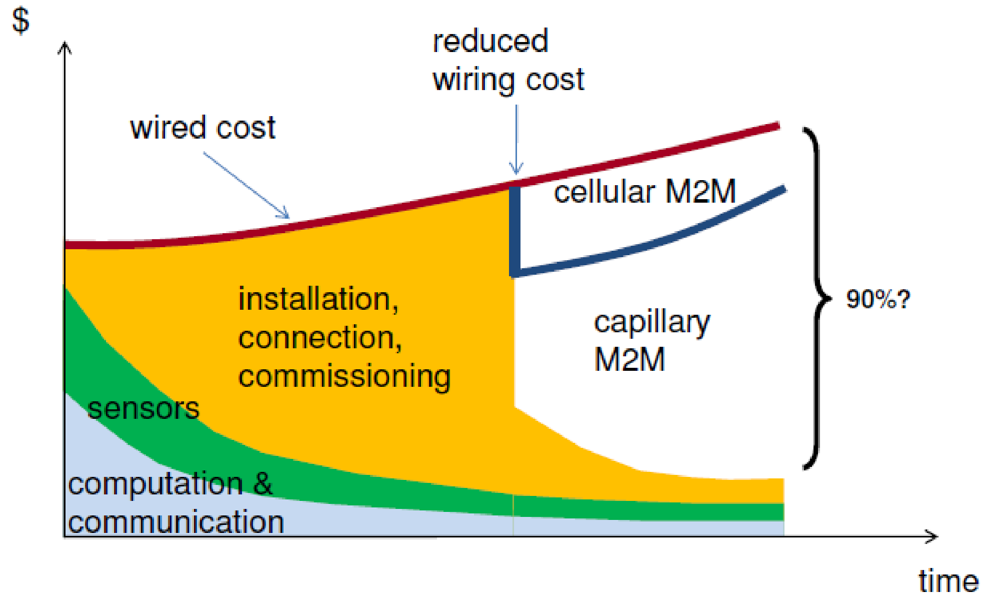

Figure 2.1 Cost comparison (evolved in time) for different solutions [6]

Due to the sporadic nature and the low amount of traffic generated by most M2M devices, communication providers can expect very low average revenue per user (ARPU), but high average revenue per application [9]. The connectivity revenue per connection, measured as ARPU, is generally much lower than the $40-50 a month generated by consumer devices such as smartphones and mobile broadband-connected laptops and tablets. As most M2M traffic is still characterized by low-speed, low usage applications comfortably served by 2G networks, connected devices may generate as little as $2-5 per device per month for mobile operators. However, the asset of connectivity is data availability. M2M applications with the use of wireless networks lead to an increased amount of transmitted data and consequently to new sources of revenue for the service providers. Large service providers such as Sprint, Telenor, Vodafone and Orange have oriented their initiatives and their overall policy towards the research on developing applications for M2M and the facilitation of finding the best route to the market. M2M, cloud computing, and application stores top the list of potential revenue-generating services. In addition, there are cases where strong incentives from public funding are provided in order to pursue to large scale applications related to smart metering, automotive and e-Health [9].

In order to integrate these needs, future M2M markets will need to be based on industry standards to achieve growth. Unlike current M2M markets, which are highly segmented and often rely on proprietary solutions, the M2M industry needs to leverage existing vertical market solutions, design platforms that horizontalize the market, and avoid the narrow solutions. The industry also needs to develop critical technologies for an optimized air interface, device manageability, network architecture, and security in order to enable future mass deployment of embedded devices [1]. These unique market dynamics call for innovative M2M solutions that enhance efficiency, bring down the costs of deployment and ongoing management, and will allow these deployments to scale to the billions of connections anticipated by the service providers.

As MNOs are increasingly playing a crucial role in the M2M value chain, Mobile Virtual Network Operators (MVNO) and other types of M2M connectivity services providers are becoming more innovative in their technology offerings and competitive strategies. Many MNOs have established M2M business units as they have expanded their market strategies beyond simply providing wholesale connectivity to MVNOs and other aggregators [10]. These capabilities lower the operational cost of M2M deployments, allowing operator margins to remain high in spite of low ARPU, and allowing operators to pass on these cost benefits to their enterprise customers. In another approach, in parallel with the establishment of M2M-specific business units, MNOs are seeking for market partnerships with Application Delivery Platforms (ADP) providers that focus on the development and ongoing support of M2M applications. ADPs show reasonable success in the market as a way to get machines to talk to each other regardless of different protocols and data formats. Using the concept of cloud-based M2M application enablement and delivery, they provide device management, software distribution and security, and backhaul enterprise integration, based on the absence of M2M standards (although standards organizations such as ETSI are working on this).

Chapter 3

Cellular and Capillary M2M technology

As mentioned in Chapter 1, M2M communications can be offered over any type of technologies or a combination of them. In the context of the project, emphasis is given on the capillary and cellular solutions for accessing the backhaul M2M network. Thus, in the following, the characteristics of these two different network architectures are further presented when applied to M2M technology.

3.1 Cellular M2M

In the cellular architecture, individual M2M devices are equipped with cellular wireless interfaces (GSM, UMTS, 3G, LTE, WiMAX, etc.) and are thus able to communicate directly with existing mobile operator networks through cellular base stations. Figure 3.1 illustrates an example of a smart home where cellular M2M technology is adopted.

As indicated in Chapter 1, the total mobile traffic is rapidly increasing through the recent and future years. Following this trend, cellular technology evolves and achieves higher data rates by investing on spectrum availability, managing more efficiently the radio resources and making use of smaller cells. The motivation of cellular technology on M2M applications lies on the excellent, ubiquitous coverage and global connectivity

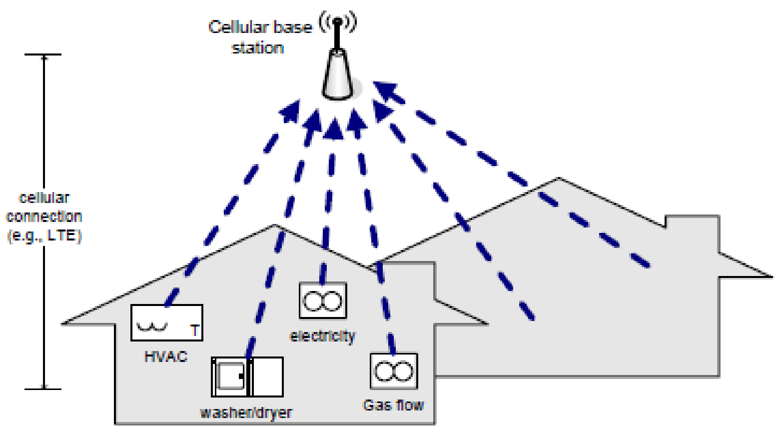

Figure 3.1 A cellular M2M network [34]

that it can provide. Cellular M2M offers easier configuration which is suitable for short-term deployments. Moreover, it uses the existing infrastructure for cellular networks with which users are already familiar. Furthermore, whenever connectivity is debated, an important issue is mobility and mobile connectivity can be considered almost synonymous with cellular communications. Security and interference control is achieved with the licensed bands in which individual companies/operators pay a licensing fee for the exclusive right to transmit on assigned channels within that band in a given geographic area. While offering significant potential in terms of coverage and mobility, this solution presents also some drawbacks, primarily on account of its high cost and higher energy consumption.

