Assessment of wireless solutions in emerging broadband markets

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ABSTRACT OF THE
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Although broadband markets have grown steadily since the advent of the mobile Internet, penetration levels for developing countries are far from reaching the ordinary citizen. This thesis analyses three hypotheses as bottlenecks to the growth of emerging mobile broadband markets: (i) the low competence of users, (ii) the low quality of service, (iii) the high access price and, based on the results, alternative wireless solutions are studied to accelerate the Internet diffusion.

Bottleneck hypotheses are evaluated through a quantitative bottleneck analysis that includes measured mobile QoS levels and macroeconomic indicators from a total of 9 cities including emerging (6) and advanced markets (3).
Provided that low quality of service and data prices are identified as the main bottlenecks, a qualitative value network analysis evaluates wireless access technologies, caching technologies, collaborative business environments and, operator revenue models seeking a cost-effective solution.

As a result, the thesis concludes that the affordability of broadband Internet is limited, in the first place, by the least cost-effective network technology (network costs need to be minimized), secondly by the level of competition in the market (profits of operators need to be minimized), and finally by business models of operators which could include subsidies from advertisers, content providers, governments, or implement a freemium model (access prices are minimized).

Keywords: Broadband market, Scalable Networks, Affordable Internet, Wireless Access, Alternative Networks

Preface

I want to thank Professor Heikki Hämmäinen for his dedicated help and guidance.

I am also grateful to the Network Economics team for their friendship and advice: to Benjamin who introduced me to the SCALA programming language, to Alexandr for his supervision as tutor, to Tapio who taught me how to design value networks, to Arturo for his pro-activeness and support, to Nancy for referring me to the best sources, and to Joonas and Kalevi.

Finally, this thesis would have not been possible without the decisive and encouraging support of Sonja and both my Catalan and Finnish families.

Otaniemi, 18.04.2016

Jaume Benseny Quintana

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Abbreviations

3GPP	3rd Generation Partnership Project
ARPU	Average Revenue Per User
BH	Backhaul portion of a network
BHO	Backhaul Operator
BS	Base Station
CAGR	Compound Annual Growth Rate
CAPEX	Capital Expenditure
CDI	Critical Design Issue
CDMA-CA	Carrier sense Multiple Access with Collision Avoidance
CDN	Content Delivery Network
CFI	Competition Framework Index
CPE	Customer Premises Equipment
CN	Community Network
DSL	Digital Subscription Loop
DVB-S2	Digital Video Broadcasting - Second Generation
DWDM	Dense Wavelength Division Multiplexing
EDFA	Erbium Doped Fiber Amplifiers
ETSI	European Telecommunications Standards Institute
FH	Fronthaul portion of a network
FSS	Fixed Satellite Services
GAIA	The Global Access to the Internet for All
GGC	Google Global Cache
GNI p.c.	Gross National Income per capita
HHI	Herfindahl-Hirschman Index
HTTP	Hypertext Transfer Protocol
HTTPS	HTTP Secure
HTS	High-Throughput satellite Services
KPI	Key Performance Indicator
OFDM	Orthogonal Frequency-Division Multiplexing
OFDMA	Orthogonal Frequency-Division Multiple Access
QoS	Quality of Service
ICT	Information and Communication Technologies
IDI	ICT development Index
IIB	Internet International Bandwidth
IP	Internet Protocol
IRTF	Internet Research Task Force
IEEE	Institute of Electrical and Electronics
ISM	Industrial, Scientific and Medical
ISP	Internet Service Provider
INFODEV	Information for Development Program
ITU	International Telecommunication Union
ITU-R	International Telecommunication Union - Radiocommunications
IXP	Internet eXchange Point
LEO	Low Earth Orbit satellite
LTE	Long Term Evolution
MVNO	Mobile Virtual Network Operator

NO	Network Operator
OCDE	Organisation for Economic Co-operation and Development
OPEX	Operational Expenditure
OTT	Over The Top content providers
PSN	Publish and Subscribe Networking
RIFE	architectuRe for an Internet For Everybody
ROI	Return on Investment
RTT	Round Trip Time
SMS	Short Message Service
SONET	Synchronous Optical Networking
SP	Service Provider
TCP	Transmission Control Protocol
TLS	Transport Layer Security Protocol
UE	User Equipment
UHF	Ultra High Frequency
UN	United Nations
VHF	Very High Frequency
VNA	Value Network Analysis
VNC	Value Network Configuration
VNO	Virtual Network Operator
VOD	Video On Demand service
VOIP	Voice Over IP service
WI-FI	"Wireless Fidelity"
WIMAX	Worldwide Interoperability for Microwave Access
WISP	Wireless Internet Service Provider

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1 Introduction

1.1 Motivation

The first wave of Internet services arrived in developing countries through personal computers and fixed-line connections, just as it had happened before in Western Europe and the United States. Unfortunately, only privileged citizens had access at few aggregation points such as Internet cafes and Universities. To address this disparity between citizens, at the beginning of the millennium governments and international organizations actively supported the diffusion of the Internet. For instance, in 2003 India implemented a state-scale program to deploy and promote e-kiosks. Lamentably, the associated e-literacy campaigns showed low participation rates. The most frequent reason not to participate was "Computers are of no use to me" [1]. Another similar example is the e-Sri Lanka programme funded by the World Bank in 2005. In this case, the observed low Internet usage was caused by: the lack of local content, the lack of awareness of relevant online resources and language difficulties [2]. Therefore the diffusion of the fixed-Internet was not only limited by its geographical availability, but also by a low user adoption rate.

With the emergence of mobile broadband technologies, the mobile phone has become the key enabler of Internet access in developing countries. According to a survey carried out in 2011, more than 80% of Internet users in Namibia, Uganda and Ethiopia accessed the Internet via a mobile phone. For South Africa, Kenya, Nigeria, Tanzania, and Rwanda, the corresponding number was 70% [3]. However, the disparity between mobile penetration levels remains huge across developed (84%) and developing (21%) countries [4].

Nevertheless, the mobile broadband market is rapidly developing worldwide and an endless number of questions remain open: Why is the mobile broadband penetration expanding at different rates in different countries? And what are the main constraints that limit Internet diffusion? Are constraints from the fixed-Internet going to affect the mobile Internet as well?

1.2 Research Questions

The main objectives of the thesis research are to identify the constraints to emerging broadband markets and, to identify network technologies, Value Network Configurations (VNCs) and operator revenue models that could accelerate this in developing countries. Two research questions are addressed:

Q1: What are the bottlenecks the diffusion of the Internet faces in emerging broadband markets?

Three bottleneck hypotheses are preliminarily identified by analyzing aspects of demand and supply of the broadband market.

1. Low level of competence of users. Demand for Internet is not satisfied due to the inability of users to operate (mobile) devices or applications.

2. Low quality of service. Providers of the broadband market do not supply enough capacity or this is not properly delivered to users (e.g. low service availability, limited coverage).

3. High access price. Demand might be constrained by low-income levels of users and/or competition between suppliers might need to be increased via the regulatory framework.

Q2: Which value network configurations could accelerate the development of the broadband market in developing countries?

The following topics are taken into account when addressing the research question:

1. How could operators benefit from operating on a shared and open infrastructure? Are costs reduced? Is market competition affected?

2. What stakeholders would be interested in subsidizing the access cost of users? As a long-term investment (e.g. to support m-education)? As an operational saving (e.g. e-government, e-health services)? As partnership with operators (e.g. m-banking, advertisement)?

3. What business strategies and pricing structures might best address the needs of low-income users and local businesses (e.g. zero-rating applications, transaction-based pricing, bundle of services)?

1.3 Scope of Research

The thesis research focuses on the technological and economic factors that affect the development of the broadband market when providing services to underserved regions and communities in developing countries. In this thesis, an underserved region is defined as a geographical location which lacks the ICT infrastructure to provide broadband services to the population. And, an underserved community is understood as a group of users that cannot afford market prices of Internet access. A relevant organization that works in this context is the Global Access to the Internet for All (GAIA) Research Group [5]. This is an Internet Research Task Force (IRTF) initiative that aims to increase the visibility of the challenges and opportunities for enabling global Internet access in terms of technological and socio-economic factors.

The thesis defines as the baseline the situation of several emerging mobile broadband markets (as a sub-case of emerging broadband market) including observed QoS, the price of data and, macroeconomic indicators. Next, thesis research explores the potential of alternative networks [6] to provide underserved communities taking the mentioned baseline as reference.

Alternative network deployments are defined by GAIA as: *"Set of network access models that have emerged in the last decade with the aim of providing Internet connection, following topological, architectural and business models that differ from the so-called "mainstream" ones, where a company deploys the infrastructure connecting the users, who pay a subscription fee to be connected and make use of it."*

Therefore, it is in the scope of this thesis research to explore ecosystem around Alternative Networks. Although previous research on business models to support these and their associated services exist (telephony [7] and data [8]), scalability and sustainability problems persist [9], particularly in developing countries. Part of this research is executed in the context of the Horizon 2020 architectuRe for an Internet For Everybody (RIFE) Project [10] which aims at developing a system architecture to keep costs of deployment at an affordable level for communities, while providing novel community-oriented services.

1.4 Research Methods

First, an extensive **literature review** presents the main enablers of international Internet bandwidth as well as last-mile connectivity in developing countries. Major attention is devoted to the comparison between technical and businesses features between wireless access technologies. In addition, the benefits of Content Delivery Networks (CDNs) are also introduced as the principal enablers of digital content. Finally, the role of regulation and competition is described based on guidelines elaborated by the ITU as well as the observed impact of prices in emerging markets. Complementary approaches to competition are also reviewed including Mobile Virtual Network Operators (VNOs) and the Open Access.

Second, a **statistical analysis of network measurements** from the Netradar platform is performed to characterize the main indicators of delivered QoS of mobile networks in emerging markets. Measurements gathered in a crowd-sourced effort by individual users are statistically analysed to determine what is the median download and upload goodputs as well as latencies provided by different mobile technology generations and measured by multiple mobile devices.

Third, a quantitative **bottleneck analysis** of diverse data from nine sample countries is conducted to identify the main constraints of Internet broadband subscriptions. Candidate bottlenecks (capacity, price and user competence) are evaluated through an Internet broadband market model that assumes consumers maximize consumer surplus. The data includes mobile network measurements from a large city in 9 countries as well as national indicators of business, technical, and social factors. The studied countries include three advanced mobile markets: Finland, UK, and Spain and six emerging mobile markets: Brazil, India, Iran, Mexico, Indonesia, and Tanzania. As a result, the dominant bottleneck in each city is identified and recommendations suggested.

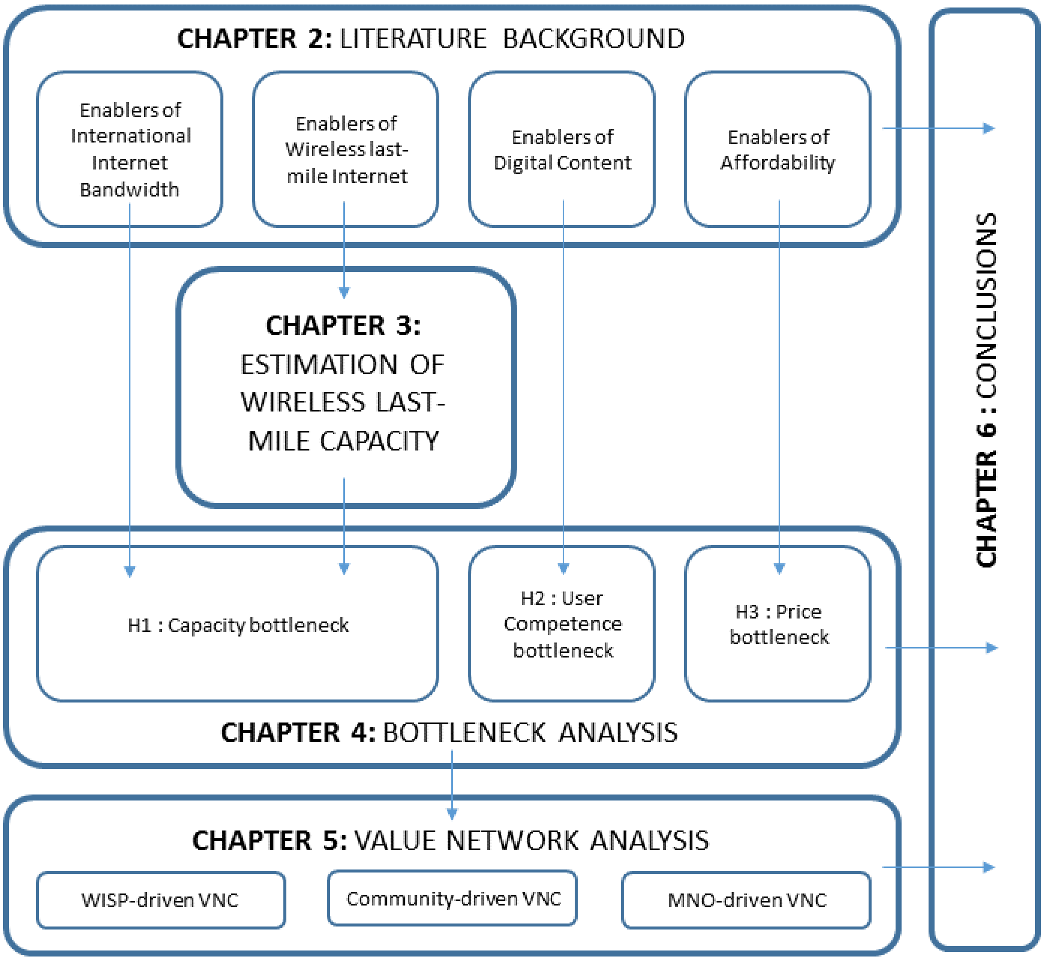
Last, literature review and identified constraints are utilized in a qualitative **Value Network analysis** to identify plausible scenarios, related business strategies as well as operator' revenue models that aim at adding new Internet broadband subscribers. Network technologies, business contracts and subscriptions are assessed to reach underserved communities and regions. Two viewpoints are taken, one concentrating on the requirements of the RIFE project [10] and the other considering a mobile operator point of view.

1.5 Structure of Thesis

Figure 1 presents the 6 chapters of the thesis, the principal topics per chapter and, the links between these.

Chapter 2 introduces the technological enablers of both international and last-mile capacity from a technical and business standpoint. Chapter 3 estimates the capacity delivered in the last-mile by analyzing mobile network measurements. Chapter 4 studies the bottlenecks to the development of the mobile broadband market by combining the information gathered in Chapter 2 and 3. Chapter 5 assumes the results obtained in Chapter 4 as a starting point and explores three value network configurations that could accelerate broadband Internet diffusion. Finally, Chapter 6 prioritizes and discusses results obtained along previous chapters and summarizes the major outcomes.

Figure 1: Structure of Thesis



2 Literature Review

2.1 Enablers of International Internet Capacity

2.1.1 Satellite Network Technologies

Since the 1990s, the satellite industry has identified underserved regions, particularly those form Sub-Saharan Africa, as markets of enormous potential. In fact, satellite operators distribute digital television and high-end telecommunication services to the consumer and the corporate segment (e.g. oil, gas, banking, mining and government), respectively.Moreover, according to the 12th edition of the *Global Satellite Capacity Supply & Demand Study* issued in 2015 [11], total demand for data services provided through High-Throughput satellite Services (HTS) is expected to grow up to the 3 Tbps driven by new enterprises that require from IP trunking in landlocked countries (e.g. Democratic Republic of Congo).

The key advantage of satellite network technologies is the ability to provide a reliable and quickly deployable backhaul connectivity with minimal infrastructure requirements on the client side. The downside is the lack of scalability resulting from the high cost of manufacturing and launching a new satellite. In other words, the marginal cost of adding additional capacity is high and, as a result, cost of transmission per bit do not largely decrease with volume. Additionally, the delivered capacity through satellite technologies is severely limited not only by the shared medium but also by large latency times, link impairments (e.g. multipath, fading, rain attenuation and shadowing), bandwidth asymmetry (approx. 1:10 regarding uplink:downlink) and, the consequent dysfunctions in connection oriented protocols (e.g. RTT fairness, multiple segment loss of TCP) [12]. Fortunately, performance-enhancing proxies (PEPs) improve the end-to-end performance of protocol including TCP. In addition, low-earth-orbit satellites (LEO) provide latencies below the 300 ms.

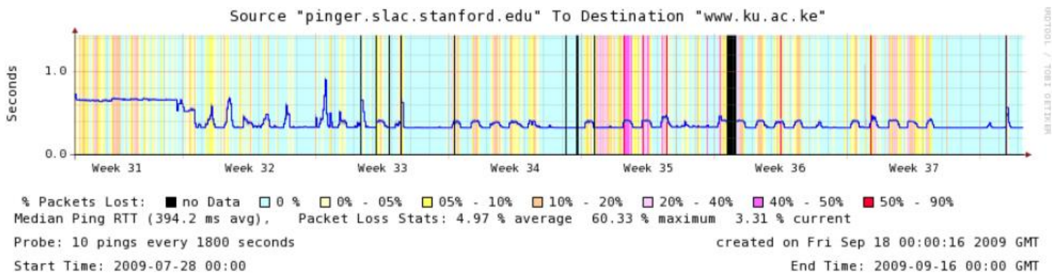
The latest standard for broadband satellite communications named Digital Video Broadcasting - Second Generation (DVB-S2) was defined by European Telecommunications Standards Institute (ETSI) in 2003 [13]. This enables: 1) Broadcast Services for standard definition TV and HDTV, 2) Interactive Services including Internet Access for consumer applications, 3) Professional Applications, such as Digital TV contribution and News Gathering, TV distribution to terrestrial VHF/UHF transmitters, Data Content distribution and Internet Trunking [13]. Compared to its predecessor, the DVB-S2 standard typically provides a 30% capacity increase [13]. This was developed around three key concepts: 1) best transmission performance achieved by the adoption of improved channel coding and efficient modulations starting with QPSK up to 32APSK, 2) reasonable receiver complexity by keeping a single-chip decoder and finally 3) improved flexibility that enables point-to point services and point-to-multipoint services.

2.1.2 Submarine and Terrestrial Fiber Technologies

Submarine cables have been laid on the sea-bed since 1850 and in 2006, these accounted for 99% of all international traffic. Regarding Africa, the last unconnected coastal cities of the continent, in the east cost, got access to the SEACOM cable (1280 Gbps) in July 2009. During following years, several other cables reached the same area and, according to the conclusions of the FEAST project [14], in 2010 Africa become the best interconnected continent in the world through submarine cable.

The research project PingER [15] monitored the migration of local services from satellite links to terrestrial fiber routes by measuring Round Trip Times (RTT) from the US and Italy on the days following the start of operation of the SEACOM cable. Figure 2 shows how RTT times were reduced from 400ms associated with satellite links to values between 200-300ms. This phenomenon was observed at the continental level including countries such as Angola, Ethiopia and Mozambique.

Figure 2: RTT reduction in a transition from satellite to terrestrial connection in Kenya [15]



The advance of terrestrial fiber towards landlocked countries in the African continent is happening lead by governments and wholesale operators (e.g. Liquid Telecom, EASSy consortium) to increase the utilization of the massive available submarine capacity. The following projects are ongoing: Central African Backbone, East Africa Broadband Network, Maritime Communications for Safety on Lake Victoria, South Africa Region Backbone, West Africa Network, ECOWAS Power Pool-based Fibre Network.

The technology that enables high-throughput communication through fiber strands (single optical fiber made of glass) both in submarine and terrestrial networks is known as Dense Wavelength Division Multiplexing (DWDM). This goes beyond existing single-channel optical links utilized in Synchronous Optical Networking (SONET) networks by introducing concept of spectral grids as parallel optical channels of variable wave-length [16]. Such new approach is implemented by the new Erbium Doped Fiber Amplifiers (EDFAs) in substitution of Optical-Electrical-Optical re-generators. Consequently, optical channels can be multiplexed across more wavelengths including C band (1525–1565 nm) and L band (1570–1610 nm). One of the crucial benefits of DWDM is that EDFA enables easy upgrade of existing SONET infrastructure due to compatibility with old single-wavelengths and ability to amplify any optical signal in its operational range. Last but not least, it enables the transport of over

100 different wavelengths per fiber and reduces the number of required repeaters to compensate for optical power loss, which can be distanced up to 100 km [16].

2.1.3 Comparison between Satellite and Fiber Technologies

The two enablers of international Internet capacity are compared first, based on the potential to deliver large volumes of capacity, second on their requirements in terms of capital investment, third regarding operational costs with focus on service provision and, finally, a summary is presented in Table 1 taking into account the 4 basic business activities performed by NOs.

In terms of aggregated capacity, while the expected global capacity through HTS is limited to 3 Tbps in 2015 [11], submarine cables already provide several hundred Tbps to the African continent alone. Such disparity is caused by the dissimilar transmission mediums. While satellite technology transmits through a unique and shared medium, fiber allows the multiplex of communication between glass fibers and wave-lengths. With respect to capital investment, the manufacture and launch of one new satellite demands several hundred millions dollars. In contrast, terrestrial cable is currently deployed in China and India at aprox. $2000/km including the cable itself [17]. Regarding operational costs, preservation of terrestrial fiber infrastructure (sensitive to vandalism and public works) is significantly higher than satellite terrestrial stations and receiving antennas. However, compared to copper lines used in telephony, the market value of fiber cable is almost zero and incentives for thieves are nonexistent. In terms of service provision costs, satellite connectivity can be directly provided to the point of need through reliable and quickly deployable backhaul connectivity. This only requires the installation of a satellite dish the costs of which are negligible compared to the price of the subscription. On the other hand, fiber connectivity might require from extra links to connect the point of need with the closest point of presence. The cost of such additional infrastructure, which might include several sites (e.g. base stations of a MNO), might become relevant in the context of larger networks.

Table 1: Comparison between cost drivers of international capacity enablers

Activities	**Terrestrial fiber**	**Satellite**
Equipment acquisition and network deployment	• Low marginal cost of adding additional capacity • Deployment of 1km costs $2000 in developing countries	• High marginal cost of adding additional capacity • Spectrum license required • A new satellite in orbit costs several hundred million dollars
Network promotion and contract management	• Typically, small network of retailers	• Typically, centralized management
Service provisioning	• Typically, an operator is required to connect point of presence and point of need	• Service delivered straight to the point of need
Network infrastructure operation	• Maintenance of a capillary-like terrestrial network	• Maintenance of few ground stations

As a result, it can be concluded that the scalability of satellite technologies is severely limited by the broadcast nature of the radio medium and the constant marginal cost of serving additional customers. Conversely, fiber technologies transmit over an economical, durable and highly multiplex-able medium that provides an scalable solution able to deliver high volume of data at a lower price.

2.2 Enablers of Wireless Last-mile Internet

2.2.1 IEEE Wireless Technologies in Unlicensed Frequencies

Wireless technologies that operate in the Industrial, Scientific and Medical (ISM) radio band reduce the network deployment cost of access operators because no longer require spectrum licenses. As an example, in this section the 802.11 and the 802.16 families of protocols standardized by the Institute of Electrical and Electronics Engineers (IEEE) are presented. While 802.11 is used as access technology that provides tens of Mbps in a 100 m range, the 802.16 is employed as backhaul connectivity enabling 72 Mbps in a 50 km point-to-point with line of side conditions (802.16d) [18]. Both protocols present also differences with regard to media access control mechanisms. While 802.11 implements a connectionless approach based on contention as explained further in this section, media access control in the 802.16 is strictly controlled scheduling algorithm which allows certain guarantee on QoS in a point-to-multipoint setting. As a result, the combination of both protocols fits well the requirements of the last-mile where Digital Subscriber Loop (DSL) cannot be deployed because of the lack of telephone lines.

The network equipment acquisition costs are low because network equipment and device manufacturers benefit from economies of scale and scope caused by: the successful standardization and certification processes by the Worldwide Interoperability for Microwave Access (WiMAX) Forum and the Wi-Fi Alliance, the large installed base of 802.11, the growing spread of 802.16 (more than 477 operators have deployed 802.16 networks in 150 countries [19]), the benefits of scale in terms of learning for users and vendors. As a result, operators in developing countries are able to locally acquire and economically deploy a network through small investment cycles. The downside is the lack of scalability of networks implementing IEEE technologies due to limitations of its infrastructure working mode (e.g. roaming between operators, handovers between access points) as explained later on in this section. From a service provisioning point of view, in the context of cities or campus networks, users can access the network with User Terminals (UE) when in coverage. Alternatively, households require from installation of Customer Premises Equipment (CPE).

Regarding the 802.11 family of standards enabling the access to the network, the 802.11b and the 802.11g versions use the 2.400–2.500 GHz spectrum and provide a maximum theoretical bandwidth of 11 Mbps and 54 Mbps respectively. Alternatively, the 802.11a and 802.11ac use the 4.915–5.825 GHz spectrum and implement different number of channels according to country regulations; its maximum throughput is also 54 Mbps. Although the 4.915–5.825 Ghz band counts with the advantage that it was used later in time and less interference is present, its range of action is smaller due to propagation characteristics. Transmission over multiple frequency carriers is implemented through the Orthogonal Frequency-Division Multiplexing (OFDM) modulation in all versions of the standard after 802.11b [20]. Possible interference between base stations is controlled by the limited power at which radio emission is permitted. As mentioned earlier, the typical radius of coverage of 802.11 access point is of 100 m, nevertheless outdoor ranges can be improved to few kilometers through the use of high gain directional antennas at both the router and remote devices. An extreme example is the WiFi-based Long Distance [21].

The 802.11 family of standards implements the Carrier Sense Multiple Access - Collision Avoidance (CSMA-CA) as medium access protocol. This determines when frames are transmitted based on a randomized back-off time. As a result, the radio spectrum is not used optimally and, its total capacity decreases under congestion. QoS conditions cannot be guaranteed with the 802.11 and interferences from other radio-frequency sources in the shared spectrum provoke degradation of service [20].

Present versions of 802.11 standard implement robust security network access techniques such as Wi-Fi Protected Access II to exchange secure cryptographic keys after a 4 way handshake and cipher of communication with the Advanced Encryption Standard. The basic building block of the 802.11 architecture is the Basis Service Set in which wireless stations can establish either direct connection in ad-hoc mode or through an access point. An Extended Service Set is the result of the interconnection of multiple Basis Service Sets.

2.2.2 3GPP Wireless Technologies in Licensed Frequencies

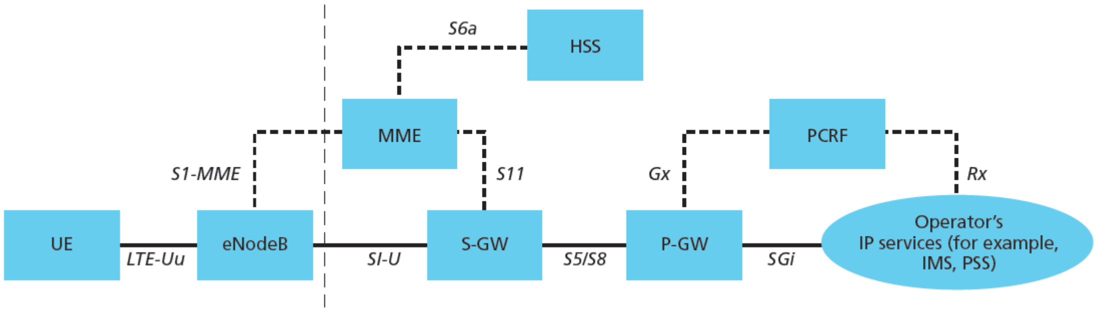
Since the first call was made in July 1rst 1991, mobile services and technologies have spread to all countries in the world. Mobile technologies were developed as the evolution of fixed voice telephony and therefore required network connections to be maintained across adjacent cells. For this to be possible, several key features are required including a centralized management, a strict QoS guarantee and, an exclusive use of the radio spectrum.