The accommodation of M2M applications under cellular technology requires a significant technological shift. There will be a lot of M2M devices, i.e. by orders of magnitude more than humans. More and more applications (mainly control) are delay-intolerant whereas today humans can tolerate delay/jitter, even for voice connections. The traffic nature will also change. Humans desire high-bandwidth data and the flow is mainly on the download whereas M2M is associated with little traffic per node, and mainly in the uplink direction. In addition, nodes need to run autonomously for a long time which means that energy requirements are higher with respect to human users who do not mind recharging their mobiles on a daily basis. Security is also of paramount concern. A major security breach in a network connecting billions of devices is unthinkable. It is expected that advanced solutions including 'security-on-chip' will be developed [1]. All these technical novelties for cellular M2M have to be implemented without jeopardizing the current cellular services[3].

3.2 Capillary M2M

In the capillary architecture, M2M devices are organized in short-range wireless networks (ZigBee, Bluetooth, WiFi, WirelessHART, etc.) similar to wireless sensor networks, through which they send data to an appropriate gateway that aggregates the data and sends it over to the mobile operator network or, sometimes, directly to the M2M server through a wireline network.

Each node typically consists of a sensor, a radio chip, a microprocessor and an energy supply [7]. Figure 3.2 illustrates the smart home example where capillary M2M architecture is provided[1]. The capillary approach is especially cost-effective when there are frequent requirements for software updates, and in high volume deployments with thousands of end devices such as meters or sensors. While scalable and much cheaper to implement and deploy, this architecture may suffer from insufficient performance compared to its cellular counterpart.

There are also some practical challenges that occur when deploying this kind of networks. At first, external interference is an important factor that is often neglected in protocol design. Figure 3.3 shows the interference between different small-range wireless technologies (WiFi, Bluetooth and Zigbee) in the unlicensed 2.4 GHz ISM frequency band.

In addition, the stochastic nature of the wireless channel (multipath fading) affects the overall performance especially in multi-hop communications [6]. This lack of reliability together with the lack of standardization are also major factors that should be taken into account. Thus, interoperability between devices can not be achieved.

[1] In this example, PAN coordinators are used as intermediate aggregation points of the data traffic from different smart houses. PAN coordinators are nodes with enhanced capabilities within the WPAN.

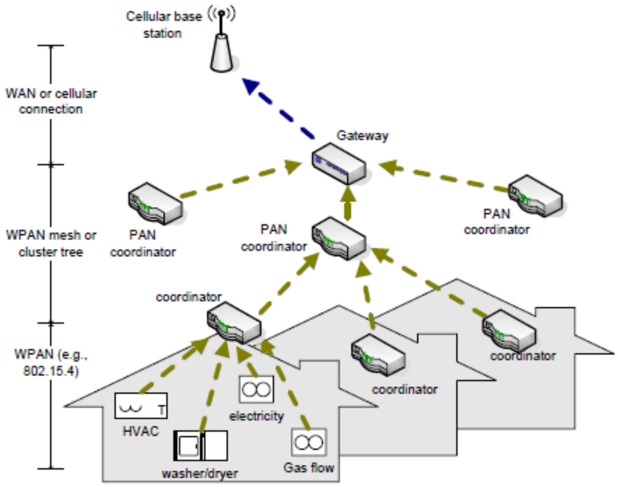

Figure 3.2 A capillary M2M network [33]

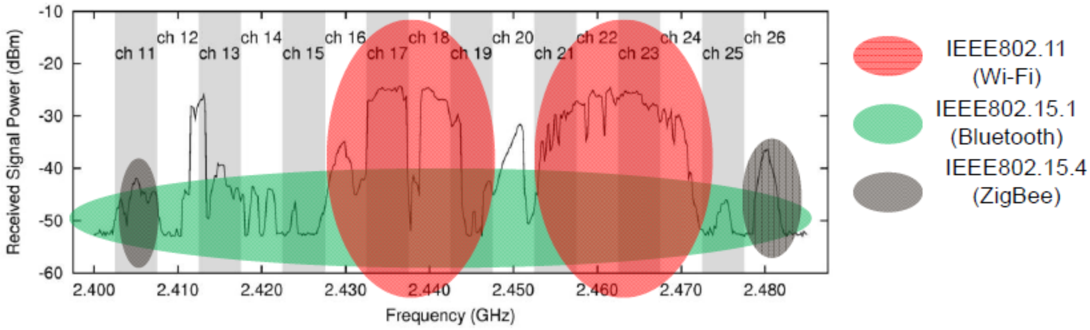

Figure 3.3 External interference [3]

Towards this, several standardization efforts pertinent to capillary M2M have been made (IEEE, IETF, ISA, ETSI, oneM2M)[3]. Finally, the lack of universal infrastructure/coverage hinders the true uptake of M2M technologies.

Whilst many insights from academic research on WSNs can be used, the capillary M2M will be dominated by industry-driven standardized low-power solutions [3]. WSNs promise significant financial cost savings. In addition, M2M gateway/aggregation points are expected to play a key role in bringing the installed short-range sensors online and providing interworking with different wireless technologies. These gateway/aggregation points can also become a platform for value-added services to enable an explosive growth of short-range smart sensors.

3.3 Comparison

According to the previous sections, by evaluating the different approaches it can be summarized that:

- The wireless cellular solution provides a dedicated cellular link between each M2M device and the backhaul M2M network. Therefore, it shows significantly high performance in terms of coverage using the already existing cellular network infrastructure. Moreover, it provides higher security and more flexibility allowing for mobile nodes. However, it has a higher operational and maintenance cost and it is less power efficient which can have disastrous effects in the lifetime on the battery-powered M2M devices.