Spectrum licences define the frequency band, the geographical limits and, the duration of usage rights of the radio spectrum. More importantly, these are assigned by national regulatory authorities which may introduce additional conditions (e.g. the network coverage, roll-out requirements) and typically require costly fees from operators. In addition, 3GPP network equipment is developed and heavily patented by 3rd Generation Partnership Project (3GPP) industry alliance in charge also of GSM, GPRS, EDGE, UMTS, HSPA, and LTE maintenance. Moreover, network equipment is globally distributed by a limited number of manufacturers resulting in high prices of the network infrastructure. As a result of both costly equipment and licenses, the deployment of 3GPP technologies require from a large upfront capital investment which forces operators to invest via large cycles and, imposes strict business constraints to guarantee the return of the investment.

The 3GPP technologies advantage is the ability to deliver a large volume of network capacity to an extensive and geographically dispersed population thanks to: the use of exclusive and centrally allocated frequencies, an scheduled medium access and, large coverage radius per base station (30 km in rural areas). Moreover, from a service provision point of view, users are able to access the network through economical and available mobile devices when in coverage. Both manufacturers of 3GPP network equipment and mobile devices benefit from economies of scale and scope, however, while prices of 3GPP network remain high because of patents and a market dominant position, the price of mobile devices dropped as global competition increases.

As an example, the Long Term Evolution (LTE) mobile communication standard defines Orthogonal Frequency-Division Multiple Access (OFDMA) as the mechanism to manage the radio access on the download link interface and, the Single Carrier Frequency Division Multiple Access in the uplink. The later reduces power requirements of the User Equipment (UE). LTE was developed to support a wide range of bands starting from 700 MHz up to 2.7 GHz and implements adaptive modulation up to 64 QAM. As a result, the highest theoretical throughput is 300 Mbps in the downlink and 75 Mbps in the uplink. Figure 3 shows the overall network architecture of LTE including network elements and standardized interfaces.

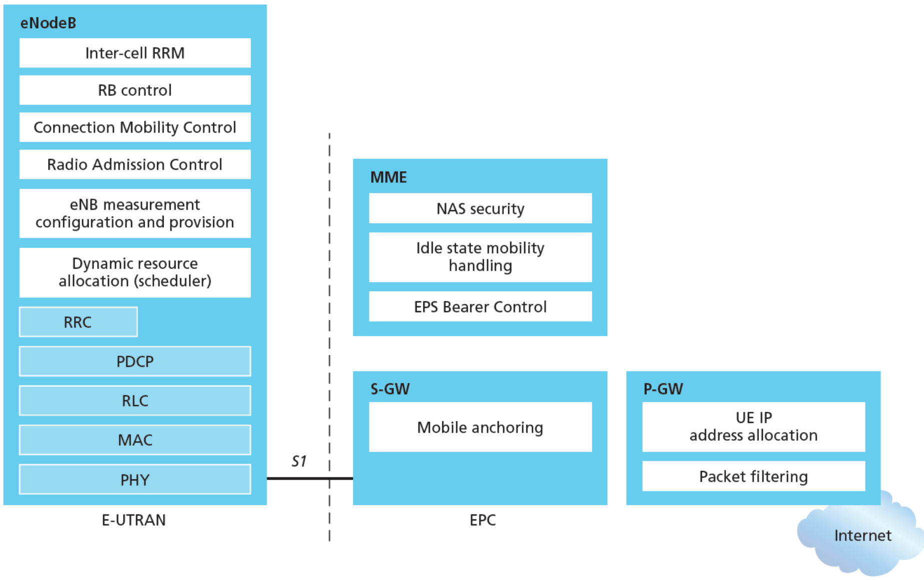
Figure 3: LTE Network Architecture [22]



This is divided in two, the access network named as E-UTRAN which is composed of Base Stations (BSs) with name eNodeB and, the the core network known as EPC which requires from several logical entities including: (1) Serving Gateway or S-GW that acts as IP gateway and local mobility anchor, (2) the PDN Gateway or P-GW that provides UEs with IP configuration and enforces QoS levels and, (3) the Mobility Management Entity or MME which processes the signalling between the core network and the UE. Further detail on the distribution of functions is shown in 4. The EPC is purely packet-switched and implements IP including both the control plane (signalling) and the user plane (user data).

More importantly, in LTE, a bearer is defined as a IP packet flow with particular QoS requirements between the P-GW and the UE. Based on this, LTE is able to provide adaptive QoS to UEs by assigning multiple bearers. In addition, user authentication is performed based on the unique authentication key provided by the operator in the form of a physical SIM card. Finally, communication in the radio link is ciphered and multiple algorithms are allowed.

Figure 4: Functional split between E-UTRAN and EPC in LTE [22]



2.2.3 Comparison between IEEE and 3GPP Wireless Technologies

The IEEE and 3GPP families of wireless standards represent two fundamentally different approaches to the provision of network services due to the different nature of the business models these were designed to support. As mentioned early, the 3GPP umbrella of technologies was elaborated as the natural extension of subscription based business models of mobile operators. Alternatively, technologies developed by the IEEE address the business logic of equipment manufacturers that commercialize products through single monetary transactions. According to Lehr [23], the former offer a vertically integrated, top-down, service-provider approach to delivering wireless services, while in the later case, this is decentralized and user centric.

The present section compares the 2 families of technologies from multiples angles. First, technical features with impact to the resulting broadband service are taken into account. Second, drivers of costs faced by NOs are presented and, third, their translation to the context of developing countries is assessed. This comparison assumes that services provided through IEEE technologies implement 802.11ac as access technology and 802.16d as WAN technology while in the side of 3GPP technologies, LTE is the enabling standard. This way, technologies are compared based on a analogous deployment setting with a similar range between an imaginary point of presence connected to the backbone network and the customer.

Table 2 compares the technical features of both technologies as presented in previous sections.

If we analyse the bandwidth-to-coverage ratio per base station, it becomes clear that the 3GPP family of technologies serve larger cells and cover larger distances than those from the IEEE. However, as counter-effect, the supplied bandwidth is significantly smaller. Regarding the utilization of the radio spectrum, the former allocates this in a centralized way and it controls access through an strict scheduler

Table 2: Comparison between technical features of last-mile enablers

Technical features	802.11ac / 802.16d	LTE
Cell coverage	• 100 m (802.11ac) • point to point backhaul link of 50 km (802.16d)	• 30 km (reasonable performance in rural areas) • 100 km (macro-cell theoretical max)
Frequency bands	• 2.400-2.500 Ghz (802.16d) • 4.915–5.825 GHz (802.11ac)	• 700 MHz-2.700 GHz
Medium access control	• OFDM (frequency multiplexing modulation) • CSMA/CA (access control)	• OFDMA (download) • SC-FDMA (upload)
Radio interference control	• Power limitation • Shared and non-coordinated use of the spectrum	• Exclusive and centralized allocation of spectrum
Bandwidth per link (theoretical max)	• 500 Mbps • point to point backhaul link of 72 Mbps (802.16d)	• 300 Mbps
Ad-hoc connectivity	• Built-in	• No
Mobility within a single operator coverage	• local mobility (100 m) • Optional extension to ESS (campus network)	• continuous mobility (handover)
Roaming between operators	• Optional RADIUS service	• Built-in
QoS mechanims	• Optional coordination functions between UEs	• Adaptive assignation of packet flows with guaranteed QoS (bearers)

algorithm. Less efficiently, the later implements a contention based access with impact on service performance in case of network congestion. Moreover, interferences from other radio-frequency sources are also possible due to non-exclusivity over the ISM radio band.

The second step of the comparison analyzes the drivers of cost faced by NOs when implementing the mentioned wireless technologies. For simplicity, operation of these is divided in 4 activities. Table 3 compare the two technologies under study.

The fundamental conclusion that can be extracted from Table 3 is that, although the deployment of IEEE technologies require less capital that 3GPP, these do not scale up as cost-efficiently. Therefore, for large sized networks, the overhead costs of operation of IEEE technologies could, at the long term, overcome those of the deployment of 3GPP. Due to the fact that IEEE technologies fit well networks of reduced size, network promotion and management activities are more receptive to customer feedback which could allow service flexibility. However, as described previously, the contention nature of the radio access mechanisms of IEEE technologies does not guarantee the provision of QoS and therefore such flexibility is limited, for example, in latency sensitive services.

So far, this comparison has assumed that the economic actor providing the network service resembles the traditional NO. Nevertheless, other approaches exist such as those of the Community Networks (CN) [8] in which a crowd-sourced approach to the deployment and operation of infrastructure change the traditional cost structure of

Table 3: Comparison between cost drivers of the last-mile enablers

Activities	**802.11ac / 802.16d**	**LTE**
Equipment acquisition and network deployment	• Small investment cycles • Low-cost equipment available • No spectrum license required	• Large investment cycles • Heavily patented technology • Spectrum license required • Few and global equipment providers
Network promotion and contract management	• Local management • Service more easily customized • Customer Premises Equipment (CPE) bundling with subscription	• Centralized management • Network of retailers • UE bundling with subscription
Service provisioning	• CPE installation required	• Access with UE when in coverage • Metering and billing scale up with size
Network infrastructure operation	• Generally, costs increase with scale	• Generally, costs decrease with scale

NO and challenges the previously identified scalability problems of IEEE technologies.

The third step of the comparison shown in Table 4 presents the economic implications of working in developing countries:

Table 4: Comparison between implications of operating in developing countries

Activities	**802.11ac / 802.16d**	**LTE**
Equipment acquisition and network deployment	• Local distributors typically available • Small investment cycles reduces business uncertainty (predictable demand) • Low labor costs	• Typically, imported from manufacturers with no presence in the country • Large investment cycles increases business uncertainty (uncertain demand) • Low labor costs
Network promotion and contract management	• Low customer acquisition costs • Dramatically high transit costs	• Low customer acquisition costs • Bargaining power due to size when negotiating transit costs
Service provisioning	• Low cost of equipment as disincentive to theft • Low regulation requirements for installation • Low installation costs	• High cost of equipment requires enhanced security • High installation costs
Network infrastructure operation	• Availability of free training content	• Difficulties to find skilled personnel

As a result of the last comparison, it can be concluded that 3GPP technologies face more difficulties than those of the IEEE in developing countries. The financial risks resulting from a larger initial capital investment might limit the deployment of 3GPP technologies due to uncertain demand and, income inequality leading to low ARPU. In addition, the available number of skilled technical personnel competent with 3GPP technologies is limited due to the few number of 3GPP equipment manufacturers and the comparatively higher prices of their products.

As final conclusion of the three-step comparison, it can be argued that the combination of 802.11 and 802.16 standards (used respectively as access and WAN technologies) is able to rapidly address unserved demand thanks to the short investment cycle of its deployment. This is mainly explained because of the availability of low-cost of equipment, local distributors in the computer retail business and, personnel with computer science competence from local universities. On the other hand, the 3GPP technologies require from larger investment cycles due to first, the large scale nature of their networks, second, the limited number of equipment manufacturers, and third, the requirement of spectrum licenses. As a result, a large capital expenditure is required upfront which, in the context of developing countries, might face business uncertainty due to uncertain demand and revenues. Nevertheless, 3GPP technologies enable larger coverage sites per base station, better utilization of the spectrum and improved mechanisms to guarantee QoS. In addition, they scale up in a cost-effective way and, in the long run, operational costs could overcome initial savings in capital expenditure as the network grows in size and complexity.

One example of the inability of 802.11 standards to deliver services due to congestion, it is the case of a village in rural Zambia were a 256 kbps satellite link was updated to a 2 Mbps terrestial wireless link [24]. Although performance of the overall Internet service rapidly improved, after 3 months users began to use more bandwidth-hungry applications and congestion in form of failed uploads and downloads and longer RTT times appeared. As a conclusion of the experience, authors of [24] assert that traffic prioritization techniques are required to guarantee certain basic network protocols to work.

2.3 Enablers of Digital Content

2.3.1 IXPs, Caches, and Content Delivery Networks

Investments in network infrastructure are concentrated in the first-mile (as companies pay for hosting) or in the last-mile (as end-users pay for access).This phenomenon was defined as the middle-mile problem by Leighton [25]. The rapid growth of demand for video (in both developing and developed countries) worsens this problem particularly in peering and transit points which are already overloaded.

Content Delivery Networks (CDNs) were developed to offload cacheable content from central servers onto a network of caches, and thus, distribute content to backbones of operators. As result, the degree of distribution of content towards the interior of Internet Service Providers (ISPs) increases and, at the same time, this reduces the crossed number of peerings and transit points. As a counter-effect, protocols that manage global-scheduling, load-balancing and cache-management suffer from scalability problems [25].

In the context of underserved regions, such problems are magnified by the lack of Internet Exchange Points (IXPs) and content caches. As a result, users often request content placed in a distant continent [26]. Public and private effort addresses this need such as: The African Internet eXchange System project which provides capacity building and technical assistance to support the establishment of National IXPs, and the Google Global Cache (GGC) with more than 3000 caches across Africa [26].

As an example of the middle-mile problem, according to Fanou [26], GGC caches located in Africa discriminate by country. More precisely, Fanou speculates that Google might enforce such behaviour in its cache-management algorithms to avoid particular peering points in which operators charge high fees. As a result of this, the overall performance of the distribution of content becomes suboptimal.

2.3.2 Caching in Mobile Networks

Operators are reluctant to locate third-party systems within their networks because they cannot control the amount of traffic these generate. However, in the context of isolated networks with very limited backhaul connectivity, the benefits of storing content at the edge of the network might counter-balance the inconveniences.

To this purpose, Costa presents in [27] the possibility of introducing Software Defined Networks (SDN) in the context of LTE mobile networks. More precisely, the idea consists in transforming the LTE data plane into a network of simplified access points and SDN-enabled switches. Costa's approach proposes the removal of GPRS Tunneling Protocol that channels the communication between eNodeB and both S-GW and P-GW and substitute this by Ethernet VPN tunnels. Experiments performed by Costa show that mobility management, QoS and security could rely on L2 and L3 transport controlled by a floating SDN-controller acting as S-GW and P-GW. As a result of this change on the LTE architecture, caches could be placed beside any switch in the access network and, this way, content could be placed closer to the BS reducing latencies and avoiding network bottlenecks.

The introduction of SDN in mobile networks would as well introduce complementary benefits in terms of cost reduction and flexibility beyond the scope of this analysis.

2.3.3 Content Cacheability

Although caching theoretically is a very efficient way to optimize content delivery, in reality not all content that traverses the Internet is cacheable. As an example, Ramanan [28] analysed HTTP traffic in an operational LTE network and found that 9% of the data volume and 54% of the requests could be considered cacheable. Among the popular hosts considered, Netflix and YouTube constitute the bulk of the cacheable data volume whereas Facebook and Google constituted the bulk of cacheable URL requests.

Although content might be classified as cacheable, several technical aspects might prevent this to happen. For example, content could be protected by cache control (HTTP headers), personalized, provided through load balancing (same content server by different URLs) or have an expected low hit-rate (e.g. user generated content) [28]. In addition, the widespread use of Hypertext Transfer Protocol Secure (HTTPS) protocol requires from a particular technical solutions supported by business agreements between content providers and operators.

According to Elkadi [29], cacheability is *"the technical ability and economic feasibility of caching a type of Internet traffic without degradation in the user quality* *of experience or the violation of any copyright law"*. Elkadi defines a total of 13 parameters to assess cacheability of content not only from a technical perspective but also taking into account business and user behaviour aspects.

2.4 Enablers of Internet Affordability

2.4.1 Role of Competition and Regulation

As introduced previously, affordability is one of the main constraints to both access and usage of broadband Internet in developing countries [4]. To measure the evaluation of prices, the ITU collects prices of ICT services (fixed telephone, mobile-cellular and fixed broadband) from 144 countries since 2008.

Regarding the role of competition, quantitative analysis from the 2008-2013 period show that market concentration measured by the Herfindahl-Hirschman Index (HHI) is significantly correlated to mobile-cellular prices in developing countries, and the sign indicates that increased competition reduces prices. According to the same analysis, levels of regulation are also correlated with mobile-cellular prices but with a weaker statistical significance. For instance, its estimated that prices of voice calls and SMS could decrease a 3% per cent if countries with lowest regulation levels would introduce regulatory changes such as: making interconnection prices public, publishing reference interconnection offers, allowing infrastructure sharing for mobile operators, permitting secondary trading of spectrum and implementing mobile number portability. As a result, the ITU emphasises that efforts should focus on ensuring higher levels of competition particularly in those markets where dominants operators hold more than 60% of the market share.

Complementary, the Information for Development Program (infoDev) in collaboration with the ITU produced the ICT Regulation Toolkit [30] as a practical web-based tool intended for ICT policymakers and regulators around the world. This provides a global overview of how telecommunication policy is best implemented with practical materials highlighting experience and results. The main regulatory challenges identified by [30] in developing countries where wireless demand has exceeded fixed demand are:

- The establishment of a regulatory regime requires from a demanding legal and administrative infrastructure. For example, resources to build large cost models.

- Regulatory of access prices requires from new approach due to the rapid deployment of new infrastructure. For example, policies to unbundle network elements assume that fixed incumbents enjoy a near monopoly position which may not be the case.

- Policies regarding retail pricing need to adapt to emerging technologies such as Voice over IP (VoIP). For example, per minute rates is a product of fixed-telephony.

2.4.2 Mobile Virtual Network Operators

According to the ITU [4], there is not enough evidence to assert that small but disruptive operators in the form of Mobile Virtual Network Operators (MVNOs) could have an impact on prices. However, these allow incumbent Mobile Network Operators (MNOs) to adopt complementary approaches such as: segmentation-driven strategies where MVNOs enable specific marketing mix and target particular customer segments, network utilisation-driven strategies where MVNOs exploit unused capacity and increase monetization of the infrastructure and, product-driven strategies in which MVNO can address customers with highly specialized service requirements.[30]

Complementary to this, T. Smura [31] defines that MVNO can be classified across two dimensions. First, MVNO could operate as either (1) Service Providers (SP) that sell subscriptions and bill customers, or as (2) MVNOs that own a mobile core network and establish interconnection agreements with other operators. Second, a VNO can adopt a cost leadership business strategy or alternatively a service differentiation strategy. Market analysis performed by the author revealed that, in developed countries, most VNOs belong to the SP/CostLeader group. Smura classification is used in our VNA with a wider scope beyond mobile operators. As a result, VNOs are classified as SP or NO.

2.4.3 Open Access

The Open Access concept introduced by Comstedt [32] is a broad approach to policy and regulation that aims at lowering the cost of business entry for new operators by introducing a neutral technology that enables competition at all layers in an IP network. In the context of developing countries, the open access model aims at avoiding facility-based competition that would require from the development of multiple independent infrastructures and adopt a public utility model which is not necessarily publicly owned. This model is particularly interesting for fiber networks which last for decades and retail competition can happen on the edges. Open access is now recognized as important for Africa and the World Bank supports its introduction to partially manage the EASSy submarine cable[17].

The open access model is also implemented to bridge the digital divide in developed countries. For example, cities such as Philadelphia and San Fransciso provide their own Wi-Fi services and Stockholm and Amsterdam own municipal fiber. It is also the case of Community Networks such as guifi.net [8].

2.4.4 Network Ecosystem KPIs for an Affordable Internet

According to H. Hämmäinen, the affordability of Internet access can be assessed through technical and business Key Performance Indicators (KPIs) across three domains of the network ecosystem: network cost, network competition, and user access subsidy. These are presented in the Table 5.

Table 5: Network Ecosystem KPIs for an Affordable Internet

Network Cost Domain objective: minimize provider cost	**examples**
1. Optimize network resources	improve routing, computing and data managment
2. Minimize transmission cost	use unlicensed spectrum
3. Minimize charging&billing cost	acquire wholesale instead of retailavoid AAA/HSS systems

Network Competition Domain objective: minimize provider profit	**examples**
4. Inter-protocol competition	choice: e.g. multihoming, IP&ICN, (no)-cache
5. Inter-node competition	decentralize: e.g. no single point of failure/control
6. Inter-actor competition	multiply actors per business role

User Access Domain objective: minimize price	**examples**
7. Ad revenue	advertiser subsidizes users
8. Delayed benefit	government subsidizes users
9. Freemium	rich subsidize poor
10. Microloan	banks subsidize users, increased productivity, delayed payback
11. Cache value	local cache content/ads subsidize access to global Internet

2.5 Results

The scalability of satellite technologies is severely limited by the shared nature of the radio medium and the elevated marginal cost of adding additional capacity. Conversely, fiber technologies transmit over an economical, durable and highly multiplex-able medium that provides an scalable solution able to deliver high volume of data at a lower price.

The submarine network capacity interconnecting continents is largely available and a steady growth is expected in order to address the global demand. In addition, several national and cross-border projects are deploying terrestrial fiber further inland even in the African continent. Therefore, the enablers of large scale capacity approach underserved regions.

The comparison between families of wireless network technologies bridging the last-mile revealed that 3GPP technologies theoretically are a more scalable solution to provide broadband services to a large and dispersed population compared to those of IEEE. This is true because of the comparatively lower bandwidth-to-coverage ratio of 3GPP base stations, improved use of the spectrum of their radio access technology and QoS control mechanisms. From an implementation point of view, IEEE technologies require from a much lower initial capital investment and, although the associated operational costs increase rapidly with size, these might not challenge the sustainability of small operators. In the context of developing countries, a commitment of large capital might be difficult due to business uncertainty (e.g. income inequality leading to low ARPU) and the unavailability of both local providers and skilled personnel.

The delivery of digital content to underserved regions is constrained by overloaded transit and peering points. Therefore, more IXPs and caches are required in developing countries to reduce the middle-mile problem. Technologies exist to introduce CDNs closer to the end-user, even to move caches into BSs of MNOs. Related to this, content cacheability depends not only on technical aspects (e.g. type of content, network infrastructure) but also on business (e.g. copyright, hit-rate) and user aspects (e.g. time, location).

The affordability of Internet broadband access is affected by multiple aspects of the Network Ecosystem at multiple layers. Strong correlation exists between low mobile market concentration and low mobile cellular prices. Weak association exists between high regulatory levels of a telecommunication sector and low prices of mobile cellular services. Moreover, competition in the telecommunications market might be increased by the introduction of VNOs and/or the adoption of the Open Access concept. Finally, the affordability of Internet broadband access can be evaluated through KPIs addressing the network cost, network competition and user cost subsidy domain.

3 Statistical Analysis of Wireless Last-mile Internet Capacity

3.1 Netradar Platform

Netradar is a client-server network measurement platform developed by researchers from Aalto University and launched in February 2013. The platform consists of a suite of mobile applications (for different mobile platforms) and associated measurement servers distributed in several locations around the world. The application sends and receives bulk data to and from the measurement server to estimate network properties such as TCP download and upload goodput and latency (Round Trip Time or RTT). The application also simultaneously collects a variety of device information including geospatial location and device model.

The Netradar client by default performs measurements on demand, in other words, whenever directed to measure by the user selecting the start button in the client user interface. However, the client can also be configured such that measurements are performed in the background (without the need for user intervention) at fixed or random intervals. In the context of the current study, we do not differentiate between measurements that are initiated by the user in the client user interface or in the background.

During any single network measurement, any part of the Netradar client measurement process (RTT measurement or TCP measurement) might fail for a variety of reasons. For example, the mobile network might not be available (no signal) or the Netradar measurement server might be offline. We leave analysis of these failed measurements for future work.

3.2 City and Country Selection

Availability of Netradar data from emerging mobile markets is limited to densely populated areas and therefore large cities were selected as targets of the research. From a total of 22 candidate cities, 6 were selected from emerging mobile markets based on data availability, geographical location and values of national ICT development Index (IDI) [4]. All Netradar measurements were performed between 2013-2015 while the national indexes are from 2013. Table 6 shows that the national indicators of the selected cities greatly vary thus ensuring a rich comparison.

The disparate number of measurements across cities is the result of different adoption levels of Netradar application between cities. However the network measurement procedure is the same regardless of the location, thus ensuring comparability. We note that the measurements span many operators in each city thus providing an advantage over studies with operator centric data collection.

3.3 Netradar Data Extraction

The Netradar measurement data for each city was extracted from the full global Netradar database based on approximate urban bounding rectangles (except for

Table 6: National Indicators for Countries of Selected Cities

City, Country	**IDI rank**	**IDI value**	**GNI p.c.**	**subs per 100 inh.**[a]	**% data subs**[b]	**Meas**[c]
London, UK	5	8.50	39110	123.80	64.10	2662
Helsinki, Finland	8	8.38	47110	171.70	68.00	674931
Barcelona, Spain	28	7.38	29180	106.90	75.50	770
Mexico City, Mexico	65	5.50	9940	85.80	12.00	4013
Tehran, Iran	94	4.29	5780	84.20	1.60	821
Sao Paulo, Brazil	95	4.29	11690	135.30	34.90	951
Jakarta, Indonesia	106	3.83	3580	121.50	9.70	3752
Bengalore, India	129	2.53	1570	70.80	7.50	1038
Dar es Salaam, TZ	153	1.76	630	55.70	15.80	596

[a] Mobile cellular subscriptions per 100 inhabitants [4]
[b] % of Mobile cellular subscriptions that include data from annual reports of operators and regulators.
[c] Number of Netradar measurements for the selected city

Helsinki which was based on municipal boundaries). The measurements were then processed to ensure the validity of each measurement value including sanity checks based on theoretical maximum network technology values.

3.4 Netradar Dataset Basic Statistics

The cumulative distribution functions (CDFs) of download goodputs in emerging mobile markets (dashed lines) and in advanced mobile markets (solid lines) are shown in Figure 5. Interestingly we find two distinct CDF shape patterns. Helsinki, London, Barcelona, Mexico City and Tehran show uniform CDF growth and their download goodput distribution is unimodal as shown, for example, with London in Figure 6A. Whereas Jakarta, Bangalore and Sao Paulo show non-uniform CDF growth indicating a multimodal distribution as shown, for example, with Bangalore and Jakarta in Figures 6B and 6C.

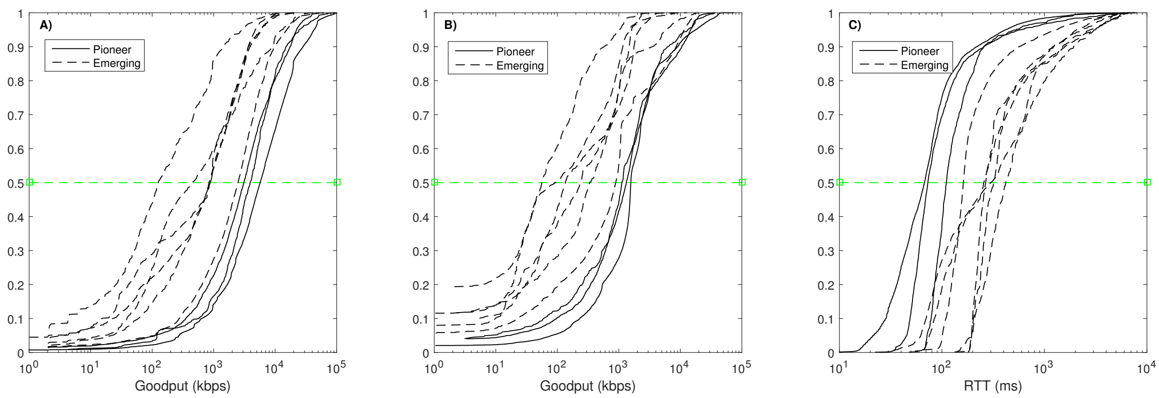


Figure 5: CDFs of Network Values for Advanced mobile and Emerging Cities - A) Download Goodput, B) Upload Goodput, C) RTT

Next we group measurements by mobile generation technology as detailed in Table 7. We find that distribution shapes are the result of overlapping measurements from different mobile generation technologies. As an example Figure 3A shows that the single mode observed in London is the result of a combination where 4G takes the right tail of the distribution and 3G the left side. The same grouping analysis is performed for upload goodput and latency and we find similar unimodal or multimodal shapes as for download goodput.