- The wireless capillary solution provides a cheaper implementation after the establishment of a shared short-range network. It offers scalability and low power consumption which is important considering the strict energy constraints of M2M devices (sensors, actuators, etc.). The main drawbacks of this method refer to the short-range coverage resulting in a lack of universal infrastructure, the low data rate, the weaker security and the delay that the multi-hop communication causes.

Table 3.1 illustrates the technical overview and comparison of the two technologies. It can be observed that cellular solution provides many technical advantages with respect to capillary one.

M2M Technology	**Cellular**	**Capillary**
Scalability		✓
Coverage	✓	
Existing infrastructure	✓	
Power consumption		✓
Delay	✓	
Security	✓	
Interference	✓	
Mobility	✓	
Data rate	✓	

Table 3.1 Technical comparison of the two technologies

Chapter 4

Scenarios

4.1 Introduction

After comparing the cellular and capillary architectures for M2M access from a technological point of view, this section presents an economic comparison of the two solutions considering some specific case studies. As mentioned in the previous qualitative analysis, both solutions present advantages and disadvantages and the choice of a particular one is strongly dependent on the deployment scenario that is examined.

Unlike traditional communication scenarios with information exchange between human users, communication with a machine on one or both sides may have different characteristics than traditional conversational telecommunications. In the following sub-sections two scenarios are considered and a quantitative analysis is carried out. In particular,

- An outdoor scenario of an Automatic Meter Reading (AMR) system, one of the most important applications of Smart Grids (SG), with a large scale smart meter deployment where sensors are being polled both for billing purposes and to gather useful information about usage
- An indoor scenario of a smart building, a representative example of a Building Automation System (BAS), where M2M devices are used both to gather environmental data and to control other devices

The cost structure of the deployment of a mobile communication network consists primarily of a capital expenditure (CapEx) component and an operation expenditure (OpEx) component. In specific, the CapEx component, often referred as fixed cost component, incorporates all the cost incurred from the bidding process up to the commissioning of the network while the OpEx component, often referred as recurring charges, involves all the cost incurred in keeping the network running. In the following quantitative analysis[1], the CapEx includes the investments in the equipment acquisition and installation. On the other hand, the OpEx component includes the airtime charges per connection per end device, the operation and maintenance costs, application platform fees paid to Application Delivery Platform (ADP) vendors and system upgrades. ADP vendors provide complete M2M data integration and application development platform with infrastructure delivered as a cloud-based service.

The following case studies help illustrate the different costs associated with M2M deployments using either cellular or capillary architectures.

[1] In this study, only the cost components that are different in the two alternative solutions are considered for simplicity. In addition, the CapEx and OpEx of the backhaul network are not examined.

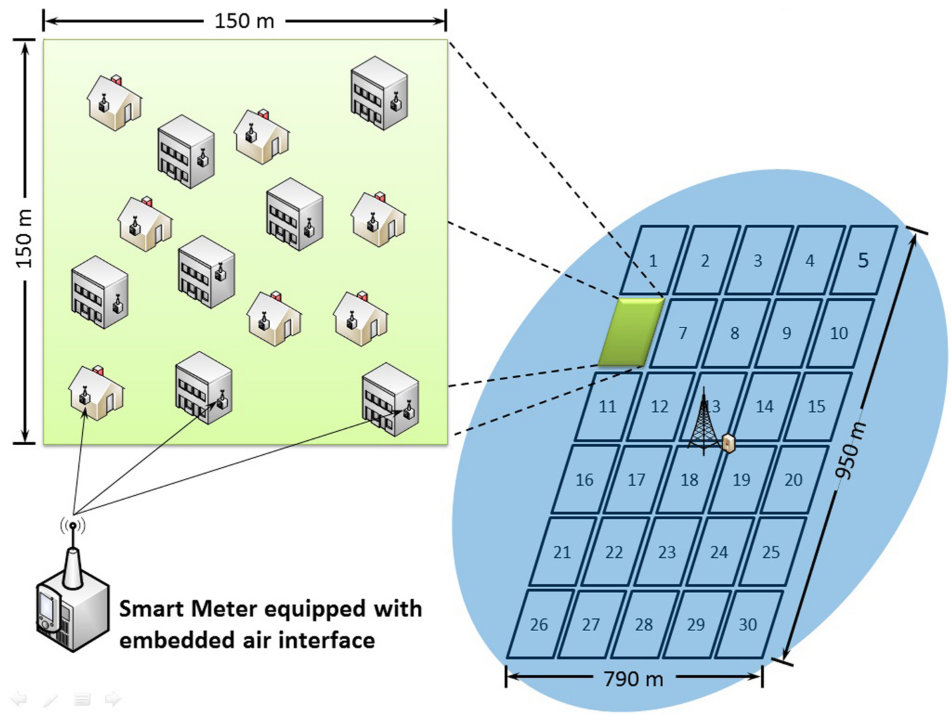

Figure 4.1 Automatic Meter Reading - Scenario Topology

4.2 Scenario A: Automatic Meter Reading

Automatic Meter Reading (AMR) is considered as one of the most important applications of Smart Grid (SG). With AMR technology, consumption, diagnostic, and status data could be collected automatically from remote (electricity/water/gas) meters and be transferred to utility offices for billing, troubleshooting, and analysing. At the present stage, AMR is typically achieved by using 2G/3G modems together with AMR devices (smart meters). The emerging LTE technology seems to be a logical continuum to this. However, some other wireless communication technologies become competitive alternatives for AMR at the same time [22].

Figure 4.1 illustrates the topology of the scenario that is examined in this section. It can be seen as a generalized model of a suburban environment. The terrain of this region is relatively flat and the 790m $\times$ 950m area is divided into 30 150m $\times$ 150m blocks. Each of the 30 blocks contains 25 houses/apartments with smart meters, each equipped with an air interface (could be cellular-based or capillary-based). The smart meters are randomly placed in each house/apartment so that the assumption that end-devices are uniformly distributed in the whole area is rational. In this scenario, it is considered that the local utility provider is planning to deploy a wireless network in this area in order to connect the smart meters (with the underlay premise that all of the 750 smart meters are belonging to this specific utility provider) with its central control system. Two different approaches and architectures i.e. the pure LTE solution and the hybrid sensor-LTE network are compared.