Table 7: Mapping of Network Technologies to Network Generations

Gen	Technologies
2G	iDen, GPRS, EDGE, CDMA
3G	UMTS, HSDPA, HSUPA, HSPA+, HSPA, HSDPA, eHRPD, EVDO revision (A,0,B), 1xRTT
4G	LTE

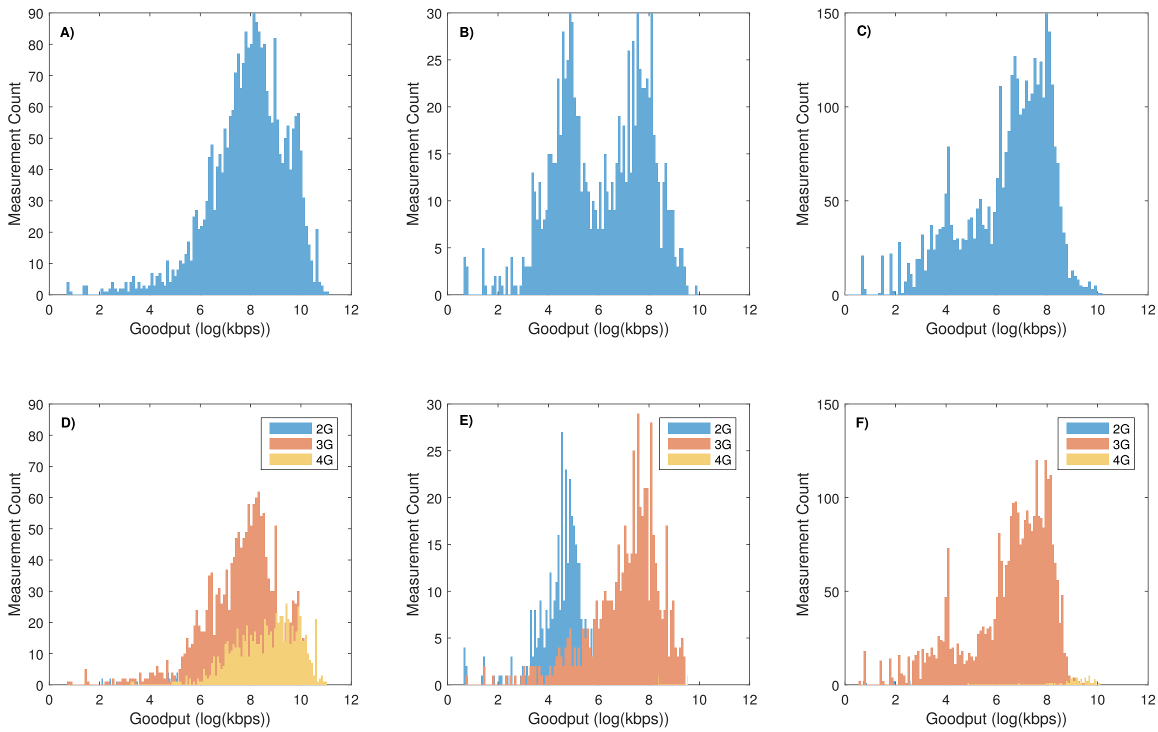


Figure 6: Histograms of Download Goodput (log scale) - A) London, B) Bangalore, C) Jakarta, D) London by Network Tech Generation, E) Bangalore by Network Tech Generation, F) Jakarta by Network Tech Generation

3.5 Estimation of Available Capacity

As described in [33] five major factors affect and limit mobile capacity including: radio technology, radio conditions (coverage), congestion caused by other users, mobile device and handovers. As seen in the Section 3.4, measurements grouped by mobile technology typically present unimodal distributions therefore we assume that the radio technology associated with the mobile generation is the principal constraint to capacity. Thus next we compare capacity between cities based on mobile generations.

To compare the available capacity between cities, we compare medians due to significant outliers. To compare spreads between cities we compare inter-quartile ranges (IQR) as a fraction of the median. The IQR is calculated as the difference between the 75th and 25th quartiles, $Q3 - Q1$. These comparisons are detailed in Table 8. To ensure reliability medians are not detailed when the number of measurements (for that generation) is smaller than 100. We also does not include measurements with unknown mobile generation technology that were utilized in the overall analysis.

Table 8: Available capacity per mobile generation technology

Download Capacity (kbps)								
	2G	IQR	3G	IQR	4G	IQR	City level	IQR
Helsinki	234	*0.94*	4342	*1.67*	26179	*1.17*	5691	*2.11*
Barcelona			2905	*1.21*	11003	*1.11*	3928	*1.65*
London			2477	*1.74*	6431	*1.95*	3096	*2.17*
Mexico City			1982	*1.47*	6665	*1.46*	2500	*1.73*
Sao Paolo			783	*1.78*	8044	*1.37*	885	*2.88*
Jakarta	85	*1.45*	928	*2.18*			841	*2.46*
Bangalore	99	*0.95*	1599	*1.59*			457	*4.26*
Tehran	33	*1.65*	438	*1.91*			126	*4.85*
Upload Capacity (kbps)								
	2G	IQR	3G	IQR	4G	IQR	City level	IQR
Helsinki	96	*1.49*	1519	*0.94*	7768	*1.86*	1568	*1.41*
Barcelona			985	*1.61*	4930	*1.74*	1127	*2.22*
London			934	*1.33*	5719	*1.80*	1332	*1.69*
Mexico City			650	*1.39*	6522	*1.02*	893	*1.75*
Sao Paolo			201	*2.98*	2540	*1.94*	236	*3.89*
Jakarta	20	*1.06*	136	*5.37*			93	*7.49*
Bangalore	48	*1.55*	745	*1.97*			135	*8.11*
Tehran	26	*1.98*	157	*1.92*			56	*3.24*
Latency (ms)								
	2G	IQR	3G	IQR	4G	IQR	City level	IQR
Helsinki	178	*1.73*	72	*0.79*	34	*1.39*	68	*0.88*
Barcelona			84	*0.73*	58	*0.39*	73	*0.78*
London			117	*0.72*	95	*0.43*	111	*0.66*
Mexico City			168	*0.75*	146	*0.40*	162	*0.66*
Sao Paolo			263	*0.95*	235	*0.50*	267	*0.83*
Jakarta	506	*1.60*	273	*2.21*			301	*2.02*
Bangalore	383	*1.07*	135	*1.56*			256	*1.61*
Tehran	764	*1.49*	332	*0.83*			420	*1.29*

As expected, Table 8 shows that available capacity in advanced mobile markets present higher goodputs and lower latencies than in emerging mobile markets. For example, 2G download capacities in Bangalore and Jakarta are two times smaller than in Helsinki while in the case of Tehran capacity is seven times smaller. Interestingly for 3G download, Mexico City and Bangalore show significantly higher capacities than the rest of the emerging mobile markets. Regarding 4G, we find that download capacity is similar to upload capacity in London and Mexico City; this could be a sign of congestion.

3.6 Results

Although 3G technology is available in all cities, the measured download goodput is significantly lower in the emerging than in the advanced mobile markets. The same applies to 2G and 4G. Among emerging mobile markets alone, the median value of download goodput presents high variability. For example, if Tehran (min) and Mexico City (max) are considered outliers, the value in Bangalore still doubles the one in Sao Paolo.

4 Bottleneck Analysis

4.1 Methodology and Bottleneck Hypotheses

The Theory of Constraints defines system as a chain of interconnected activities in which the weakest link limits the overall throughput of operation. A systematic management approach is derived from this assertion which claims that the performance of the entire system needs to be optimized by actively managing constraints that restrict organisational goal achievement [34] [35]. In this chapter, The Theory of Constraints is used as a conceptual framework to analyse the mobile broadband market from a system-oriented perspective in the context of a competitive and dynamic marketplace with the main goal of increasing mobile data subscriptions. Three hypotheses are assumed as potential bottlenecks limiting the mobile Internet diffusion:

- Hypothesis 1: Level of competence of users and mobile device features are the main bottlenecks in mobile Internet diffusion in emerging mobile markets
- Hypothesis 2: Pricing is the main bottleneck in mobile Internet diffusion in emerging mobile markets
- Hypothesis 3: Capacity is the main bottleneck in mobile Internet diffusion in emerging mobile markets

The bottleneck analysis executed in this chapter has two steps. First, per each city, a model of the mobile broadband market is evaluated and, as a result, the dominant bottleneck is identified by comparing obtained values across cities. Second, all three hypotheses are analysed in detail to understand the underlying causes of dominant bottlenecks. More precisely, socio-economic and regulatory factors such as levels of market concentration, regulatory frameworks (ITU Tracker), Gross National Income per capita, deployed mobile technology are taken into account. Finally, in the result section, dominant bottlenecks and their most likely cause are listed and recommendations issued.

Overall, the analysis takes into account data from 9 cities, 3 from advanced markets (Helsinki, London, Barcelona) and 6 from emerging mobile markets (Bangalore, Jakarta, Tehran, Mexico City, Sao Paulo, Dar es Salaam) as described in 3.2.

4.2 Model of Mobile Broadband Market

The mobile broadband market is modeled as a chain of multiplicative coefficients that take the total population as input (C) and give as result the number of subscriptions (S) in a particular country. Two coefficients are taken into account in the analysis: B_0 as Market Satisfaction that addresses the satisfaction rate of users' economic Utility and, B_1 as User Competence.

$$S = B_0 \cdot B_1 \cdot C \quad (1)$$

We introduce the consumer problem as the maximization of consumer surplus (CS) depending on Utility (U) and price (P) regarding the mobile Internet subscription x and consumer i:

$$max(CS_{\mathrm{i}}) = max(U_{\mathrm{i}}(x) - P(x)) \geq \gamma_{\mathrm{i}}$$

Therefore, it could be assumed that Market Satisfaction B_0 equals to the number of citizens that satisfy the consumer problem (n) divided by the number of those that do not (m).

$$B_0 = \frac{n \quad \text{that} \quad CS_{\mathrm{i}} \geq \gamma_{\mathrm{i}}}{m \quad \text{that} \quad CS_{\mathrm{j}} < \gamma_{\mathrm{j}}} \quad \forall i, j$$

For simplicity, two assumptions narrow down the scope of the analysis: consumers value the web browsing experience most and, broadband subscription growth mainly occurs in urban areas. Concerning consumer surplus, the economic Utility is calculated in a two-step sequence. Initially, this is estimated as the Mean Opinion Scores (MOS) for urban consumers in the web browsing context. Afterward, the MOS scores are predicted by a logistic QoE model developed by Hosek [36] that relates throughput and latency to MOS.

$$U_{\text{urban,browsing}} = MOS(BR, D) = \frac{(b-a)}{1 + c_0(BR)^{-c_1 - c_3 D} C_1{}^{-D}} + a$$

Where BR stands for Bit Rate, D for delay time, coefficients c tune the model, and finally constants a and b define the maximum and minimum value of MOS. As a result, B_0 is characterized depending on BR, D and P as follows:

$$max(B_0) \Rightarrow max(MOS(BR, D)) \quad AND \quad min(P) \quad (2)$$

4.3 Identification of Dominant Bottleneck

The presented broadband market model is fed with 2 data-sets. First, values of mobile network performance required to estimate MOS are derived from measurements collected via the Netradar mobile application during the 2013-2015 period as described in 3.2. Second, prices of data are derived from the ITU Report Measuring the Information Society 2014 [4]. Table 9 shows the selected parameters as well as complementary sources of information used in the analysis.

Finally, the dominant bottleneck is identified per each city by comparing values between Market Satisfaction B_0 and User Competence B_1. Values of B_0 are simply deduced by solving the equation:

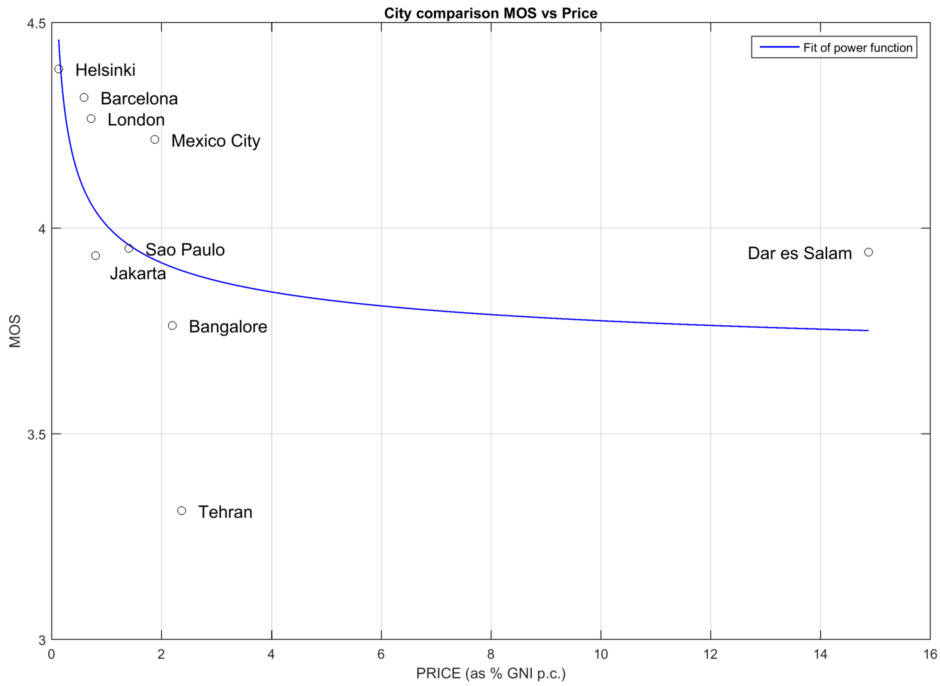
$$B_0 = \frac{S}{B_1 \cdot C}$$

Due to the fact that B_0 is larger than B_1 across all cities, we conclude that User Competence is not the dominant bottleneck in any city. Regarding the two remaining hypotheses, more detailed analysis of Market Satisfaction B_0 is required and, for this reason, relationship between its 2 main predictors MOS and price of data is shown in Figure 7.