As illustrated in Figure 4.2, emphasis is given on one block due to the symmetric topology. An embedded LTE module is integrated in each smart meter so that it is directly connected to eNodeB.

In Figure 4.3, the hybrid sensor-LTE network approach is presented. Borrowed from the concept of Wireless Sensor Networks (WSN), each block forms a cluster and

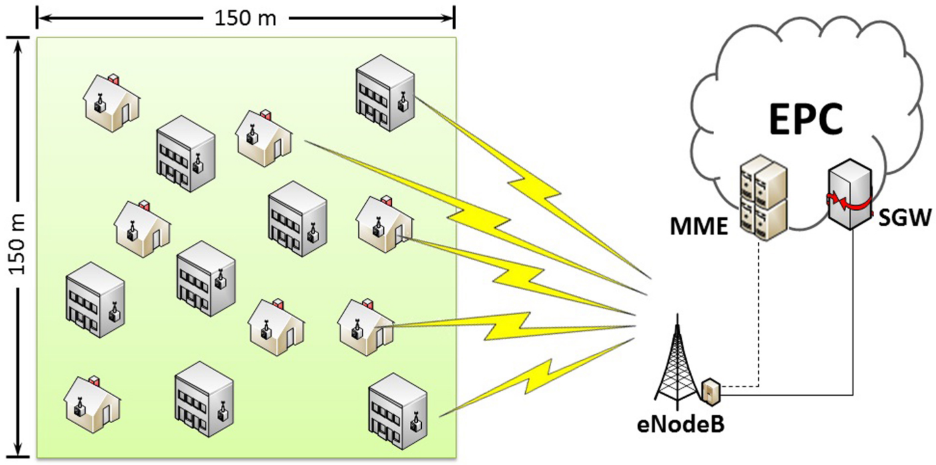

Figure 4.2 Pure LTE Solution

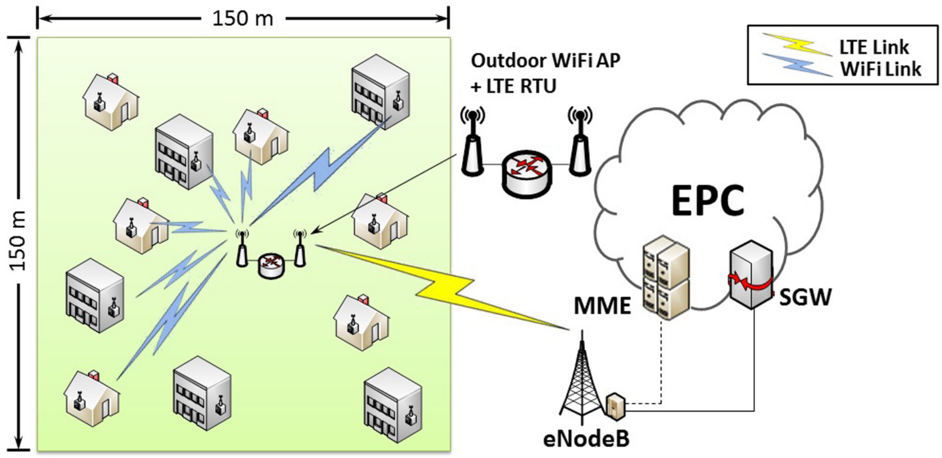

Figure 4.3 Hybrid sensor-LTE Network

the 25 smart meters in a cluster connect to an aggregation point (often referred to as cluster head (CLH)). In this context, a CLH consists of an outdoor WiFi Access Point (AP) and an LTE Remote Terminal Unit (RTU)[2]. Since the CLHs must be installed on street lampposts or building façades, the utility provider has to rent sites to place the CLHs [24]. The communication link between CLH and smart meter is a WiFi connection while CLHs are communicating with eNodeB using LTE technology. Obviously, a smart meter must be equipped with a WiFi module in this solution.

The simulation results in [22] show that both of the two solutions, as presented above, satisfy AMR requirements without causing significant hindrance to typical H2H LTE traffic from technical perspective, and then the economic requirements (both CapEx and OpEx) become the major decision factors consequently. In this study, the focus is on the utility provider's position to examine the cost of deploying a network for AMR purpose. The cost of smart meters (except for the air interface units) is not taken into consideration because it is identical in the two alternative solutions.

[2]An RTU is a device installed at a remote location and collects data, codes the data into a format that is transmittable and transmits the data back to a central station, or master [27]. An LTE RTU acts as a gateway between LTE network and Ethernet with full router capability [28].

Before comparing the total costs of ownership (TCO) of pure LTE approach and hybrid sensor-LTE approach, necessary assumptions need to be made.

- Traffic load assumption. Without loss of generality, the uplink of the SG system is only considered. It is assumed that each smart meter generates 250 bytes of information data and sends it to utility every 15 minutes [22]. The total information sent by one smart meter within one month is about 0.25×4×24×30=720 KB. For the pure LTE solution, meter reading occurs 2880 times per smart meter per month and the data generated by one meter is 8.64 MB within 1 year. For the hybrid sensor-LTE solution, meter reading occurs 2880 times per CLH per month (CLHs are scheduled to transmit the aggregated data every 15 minutes) and the data transmitted by one CLH is 216 MB per year.

- Airtime charges. The utility provider uses the existing cellular network to connect its central control system with the smart meters or CLHs. The M2M communication fee charged by the mobile operator is typically volume based and is assumed to be 4.5 SEK[3] per MB per month or 29 SEK for a 50 MB per month [16].

- Cloud-based M2M service platform access cost. The utility provider uses cloud-based application platform to collect and store data. The subscription fee paid to application platform vendor is assumed to be 0.1€[4] per 1000 meter reading requests and the cost of storing 20 MB of data for 1 year is assumed to be 0.1€ per month [13].

- CLH site rental expenditure. The authors of [24] claim that the average price for renting a site to install an outdoor WiFi AP is 120€/year for public sites and 240€/year for private sites in Belgium. Based on this information, a site rental cost of 200€ is assumed to be a typical value in European countries.

- CLH Installation and network O&M expenditure. The installation cost of CLH and the annual operation and maintenance (O&M) cost of the network are typically percentages of the CapEx. According to [23], the installation and O&M expenditure represent 5% and 10% of the CapEx respectively. In this context, the installation cost is 5% of the money invested for LTE RTUs and outdoor WiFi APs while the O&M cost of the small-range network in hybrid sensor-LTE solution is 10% of the fixed expenditure (CLH hardware cost + CLH installation cost). The O&M cost of LTE network is not considered in both solutions because of the fact that mobile operator and application platform vendor are responsible for operational issues and maintenance.