Table 9: Data sources in the mobile market model

Variable	Value
S	number of data subscriptions per 100 inhabitants as described in 4.5.1
C	100
B_1	Adult literacy rate [4]
BR	Median goodput speed as described in 3.5
D	Latency as described in 3.5
$c_{0,1,2,3}$	Logistic regression coeficients as described in [36]
b; a	5; 0 as describe in [36]
P	minimum price of data available including pre and post paid.[4]

Figure 7: Comparison between MOS and data price



Tendency line is fit to the data as power function of second degree. Although the number of data points is rather small, bottleneck per city is defined based on comparison to the rest of the cities by classifying those above the curve as price dominant and consequently, those under the curve as capacity dominant as shown in Table 10. It is worth mentioning that all cities, except Dar es Salaam, present prices of 500MB data block below the 5% of the GNI p.c. which was defined by the UN Broadband Commission as affordability limit.

4.4 User Competence Bottleneck

Hypothesis 1: Level of competence of users and mobile device features are the main bottlenecks in mobile Internet diffusion in emerging mobile markets.

Table 10: Identified dominant bottlenecks

City,Country	**Dominant bottleneck**
Tehran, Iran	Capacity
Jakarta, Indonesia	Capacity
Bangalore, India	Capacity
Dar es Salaam, Tanzania	Pricing
Mexico City, Mexico	Pricing
Sao Paulo, Brazil	Capacity / Pricing

In order to examine the underlying causes of this particular bottleneck, we analyze and compare user competence and user device data.

4.4.1 Level of User Competence

Fundamental requirements of mobile Internet are: user literacy and availability of content in the language the user is competent with. Table 11 presents the results of building the bottleneck-chain which relates constraints and number of mobile broadband subscriptions. Adult literacy rates [4] alongside IDI skills sub-indexes[1] present different levels of competence. Assuming Internet content is mainly available in English, low levels of English competence[2] are compensated by a relatively high number of local content. Number of Wikipedia articles in the official language of the country are used as proxy[3].

Table 11: User competences bottleneck-chain

Country	**Screen size(in.)**	**Literacy rate**	**English competence**	**Wikipedia articles (K)**	**IDI skills sub-index**	**data subs[a]**
Finland		99	62,6	384	9,7	116,8
Spain		97,9	53,5	1219	9,4	80,7
UK	4,8	95,2	99	5034	8,4	79,4
Brazil		91,3	50,0	897	**7,2**	47,2
Mexico	4,8	94,2	49,9	1219	**6,9**	10,3
Indonesia		92,8	**53,4**	**279**	6,8	11,8
Iran	5	84,3	**49,3**	**477**	7,5	1,3
Tanzania		**67,8**		31	3,5	8,8
India	4,7	**62,8**	54,3	100	5,2	5,3

[a] Mobile cellular data subscriptions per 100 inhabitants [4]

[1] IDI skill sub-index includes national levels of adult literacy, gross secondary school enrolment and gross tertiary enrolment and adult literacy rate [4].

[2] EF English Proficieny Level - Report 2013

[3] Last accessed : 2015-11-11. https://meta.wikimedia.org/wiki/List_of_Wikipedias

4.4.2 Device Features

The study of traces from a global proxy cache published in [37], shows that developing regions almost uniformly download more rich media as a fraction of their traffic when compared to the OECD countries. At the same time, interesting research exists from academia [38] and industry [39] implying that mobile data usage increases with device screen size.

It could be speculated that in emerging mobile markets preference of users is biased towards non-text content due to low literacy levels. As a consequence, devices with larger screens would necessarily be observed. In order to validate such hypothesis, median values of observed screen sizes of devices (including phones and tablets) of Netradar users are presented for some cities in Table 11. Screen size information of device models was collected from publicly available online sources. The information covers those top device models which represent 80% of all measurements in each city. It can be concluded that devices used in Netradar measurements present similar screen sizes across selected cities. This observation might be due to Netradar users being generally more advanced ICT users (after all these users are sophisticated enough to be interested in measuring the mobile network). These advanced users likely select devices from a smaller subset of available high quality devices.

4.5 Pricing Bottleneck

Hypothesis 2: Pricing is the main bottleneck in mobile Internet diffusion in emerging mobile markets.

In order to examine this hypothesis we analyze and compare a variety of pricing and market competition data. The information is primarily from 2013.

4.5.1 Mobile Prices and Subscription Levels

According to the ITU [4], mobile-cellular prices have declined in the period 2008-2013, with a Compound Annual Growth Rate (CAGR) of -5.7% globally. The decrease in prices has affected developed and developing countries alike, with -4.3 and -6.4% CAGR, respectively.

Table 12 presents prices of mobile cellular broadband data and more precisely the average price of blocks of 500 MB as percentage of Gross National Income per capita (GNI p.c.) devoted to handset devices in 2013. Prices in GNI p.c. provide insight into the affordability of services from a demand-side perspective for each country. Mobile cellular sub-basket prices are also presented combining prices of data, calls and SMS[4].

Overall, prices of mobile cellular data represent a very small portion of GNI p.c. in all countries except Tanzania. Prices of both pre and post-paid mobile broadband services in countries with advanced mobie markets represent less than 1% of GNI p.c. while in emerging markets the figure is generally over 2%. The only exception is Indonesia where pre-paid prices are at similar levels as in Spain and the UK. Based

Table 12: Price bottleneck-chain

Country	**CFI**[a]	**# MNO**	**# MVNO**	**HHI**[b]	**subs per 100 inh.**[c]	**sub**[d] **-backet**	**pre**[e] **-paid**	**post**[f] **-paid**	**data**[g] **subs**
Finland	27	3	5	0,34	171,7	0,4	0,23	0,13	116,8
Spain	28	4	28	0,30	106,9	1,6	0,86	0,59	80,7
UK	20,3	4	13	0,28	123,8	1,3	0,72	0,77	79,4
Indonesia		7	0	0,26	121,5	2,3	0,8	**1,76**	11,8
Brazil	28	7	0	0,25	135,3	4,96	**1,41**	4,14	47,2
India	23	15	0	0,14	70,8	2,61	**2,2**	2,58	5,3
Tanzania	20	6	0	0,28	**55,7**	**17,9**	14,88	16,07	8,8
Mexico	20	**4**	**1**	**0,53**	85,8	1,4	2,83	1,88	10,3
Iran	**12,7**	3	0	0,46	84,2	0,46	2,37	2,37	1,3

[a] ITU Competition Framework Index [40]
[b] Herfindahl-Hirschman market concentration index
[c] Mobile cellular subscriptions per 100 inhabitants [4]
[d] Mobile-cellular sub-basket as % of GNI p.c.
[e] Prepaid handset-based 500 MB as % of GNI p.c.
[f] Post-paid handset-based 500 MB as % of GNI p.c.
[g] Mobile cellular data subscriptions per 100 inhabitants [4]

on these prices, we could assume that only in Tanzania could price be considered as a bottleneck mostly due to low GNI p.c. as detailed in Table 6.

Prices of post-paid data in advanced mobile markers are equal to or more affordable than pre-paid while in emerging mobile markets the pattern is reversed except for Mexico City. This fact might be indicative of different customer behaviour in mature markets (with more than 60% of data subscriptions).

Assuming prepaid data is the most affordable Internet diffusion strategy in emerging mobile markets, we compare its costs with mobile sub-basket prices. In Brazil, Indonesia and Tanzania data is more affordable than the mobile sub-basket (as in advanced mobile markets) while in Tehran the tendency is reversed. In India and Mexico levels are comparable.

The fact that data services are more affordable than basic mobile services might be an indicator of consumer habits changing from communication based on voice to data (for example, especially OTT messaging/voice services).

Figure 8 shows the number of subscriptions at the national level depending on the most affordable price strategy.

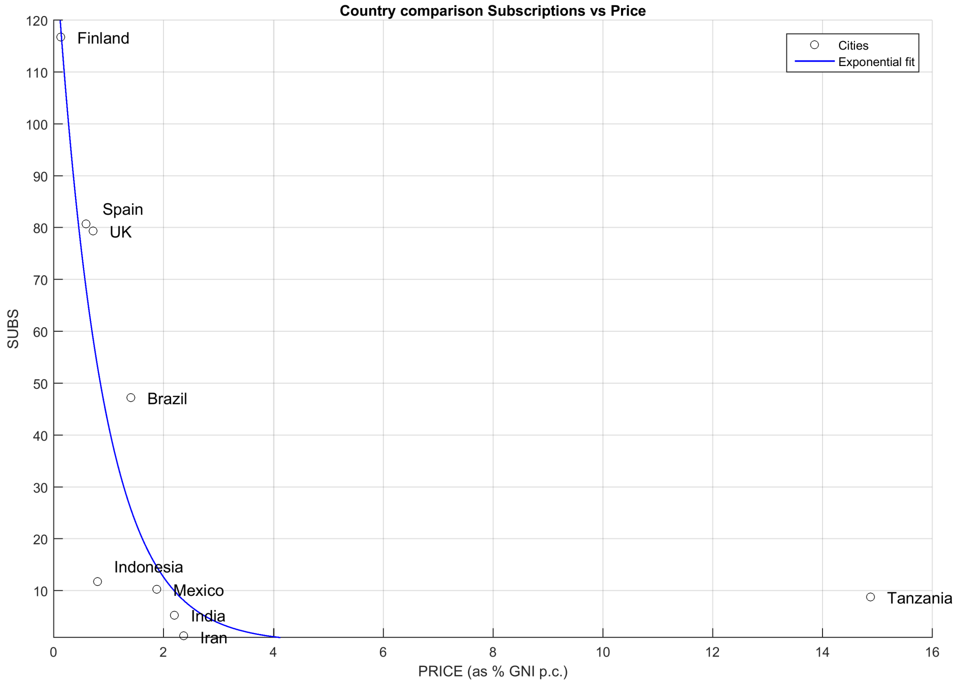
4.5.2 Market Competition and Regulation

To assess market competition and regulation we utilize the ITU Competition Framework Index[4] and the Herfindahl-Hirschman Index market concentration index[5]. The indexes are presented in alongside pre-paid and post-paid data prices in Table 12.

[4] CFI is a composite index of 14 indicators with a maximum score of 28 points. [40]

[5] HHI is calculated as the sum of the squared market shares (information is extracted from annual reports of operators and regulators) in terms of number of subscriptions of each MNO, MVNO are not taken into account. Extreme values are 0 which indicates perfect competition and 1 which indicates monopoly.

Figure 8: Comparison between data subscriptions and price



Note that all markets had in 2013 liberalized mobile markets that allow competition among numerous private sector mobile network operators (MNO) as well as Mobile Virtual Network Operators (MVNO).

The fact that levels of market concentration in developed telecom markets are higher than some other cities does not necessarily imply that competition is lower because presence of MVNOs should be taken into account. MVNOs are an indicator of market maturity and at the same time allow incumbent MNOs to exploit unused capacity.

Among emerging mobile markets, Iran and Mexico present high HHI values as well as prices. Thus it could be assumed that market concentration is a bottleneck in both these markets. In addition, CFI levels of Tehran indicate that the regulation environment could be improved. Empirical research shows the existence of water beds in the mobile industry. For example, Genakos et al. [41] conclude, based on a sample of 20 countries, that regulation that reduced mobile termination rates by about 10% led to a 5% increase in mobile retail prices.

Although, India and Tanzania present high levels of HHI, their prices still remain in the higher range of our comparison. The case of Tanzania could again be explained by comparatively low GNI p.c.

4.6 Capacity Bottleneck

Hypothesis 3: Capacity is the main bottleneck in mobile Internet diffusion in emerging mobile markets.

In order to examine this hypothesis, we study the distributions of download goodput, upload goodput, and latency from the Netradar dataset for the selected cities as described in Section 3.2. Finally, observed mobile Internet capacity is filtered by the requirements of a subset of well-known applications.

4.6.1 Mobile Internet Available Capacity

As described in [33] five major factors affect and limit mobile capacity including: radio technology, radio conditions (coverage), congestion caused by other users, mobile device and handovers. Available mobile Internet capacity is estimated per each city as described in 3. Results of goodput regarding download, upload and latency are show in Table 13 next to International Internet bandwidth (IIB) per user [6] Clarify that IIB data is at national level and estimated capacity is at the city level.

Table 13: Capacity bottleneck-chain

City	IIB [a] kbps	DOWN kbps	UP kbps	LAT ms	% STR [b]	%A[c] CLL	%V[d] CLL	% HQ VCLL	data [e] subs
Helsinki	21,02	5691,40	1567,77	67,70	0,93	0,91	0,86	0,81	116,76
Barcelona	12,50	3928,07	1127,41	73,00	0,92	0,89	0,83	0,65	80,71
London	43,04	3096,22	1331,68	111,00	0,92	0,89	0,82	0,74	79,36
Mexico City	2,76	2500,46	892,56	162,10	**0,74**	**0,71**	**0,67**	**0,63**	10,30
Sao Paulo	5,24	**884,63**	**235,65**	**267,00**	0,57	0,52	0,40	0,34	47,22
Jakarta	1,24	**841,41**	**93,29**	**301,40**	0,57	0,49	0,38	0,32	11,79
Bangalore	0,83	**457,15**	**135,34**	**256,30**	0,59	0,53	0,41	0,33	5,31
Dar es Salaam	0,79	**879,20**	**339,76**	**324,60**	0,51	0,48	0,38	0,33	8,80
Tehran	**0,57**	125,79	56,05	419,80	0,29	0,22	0,11	0,06	1,35

[a] International Internet bandwidth (IIB) per user at the national level
[b] % of measurement that comply with Streaming requirements
[c] % of measurement that comply with Audio Call requirements
[d] % of measurement that comply with Video Call requirements
[e] Mobile cellular data subscriptions per 100 inhabitants [4]

Comparing the download capacities of cities with their respective upload capacities and latencies, we find similar patterns except for Mexico City and Jakarta. Interestingly, these two cities present poor performance in upload and latency across all mobile generation technologies.

[6] International Internet bandwidth refers to the total used capacity of international Internet bandwidth, in megabits per second (Mbit/s). It is measured as the sum of used capacity of all Internet exchanges offering international bandwidth. If capacity is asymmetric, then the incoming capacity is used. International Internet bandwidth (bit/s) per Internet user is calculated by converting to bits per second and dividing by the total number of Internet users[4].

4.6.2 Analysis of App Requirements

Since the feasibility of utilizing certain applications likely affects adoption, we also compare markets in terms of application requirements. We utilize several distinct sets of application requirements: audiocall, videocall and high quality videocall requirements derived from Skype recommendations[7] and general streaming requirements. The network requirements for audiocall, videocall and high quality videocall respectively are download: 100, 300, 500 kbps, upload: 100, 300, 500 kbps, RTT: 300, 300, 300 ms, whereas for general streaming the requirements are download: 100 kbps, upload: none, RTT: 300 ms. For each application, we compare the cities in terms of the fraction of measurements that meet all three requirements. Table 13 details these comparisons.

The comparisons do not seem to suggest any relations between the fraction of measurements meeting the application requirements and data subs beyond the obvious advanced/emerging mobile market split.

4.7 City Analysis and Comparison

As a result of the detail analysis of all three hypotheses, likely causes of dominant bottlenecks has been identified. These are presented in Table 14.

Table 14: Summary of dominant bottlenecks and associated causes

City, Country	Dominant Bottleneck	Likely cause	Comments
Tehran, Iran	Capacity	Lowest IBB in the study	Low CFI indicates non-optimal regulatory conditions
Jakarta, Indonesia	Capacity	Limited mobile Internet capacity	Subscriptions expected to grow rapidly
Bangalore, India	Capacity	Limited mobile Internet capacity	Subscriptions exptected to grow rapidly. Low levels of Adult literacy.
Dar es bottleneck-chain , Tanzania	Pricing	Low GNI p.c. and lowest mobile penetration in the study	Alternative revenue models required. Low levels of Adult literacy.
Mexico City, Mexico	Pricing	High levels of market concentration (HHI)	Large mobile Internet capacity available. Extremly small data subcriptions.
Sao Paulo, Brazil	Pricing / Capacity	Limited mobile Internet capacity	Large difference in price between affordable pre-paid and post-paid.

An overview of the obtained results is elaborated per each city. The country with the smallest number of mobile data subscriptions in 2013 was Iran. According to our classification, the dominant bottleneck in Tehran is capacity and main cause identified in the bottleneck-chain is small IIB ratio. Also, lowest 3G goodput is observed in Tehran as shown in 3.5. Such a low level might be due to the lack of international capacity resulting from international economic isolation. It is worth mentioning that high levels of market concentration could also account for such result.

After Iran, India and Tanzania present the second and third lowest number of data subscriptions respectively. According to our classification, the dominant bottleneck in Bangalore is capacity presenting the slowest download goodput only after Iran.

[7]https://support.skype.com/en/faq/FA1417/how-much-bandwidth-does-skype-need

On the contrary, dominant bottleneck in Dar es Salaam is data prices due to low levels of GNI p.c. Both countries present the lowest adult literacy rates of all cities.

Regarding Mexico City, the dominant bottleneck is price most likely caused by high market concentration levels as seen in bottleneck-chain analysis. Although both capacity and MOS are at the advanced market level (4G is already deployed), the number of data subscriptions remains unexpectedly low. In the case of Jakarta, the classification method identifies the dominant bottleneck as capacity. Surprisingly observed mobile Internet capacity in Jakarta is similar to other cities with less constrained IIB levels.

Brazil has the highest number of data subscriptions of all emerging mobile markets under study. No bottleneck can be classified as dominant in the city of Sao Paulo by our method because Utility falls right on the division line. Based on previously bottleneck-chain analysis, it seems that a limited mobile Internet capacity could slow down difussion of mobile Internet specially taking into account large IIB available. Interestingly, values of capacity and MOS remain similar to cities with 3G network only when Sao Paolo already presents 4G measurements.

4.8 Results

The results obtained by this method reveal that in 3 out of the 5 cities under study, the available mobile capacity was the main bottleneck slowing down the diffusion of mobile Internet. In addition, the price of data was the second more relevant bottleneck affecting 2 cities while, in the case of Sao Paulo, the method was only able to discard the user competence hypothesis.

Therefore, the user competence is not the main bottleneck in any of the cities under study. Consequently, we conclude that the mobile device ease of use is already highly developed and, the content of mobile Internet is rich enough to satisfy users with limited literacy levels.

In addition, pricing and capacity bottlenecks can be classified in two groups according to their likely causes either as market or not market related. Market related bottlenecks need to be addressed by the regulators of the telecommunications market and policy-makers introducing changes in the regulatory framework (e.g. to increase market competition levels, to attract investments). Alternatively, bottlenecks which are not related to the nature of competitive telecommunication market would require from tailored solutions (e.g. business models that include subsidies from an extended value network).

The analysis shows 6 mobile markets in different stages of development each of which, conditioned by a particular bottleneck. Finally, we conclude that the development of the mobile market can be modelled as a sequence of bottlenecks some of which, could be addressed by the regulator (market related) and some others might require from tailored solutions (non-market related).

5 Value Network Analysis

5.1 Value Network Analysis Research

In business strategy literature, Porter's concept of value chain is well-known as a sequence of creating value activities within a single firm that transforms inputs into products. However, a linear value creation logic is less suitable to analyse activities that create value by connecting customers using a mediating technology [42].

Hence, the Value Network Analysis (VNA) aims at describing the relationships between industry actors in a business value system which co-perform at different levels. Different approaches to this same idea can be found from different fields of research. For example, from a technology management point of view, industries in which companies provide services through a modular technical architecture, establish platforms. Bresnahan [43] defines an ICT platform as a shared, stable set of hardware, software and networking technologies on which users build and run computer applications. Another example, from an economic point of view, platforms are known as coordinated interactions between two or more distinct groups of stakeholders able to internalize the externalities created by one group for the other group rather than to focus on profit maximisation in a single market. As a result, business modelling focus has shifted towards the analysis of network of firms and platforms.

5.2 Value Network Analysis Method

We define a Value Network Configuration (VNC) as a set of business actors (stakeholders) that provide one or more business roles by the execution of technical components and this way create value through services [44]. Business roles are discrete set of responsibilities which can not be sub-divided in smaller units of meaningful business. The implemented VNA systematically assesses multiple VNCs seeking for technical and business links to (1) provide competitive advantage at network level and (2) guarantee acceptable profitability. A graphical representation of a VNC arises from its linkages as shown in Figure 9. Those between stakeholders state business contracts (transit, subscription, roaming, etc.) while connections between technical components define interfaces and protocols (e.g. IP, 802.1X, PSN, etc.). VNCs are named to state what business actor has a dominant position in the configuration (e.g. WISP-driven VNC).

5.3 Value Network Analysis

The analysis is divided in three main parts. First of all, required stakeholders and business roles are identified building the technological and economic context. Next, three VNCs are discussed in detail and finally, comparison among these is performed in terms of benefit, cost and revenue model.

Table 15: RIFE Stakeholders

Stakeholder	**Definition**	**Objectives / Requirements**
Regulator	Impact of ICT technologies depends heavily on the regulatory framework. Regulator responsibilities: decision-making processes, accountability, consumer protection, dispute resolution and enforcement of regulation.	• To increase total number of data subscriptions • To foster fair market competition
Citizen and local business	Customers aim at maximizing economic surplus by accessing services and content at the lowest price. Customers develop loyalty to service providers based on satisfaction and quality of service. In this analysis, customers are very sensitive to price.	• Connectivity • Price affordability • Service flexibility • Mobility
Local community	Perceived value is shared in the local community. Top-down influence of leaders modify user preferences. Organized community could embrace cooperative management of networks and gain bargaining power.	• Local commitment • Local awareness
Virtual Network Operator (VNOs)	VNO's incentives are not necessarily economic but driven by socio-economic goals, such as connecting digitally disenfranchised social communities or increasing connectivity of public services or connecting local businesses.	• To define inclusive pricing structures • To define services that match local business requirements. • To increase local awareness and acceptance of services.
Network Operators (NOs)	Three different NOs are in the analysis: • Wireless Internet Service Provider (WISP) - Local operator implementing IEEE802.1X technologies and low level of automation in internal processes. • MNO - National operator implementing 3GPP technologies and high level of automation. • Backhaul (BH) operator - The BHO routes traffic from the FH to the Internet through the backhaul. It is in control of the main bottleneck of the system.	• To increase in number of subscriptions • To increase ARPU[a] • To low OPEX[b] • To low CAPEX[c]
Content provider	Generally, content providers provide digital content under particular contractual conditions. The main driver of cost is the management of licenses on content exploitation rights as well as infrastructure operation.	• To increase number of content subscriptions • To increase hit-rate of content

[a] Average Revenue Per User
[b] Operational Expenses
[c] Capital Expenses

5.3.1 Techno-economic context

Table 15 describes stakeholders relevant to the provision of low-cost and affordable Internet (based on Informative RFCs from GAIA [6]) and defines its objectives and/or requirements. Business roles and their respective technical components are presented in Table 16. Table 17 describes the technological and non-technological enablers of value as well as main drivers of cost responsible for exploiting unused network capacity.

Table 16: Business roles and technical components

Business role	**Responsability**	**Technical component**
Customer	Responsibility to use available services	• Video on Demand (VOD) application • Videoconference application
Accounting and billing	Responsibility to manage customer consumption and billing	• Billing machinery
LAN provision	Responsibility to guarantee network connectivity to the user equipment. It could implement IEEE-based access technologies as Wi-Fi, WiMAX or 3GPP-based as 3G,4G, etc.	• PSN client • BS LAN AP / NodeB
RIFE gateway	Responsibility to aggregate FH traffic and route it towards the Internet or caching system.	• BH gateway • Cache of local content • Cache of global content • PSN router
WAN provision	Responsible for routing aggregated traffic to the Internet.	• WAN AP • Time shift
3GPP provision	Responsible for the interoperability of local 3G/IMT2000 services towards the global mobile network.	• SDN controller • NodeB Gateway
Content provision	Responsibility for contractual conditions required for content distribution.	• Global content

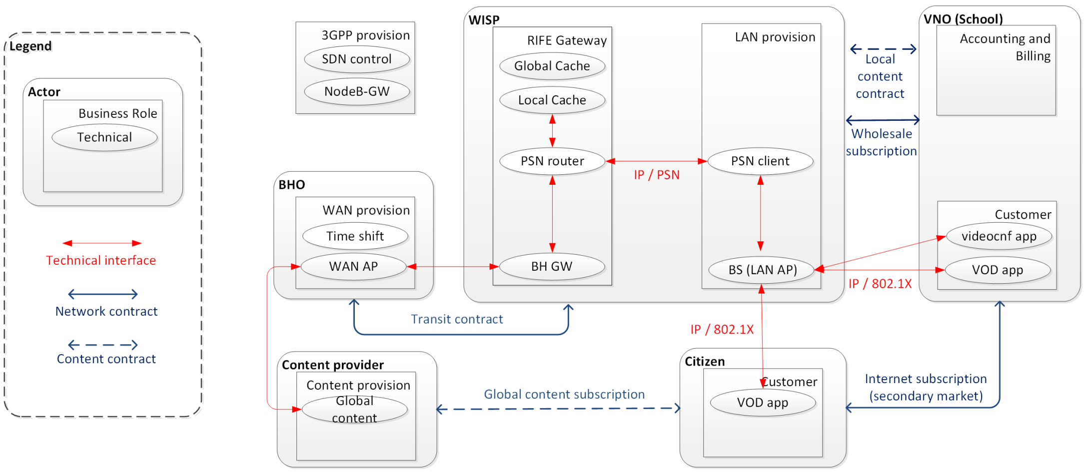
Table 17: Enablers of value and drivers of cost

Edge caching enables the storage of local and global content within the FH and therefore implies:
B1) Improved QoS on cached-content delivery B2) Contextualization of content to local preferences (demand anticipation)
C1) Increase in CAPEX and OPEX (caching system and management of content rights)
Time shifting of content delivery to the cache anticipating demand as described in [45] enables:
B3) Increase in BH available capacity during peak hours B4) Increase in resource usage in off-peak hours
C2) Increase in OPEX
Publish and subscribe networking (PSN) is a particular implementation of Information Centric Networking (ICN) that supports multicasting, caching and mobility[46]. Its functions are virtually deployed along the FH on demand in an overlay architecture which transports IP traffic:
B5) Increased FH available capacity B6) Traffic prioritization (different dissemination strategies) to enable added-value services.
C3) Reduction in OPEX
Metering is required to enable pricing that shapes demand and avoid congestion[45]:
B7) New pricing structures (metered and block pricing)
C4) Increase in CAPEX and OPEX (decreasing with network size)
Community Network agreements among citizens as seen in [8] allow:
B8) Local involvement and awareness
C5) Distributed CAPEX and OPEX across the community (distributed ownership)
802.1X access technologies allow the rapid and low-cost deployment of infrastructure operating in unlicensed frequencies and consequently:
C6) Reduction in CAPEX and OPEX (that increases with network size)
3G-femtocell [47] allows the implementation of mobile data services on unlicensed spectrum under strict QoS requirements on the BH. Consequently:
B9) Vertical integration with MNO and access to mobile extended services (SMS, m-banking, etc.).
C7) Reduction of connecting costs of Citizens

5.3.2 WISP-driven VNC

As shown in Figure 9, the interest of a local organization (school or healthcare centre) to make a specific content available for the local community under certain Quality of Service (QoS) (for example tomorrow's lessons or health campaign) creates an incentive for this organization to become a VNO and sign a contract of content-caching with the WISP. At the same time, the WISP anticipates demand and benefits from time-shifting delivery of content to off-peak hours releasing BH capacity. In order to increase usage of BH, WISP and BHO update their transit contract from time-of-the-day to congestion-based pricing.