In summary, the cost items and their corresponding values are listed in Table 4.1. Based on the assumptions and cost factors stated above, the costs of the two solutions are calculated and the results are shown in Table 4.2. Additionally, Figure 4.4 shows the cost comparisons of the two solutions during the first 5 years after deploying the network.

As illustrated in Figure 4.4, the pure LTE (cellular) solution is more cost-efficient in this scenario from utility provider's perspective. The expenditure gap between TCOs of the two solutions becomes even larger as time goes by.

[3] The current exchange rate between SEK and USD is approximately 1:0.15

[4] The current exchange rate between EUR and USD is approximately 1:1.4

Item	Cost	Source
M2M LTE Modem	$120 per device	[30]
M2M WiFi Module	$45 per device	[31]
LTE RTU (CLH Hardware)	$920 per device	[32]
Outdoor WiFi AP (CLH Hardware)	$1365 per device	[18]
Airtime charges	$0.675 per MB per month	[16]
	$4.35 for a 50MB-Pack per month	
Application platform access fee	$0.14 for every 1000 requests in 1 month	[13]
	$0.007 per month for storing 1 MB for 1 year	
CLH Installation Cost	5% of CLH Hardware	[23]
Site Rental	$280 per site per year	[24]
Capillary network O&M	10% of Fixed Cost	[23,24]

Table 4.1 Cost factors in Scenario A

Cost component	Cellular solution	Capillary solution
Fixed costs		
Connectivity Equipment	$90,000	$102,300
CLH Installation Cost	0	$3,428
Recurring charges		
Airtime Charges	$4,374/Year	$1,566/Year
Application Platform Access Fee	$4,324/Year	$695/Year
Site Rental	0	$8,400 per year
Operation and maintenance		$7,198/Year
Total costs		
Fixed Costs	$90,000	$105,728
Recurring/Annual	$8,698	$17,859
First Year Total	$98,698	$123,587

Table 4.2 Cost comparison in Scenario A

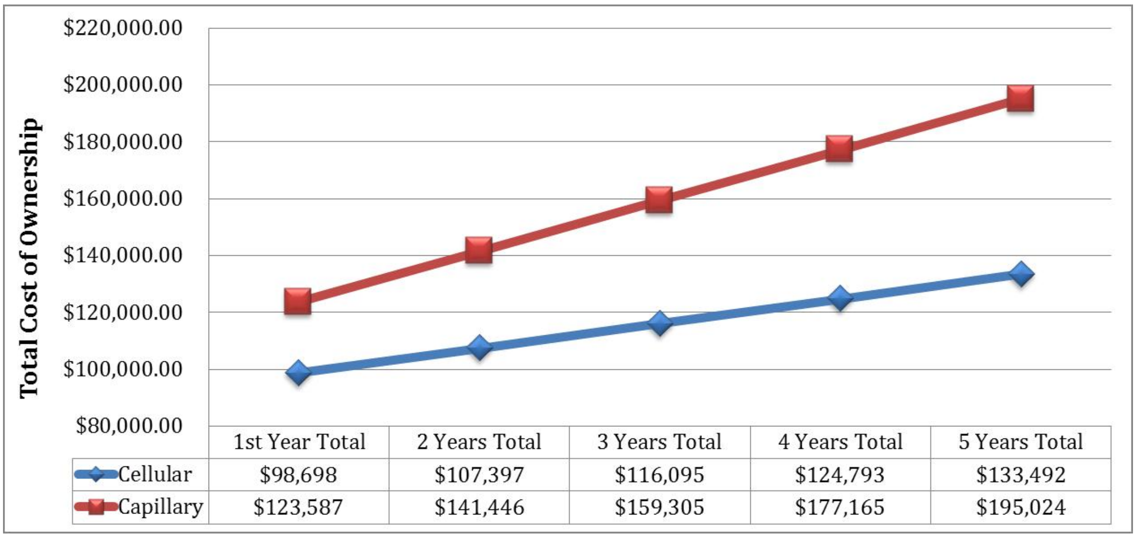

Figure 4.4 Cost comparisons of cellular and capillary solutions in a 5-year period for Scenario A

It is worthy to note that cellular solutions outweigh capillary solutions also from mobile operator's perspective. For capillary solutions, significant amount of money must be invested in deploying, operating, and maintaining small-range networks that are based on capillary technologies. While in cellular solutions, there is hardly additional investment (unless new base stations are established for capacity and/or coverage reasons).

4.3 Scenario B: Smart building system

Building automation is an area where M2M communication is a promising topic. By enabling M2M communication in building appliances, new facilities are brought to the foreground. A 'smart building' or 'intelligent building' refers to a building controlled by a Building Automation System (BAS). The aim of building automation is to monitor and to control the mechanical, security, fire and flood safety, lighting (especially emergency lighting) and Heating, Ventilation, and Air Conditioning (HVAC) systems in a building [11,29].

In the scenario proposed, the cost analysis is based on the property-owner perspective. In particular, a 10-floor smart building consisting of a mixture of M2M devices with varying traffic characteristics is considered and the owner of the building wants to decide for the most cost-efficient solution. The frequency of the data transmissions generated from the M2M devices depends on the physical quantity they measure or/and the functionality of the attached device. In specific,

- 200 temperature sensors for industrial machines sending data every 15 minutes,
- 50 humidity sensors sending data every 30 minutes,
- 10 fire detection systems with on-board intelligent controllers sending data every 6 minutes,
- 10 HVAC systems panels sending data every 30 minutes,
- 10 connections to control and manage automated elevators sending data every 10 minutes and
- 5 intelligent network printers sending data every 60 minutes

In the cellular solution, as is illustrated in Figure 4.5, each module is equipped with a cellular (UMTS or LTE) connectivity interface and therefore is capable of communicating with the base station directly. Alternatively, the capillary solution is shown in Figure 4.6, in which the end-devices communicate with the base station via hubs. A hub acts as a gateway between the cellular network and the capillary network and delivers traffic in both directions. It is assumed that a hub can accommodate up to 20 devices using small-scale technologies, such as WiFi, in a point-to-multipoint manner [17]. Therefore, in total 15 hubs are needed in order to cover the 285 end-devices. On the other hand, the link between a hub and the base station is based on cellular technology (LTE). In this scenario, it is considered that the WiFi infrastructure is held by the property owner and therefore the additional fees for WiFi access are not considered. The following assumptions are made throughout the quantitative analysis of this scenario:

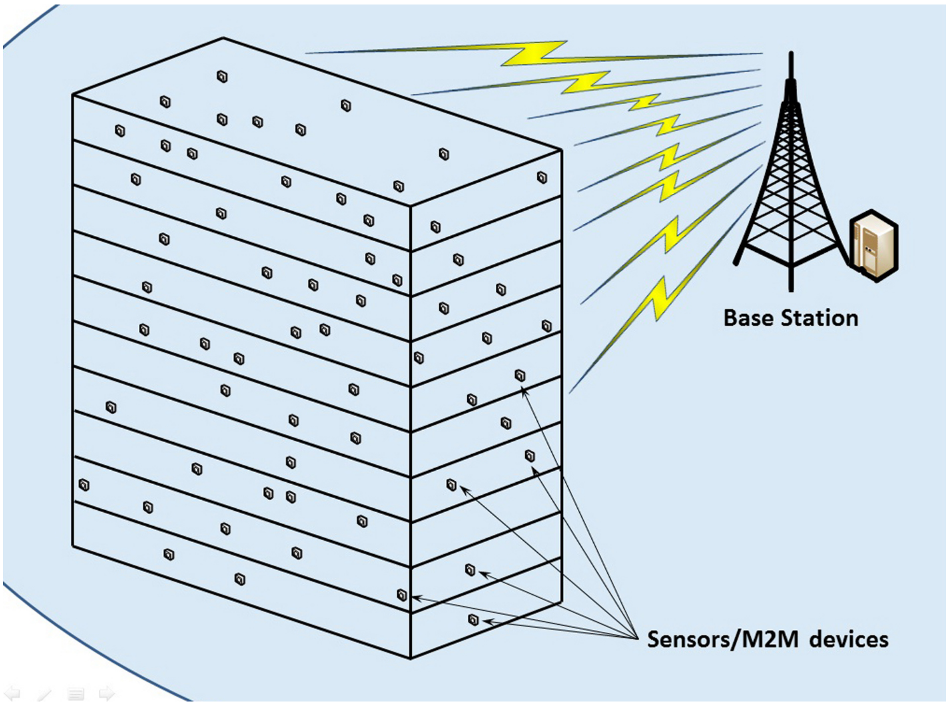

Figure 4.5 Smart Building with Cellular Solution

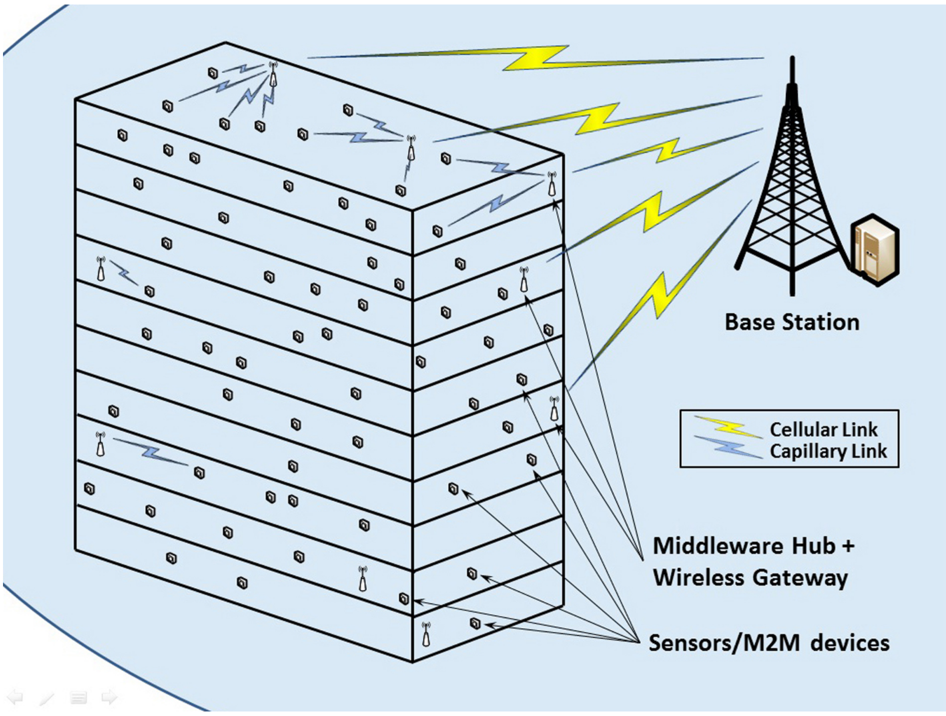

Figure 4.6 Smart Building with Capillary Solution

Type of sensor	Transmission frequency	Transmissions per device per month	Data per device per month (in MB)
Temperature sensor	15 min	2880	1.44
Humidity sensor	30 min	1440	0.72
Fire detection sensor	6 min	7200	3.6
HVAC sensor	30 min	1440	0.72
Elevator sensor	10 min	4320	2.16
Printer sensor	60 min	720	0.36

Table 4.3 Traffic data in Scenario B

- Traffic consideration of each M2M end-device per month. According to the traffic characteristics of each particular type of M2M devices that were defined before and assuming data transmissions of 0.5 KB each, Table 4.3 is constructed. The values of traffic data are used in the computation of the application platform access and airtime costs which are volume dependent. In the case of capillary architecture, assuming that the hubs are located inside the building in such a way that the average number of transmissions per month of each end-device connected to the hub is equal to the average number of transmissions of the six different types of sensors, that is 3000, the number of transmissions accommodated by a particular hub is equal to $3000\times20 = 60000$ per month. Furthermore, the amount of data settled in each hub per month is equal to 30 MB, considering transmissions of 0.5 KB each. Concerning also the data per month that each type of sensor generates per device per month, it is compatible with what was mentioned in the previous chapters, as typical M2M applications are related with hundreds of KB to few MB of data per month. According to [12], M2M applications use significantly less data per month than do consumer devices. There are a number of M2M applications that require less than 100 KB per month whereas 'high volume' M2M applications require no more than 1 MB to 5 MB of data monthly.

- Cloud-based M2M service platform access cost. Considering a cloud-based M2M application enablement and delivery, the integration cost concerning the market partnership between mobile operators and application delivery platform vendors needs to be taken into consideration, as in Scenario A. This cost is related to several operations such as device management, software distribution and security. The particular costs that will be considered in the following study are related to the volume of data transmissions that the devices produce per month and also to the data storage capabilities that the platform provides. According to the subscription details of a cloud-based application platform in [13], the cost per month and smart device for 1000 data transmissions is[5] 0.1€ and for 20 MB storage after one year, 0.1€ per month. As in Scenario A, these values are used in the computation of the ADP Integration cost for the end-devices in the cellular case and for the hubs in the capillary one. This particular cost analysis is illustrated in Table 4.4. The sum over the rows in the last column of Table 4.4 gives the overall cloud-based M2M service platform access cost per month in the cellular case. In similar way, this cost is computed for the capillary case, for the 15 in total hubs, using the previous assumption regarding the number of transmissions and data accommodated in each hub.

[5] The same exchange rate between EUR and USD is used as in Scenario A

Type of sensor	Number of sensors	Transmissions per device per month	Data per device per month (in MB)	ADP cost per device per month	ADP cost per month
Temperature sensor	200	2880	1.44	0.41328	82.656
Humidity sensor	50	1440	0.72	0.20664	10.332
Fire detection sensor	10	7200	3.6	1.0332	10.332
HVAC sensor	10	1440	0.72	0.20664	2.0664
Elevator sensor	10	4320	2.16	0.61992	6.1992
Printer sensor	5	720	0.36	0.10332	0.5166

Table 4.4 Cloud-based M2M service platform access cost in Scenario B

- Airtime charges for devices and hubs. According to [12,14,15], airtime charges for M2M devices range depending on the volume of data that they generate. In addition, MNOs formulate their price plans in prepaid data packages with a lower monthly charge/MB as long as the amount of requested data increases. Therefore, considering, as in Scenario A, the price plan in [16] charging 4.5 SEK[6] per MB per month for end-devices and 29 SEK for a 50 MB data package per month for the hubs, Table 4.5 shows the overall airtime charges per month. It should be noted that a 50 MB data package is chosen for the traffic data of a hub, which is larger than the 30 MB that in average accommodates, since the number of devices and/or the frequency they send data might change affecting the total traffic.

Type of sensor	Number of sensors	Transmissions per device per month	Data per device per month (in MB)	Airtime charges per device per month	Airtime charges per month
Temperature sensor	200	2880	1.44	0.972	194.4
Humidity sensor	50	1440	0.72	0.486	24.3
Fire detection sensor	10	7200	3.6	2.43	24.3
HVAC sensor	10	1440	0.72	0.486	4.86
Elevator sensor	10	4320	2.16	1.458	14.58
Printer sensor	5	720	0.36	0.243	1.215

Table 4.5 Airtime charges in Scenario B

The sum over the rows in the last column of Table 4.5 gives the overall airtime charges per month in the cellular case. Considering a data package of 50 MB for each of the 15 in total hubs, the airtime charges per month for the capillary case are computed similarly.

- Connectivity equipment. In the context of this scenario, according to [31] a price of $45 for a sensor is considered. Moreover, the cost of the hub equipment incorporating both LTE and WiFi interfaces is considered equal to $330 [19,20] and the cost of a sensor with direct cellular (LTE) access equals to $120 [30].

- O&M expenditure. According to [21,29], for the capillary solution, the annual O&M expenditure component can be considered equal to 10% of the fixed expenditure (equipment cost of the hubs). Software updates are also included in this cost whereas in the cellular case they are considered bundled with the hosting fee. As in Scenario A, the O&M cost of LTE network is not considered in both solutions because of the fact that mobile operator and application platform vendor are responsible for operational issues and maintenance.

In Table 4.6, the results of the quantitative analysis are presented. The costing components and the overall analysis are considered from the perspective of the property (building) owner.

[6] The same exchange rate between SEK and USD is used as in Scenario A

Cost component	Cellular solution	Capillary solution
Fixed costs		
Connectivity Equipment	$34,200	$17,775
Recurring charges		
Airtime Charges per month	$263.655 per month	$65.25 per month
Application Platform Access Fee	$112.1022 per month	$129.15 per month
Operation and maintenance	$0	$495 per year
Total costs		
Fixed Costs	$34,200	$17,775
Recurring/Annual	$4,509	$2,828
First Year Total	$38,709	$20,603

Table 4.6 Cost comparison in Scenario B

Figure 4.7 Cost comparisons of cellular and capillary solutions in a 5-year period for Scenario B

It can be seen from Table 4.6, that capillary solution performs better in terms of cost efficiency. In addition, a 5-year subscription deployment scenario has been considered in order to evaluate the long-term expenses. Figure 4.7 shows the cost comparisons of the two solutions during the first 5 years after deploying the network.

As illustrated in Figure 4.7, the capillary solution is more cost-efficient in this scenario from property (building) owner's perspective. The expenditure gap between TCOs of the two solutions becomes even larger as time goes by.

4.4 Summary

For Scenario A, as shown in section 4.2, the pure LTE solution is much more cost-efficient than the hybrid sensor-LTE solution from utility provider's perspective. However, as is clearly shown in Figure 4.8, the capillary solution becomes preferable as the cluster size (the number of smart meters per cluster) increases. Note that the analysis in this paragraph is idealized without consideration of technical issues that may be

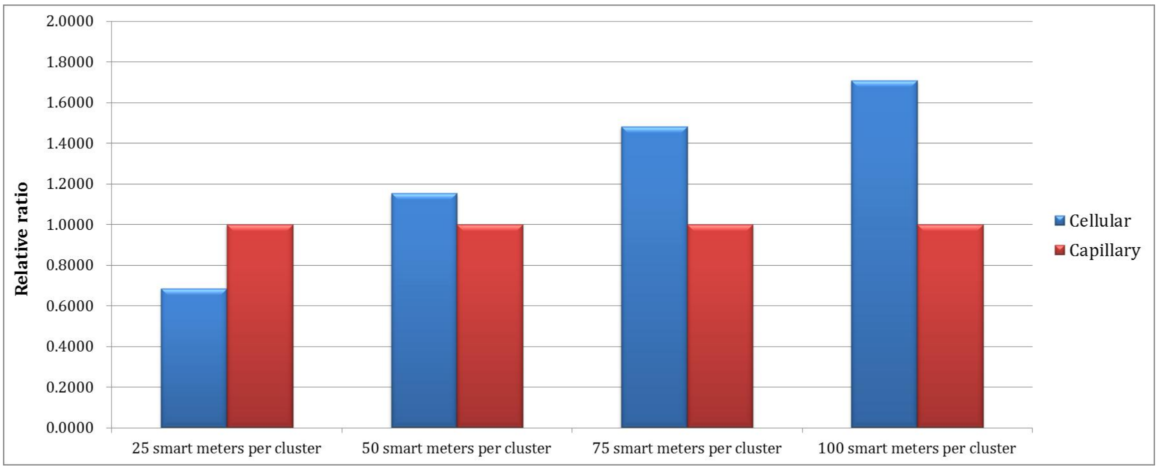

Figure 4.8 Relative ratio of the 5-year-total-costs of cellular solution and capillary solution with different cluster size (Scenario A)

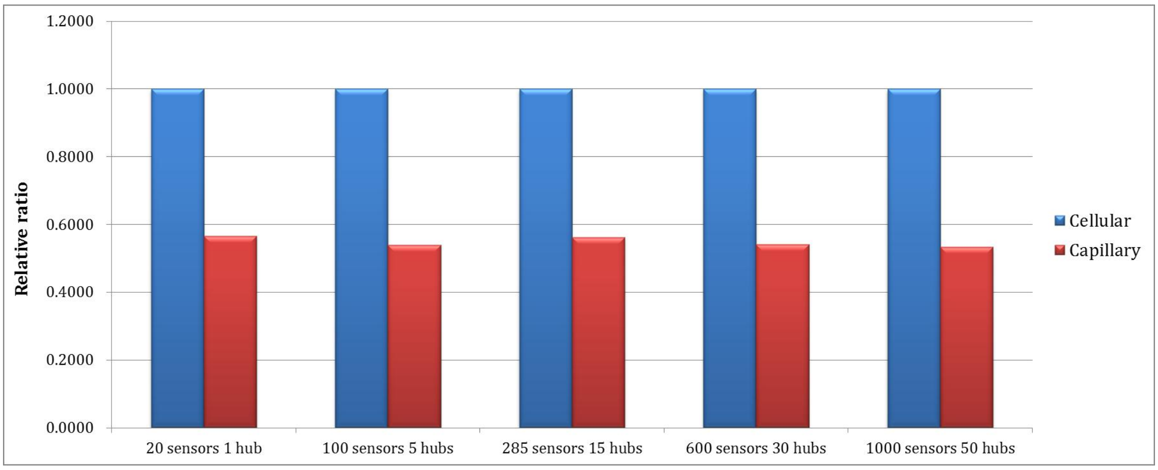

Figure 4.9 Relative ratio of the 5-year-total-costs of cellular solution and capillary solution with different number of sensors/hubs (Scenario B)

introduced by increased cluster size because that is beyond the scope of this project.

For Scenario B, as shown in section 4.3, the capillary solution outweighs the cellular one. In addition, it should be underlined that while the number of sensors deployed within the 10-floor building changes, the relative difference in the total cost from the building owner's perspective remains approximately the same, as shown in Figure 4.9. However, in case that the sensors' transmission frequency is increased, resulting in an augmented traffic load, it can be seen from Figure 4.10 that the capillary solution performs even better in terms of cost efficiency with respect to the cellular one.

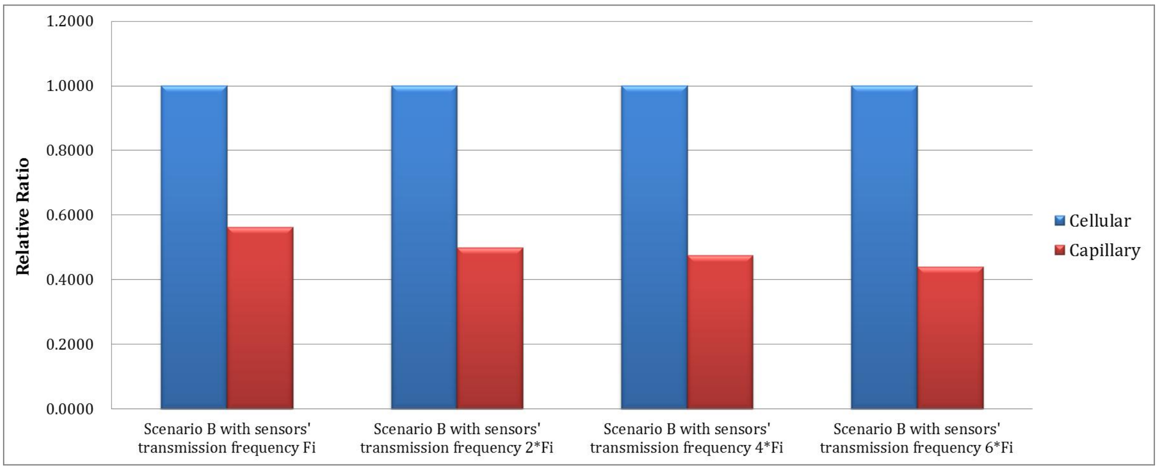

Figure 4.10 Relative ratio of the 5-year-total-costs of cellular solution and capillary solution for increasing sensors' transmission frequency (Scenario B)

Chapter 5

Conclusions

In the context of the project, a techno-economic comparison of two different architecture deployment solutions for M2M communications, the cellular and the capillary, is carried out. For this, two different scenarios are studied concerning the cost efficiency of the two solutions and the results are presented in a comparative method.

According to the cost evaluation that was performed in Chapter 4, some interesting conceptual outcomes can be summarized as follows:

- In a relative low traffic load situation, as presented in Scenario A, the number of end-devices that a small-range network can serve plays the major role in decision-making. More specifically, the more end-devices connected to an aggregation point, the more cost-efficient the capillary solution will be.

- In a higher traffic load situation, as presented in Scenario B, the traffic load, corresponding to the frequency of data transmissions, takes over the place of the number of end-devices in a way that higher traffic load makes cellular solution perform worse than the capillary one from the perspective of cost-efficiency.

- The deployment environment is also a factor that can not be neglected in decision-making as outdoor equipments are typically much more expensive than indoor devices (security, weather). Besides, significant amount of money may be needed to be invested for renting sites for placement of the outdoor equipment while this expenditure does not exist in the indoor case.

It should be underlined that the above mentioned conclusions are valid from the user's (utility provider/property owner) perspective.

Both from the qualitative and the quantitative analysis that are performed, one can argue that the preference of one solution or the other is strongly dependent on the specific deployment scenario that is assumed. Moreover, the perspective under which each scenario and its cost components are considered, affects the way the cost comparison is performed and, as a consequence, the preference of each solution.

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