Figure 9: WISP-driven VNC



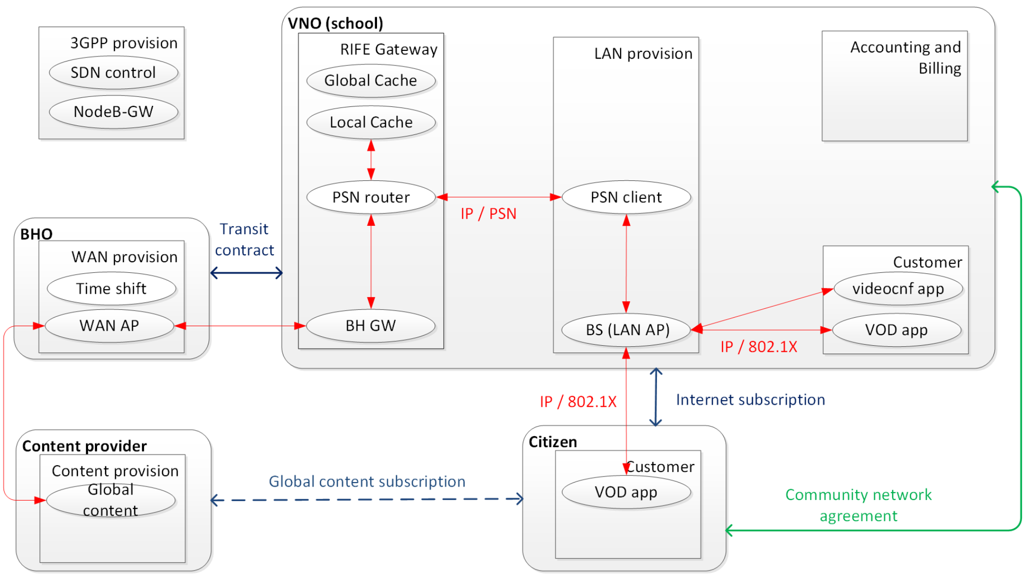
Back to the VNO, this supports other local businesses in the area through a business inclusion program (other schools or healthcare centres in town) and for this reason contracts a wholesale subscription from the WISP at a discounted price due to bargaining power. As a result, the VNO has created a secondary market of data services. Furthermore, to maximize the satisfaction of unserved demand, the VNO needs to include Transaction-based pricing such as pay-per-use to match business models of local businesses (for instance to allow videoconferencing during a limited period of time through BH) or Non-monetary pricing structures such as data-sponsorship to grant users access to content from the local cache (promotional content of health campaign). Summarizing, the WISP-driven VNC shows how a pre-existent WISP (with a cost leadership business strategy) increases its revenue through a VNO that act as reseller and increases the customer base. This VNC can also be seen as a strategy shift of the WISP towards a differentiation.

Regarding sustainability, it becomes a Critical Design Issue (CDI) to determine if revenues harvested by the VNO could cover the WISP's costs of supporting the new traffic prioritization and metering functions. Regarding the VNO, this has no control over infrastructure and assumes high operational costs of managing a secondary market. (According to Smura's classification, the VNO adopts a SP role with differentiation strategy). Unless the VNO has a complementary source of revenue, its sustainability could be challenged in the long run. The mCent application [48] is an example of this case in which the VNO could reward customers by sponsoring their data in exchange for these trying out applications or consuming certain content deployed in the cache.

5.3.3 Community-driven VNC

In this VNC, the VNO and the Citizens collaborate allowing traffic from others through their own infrastructure according to a Community Network (CN) agreement that defines responsibilities and rights over the shared equipment [8]. Growth of the infrastructure becomes organic and in under-served regions could be deployed in public strategic buildings. As a consequence, CAPEX and OPEX are distributed [8], initial required capital is reduced (compared to WISP-driven) but connecting cost of customers increased in exchange for ownership of equipment. Several members of the CN could act as ISPs what reduces switching costs and fosters service competition. Community involvement allows early identification of local requirements, increased local acceptance and infrastructure preservation. Traffic prioritization is hardly deployed across multi-vendor equipment and therefore VNO cannot provide added-value services.

Figure 10: Community-driven VNC



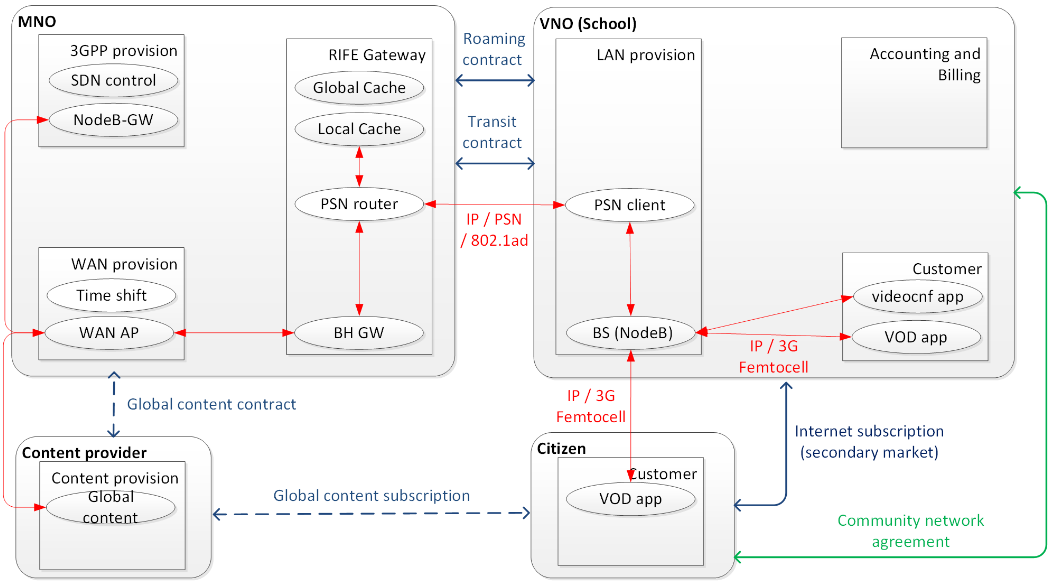
We assume that the BHO is an Internet satellite provider that has no promotion and contract management service on the ground. This way, the VNO could adopt the role of network installer and provide services autonomously after signing transit contract with the BHO. VNO's revenue model based on flat-fee Internet subscription fits well in a low OPEX running infrastructure without metering equipment. Pay-per-use could be provided for Internet browsing in Internet-cafe fashion. According to Smura's classification, the VNO adopts a NO role with cost leadership strategy.

In case the VNO faces no competition acting as gateway to the Internet, this fully benefits from an organically growing infrastructure that increases the capacity utilization of its BH link. Alternatively, in case multiple Internet gateways would compete within the CN, the VNO could use the improved QoS delivery as competitive advantage. It is up to the VNO to cache content of interest for the CN or reach an agreement with a Content-provider that targets the members of the CN seeking new revenue sources.

5.3.4 MNO-driven VNC

In this VNC, the VNO provides data services through commercially available 3G-femtocells operating in unlicensed frequencies as proposed in [47]. In order to allow interoperability between PSN, Edge-caching and 3GPP standards, a SDN controller is required to implement NFV functions [27]. Identically than in the Community-driven VNC, the VNO is a member of the CN which organically grows the 3G-femtocell infrastructure. More importantly, the interest of MNOs in expanding its customer base without increasing CAPEX or OPEX, facilitates the signature of a roaming and transit contract with the VNO. For example, in rural Mexico, the operator Telefonica seeks to partner with local organizations under a similar approach named The rural franchise [49]. As a result of this agreement, the customers of the VNO can reach the global mobile network including call management, SMS, m-banking. The adoption of 3G-femtocell technology reduces also costs of customer connection.

Figure 11: MNO-driven VNC



Due to the centralized nature of mobile architecture, the VNO acts as single operator in the CN has the monopoly of Internet broadband. It issues SIM-cards, establishes 3G subscriptions with Citizens and offers block pricing scheme to avoid congestion. 3G-femtocells implement metering and prioritization of traffic through centralized network management of 3GPP standards. Cost implications are taken into account in Table 18. As a result, the VNO matches business models of local businesses allowing Transaction-based pay-per-use pricing. According to Smura's classification, the VNO adopts a NO role.

So far, none of the VNC has been able to benefit from the existing Global content subscription between Content Provider and Citizen. Given the shared interest among MNOs and Content providers to disseminate content with a advertisement-based revenue model, it becomes a CDI to determine if the benefits of already existing Global caching-contracts between these actors could be extended to include the edge-cache and this way deliver copyrighted-content. More importantly, in case the Content Provider has an advertisement-based revenue model associated with cached-content, such new revenue source could be redistributed back to the VNO to provide sponsored access as in the case of Free Basics [50].

5.3.5 Comparison between VNCs

Systematic comparison between VNCs in Table 18 shows that the MNO-driven VNC captures the most value while reducing costs.

Table 18: Comparison of Benefits and Costs between VNCs

B	**Benefits**	**WISP**	**COM**	**MNO**
B1, 2, 5	• Improved QoS on content delivery • Increased FH available capacity • Caching of contextualized local content	√	√	√
B3,	• Increased BH available capacity during peak hours • Increased resource usage during off-peak hours	√	√	√
B6, 7	• Traffic prioritization (added-value services) • New pricing structures	√		√
B8	• Local awareness and involvement		√	√
B9	• Vertical integration with MNO • Caching of global content			√
C	**Costs**	**WISP**	**COM**	**MNO**
C1, 2, 3	• Increase in CAPEX and OPEX (caching system and management of content rights) • Incrase in OPEX (time-shifting) • Reduction in OPEX (PSN)	√	√	√
C4	• Incrase in CAPEX and OPEX (metering equipment / new pricing structures)	√		√
C6, 7	• Reduction in CAPEX and OPEX of network deployment (802.1X and femtocell)	√	√	√
C6	• Low switching cost of customers (CN multi-gateway)		√	
C5	• Reduction in CAPEX and OPEX (CN distributed ownership)		√	√
C7	• Reduction is connecting costs of customers (low-cost of mobile devices)			√

Table 19 summarizes identified revenue models in each VNC.

Table 19: Summary of revenue models

		WISP	**COM**	**MNO**
Transaction-based	Pay-per-use	$\surd$	Internet-cafe	$\surd$
Subscription	Metered			
	Block	$\surd$		$\surd$
	Flat fee		$\surd$	
Non-monetary	Data sponsorhip	$\surd$		
	Ad-based			$\surd$

5.4 Results

Three observations resulted from the VNA aiming at connecting communities constrained by a limited backhaul capacity and low-income.

First, it is acknowledged that a VNO acting as SP could implement a cost-leadership strategy and reduce prices. This is possible if flat-fee subscription is offered, metering and billing is avoided and, the service is provided via a shared infrastructure (e.g. communit network). However, the analysis also revealed that some customers, particularly from the corporate customer segment, might demand tailored solutions with particular QoS and pricing requirements. These can hardly be provided by a VNO that operates no infrastructure and only manages a secondary market of Internet subscriptions.

Alternatively, VNOs could adopt a differentiation strategy and offer both pricing flexibility and guarantee QoS levels under one condition. The revenues generated by the newly acquired customers (mainly from the corporate segment) would need to balance the increase in costs of acquiring and operating traffic prioritization and metering equipment.

The third observation of the analysis implies that customers' costs of access could be sponsored by revenues gathered in the context of an extended value network. For this to happen, particular QoS conditions need to be guaranteed. As an example, the introduction of edge-caching enables the delivery of content which could enable the business model of a content providers, advertisers, analytic companies. In this case, content-contextualization and customer base size are critical success factors heavily dependent on the implementing technology. Platforms benefiting of network externalities are better positioned to address such requirements.

6 Conclusions

6.1 Results

Submarine and terrestrial fiber technologies provide the required scalability to deliver large volumes of international Internet capacity thanks to the economical, durable and highly multiplexable nature of the optical glass medium. In comparison, satellite technologies cannot deliver capacity at the same scale due to the nature of the shared radio medium and the elevated marginal cost of adding additional capacity.

With regard to the last-mile, 3GPP technologies are a scalable solution to serve a large and dispersed population because of the broad coverage area of BSs (30 km), the centralized allocation and efficient reuse of the licensed spectrum and, QoS control mechanisms. Comparatively, the IEEE BS covers smaller areas (100 m), the communication is vulnerable to interferences in the unlicensed spectrum and, congestion results in service degradation.

However, from an implementation point of view, IEEE technologies require a lower initial capital investment not only because of the higher availability and affordability of the network equipment but mainly because spectrum licenses are not required. Conversely, 3GPP technologies demand a larger early commitment of capital because of the large-scale nature of its deployment, a costly equipment and spectrum licenses. In the context of developing countries, such commitment is even more difficult due to the business uncertainty caused by an unknown demand, income inequality that leads to low ARPU and, the lower availability of local providers and skilled personnel. As a result, smaller cycles of investment on IEEE technologies allow small operators to address smaller and more predictable portions of demand and thus, expand coverage assuming lower risks. However, as a downside, the delivered service is less robust to network congestion and delivers sub-optimal QoS.

In the 6 emerging mobile markets analyzed in this thesis, the subscription growth in urban areas is constrained by the delivered capacity to users and the price of data. Consequently, the user competence (third hypothesis) is discarded as bottleneck and its assumed that the ease-of-use of mobile devices and the richness of mobile Internet content satisfies the demand with limited literacy levels. Furthermore, causes of capacity and price bottlenecks are either market-related (require regulatory framework update), or non-market related (require from tailored solutions). Overall, the development of the mobile market can be modelled as a sequence of market-related bottlenecks (soft bottlenecks) and non-market-related bottlenecks (hard bottlenecks).

With the objective to connect communities constrained by a limited backhaul capacity and low-income conditions, two scenarios are defined based on a cost-leadership and a differentiation business strategies. A Virtual Network Operator acting as Service Provider could implement a cost-leadership strategy implementing: IEEE technologies that operate in the unlicensed spectrum, flat-fee subscriptions (e.g. to avoid metering and billing services), a shared infrastructure approach to reduce costs by collaborating with competitors (e.g. in community networks, in Open Model approach), automation and self-service (e.g. web-based subscription management). The drawback of this strategy is the low QoS levels derived from congestion which might not satisfy requirements of the corporate segment (e.g. healthcare sector). To this purpose, an operator can adopt a differentiation strategy by introducing traffic prioritization, QoS mechanisms and, flexible pricing structures (e.g. transaction-based pricing to match business models of customers). As a result, the VNO can no longer act as SP and needs to acquire and operate its own infrastructure (e.g. metering and billing). For example, the operator could adopt small 3GPP cells operating in unlicenced spectrum that allow small investment cycles and controlled risk. In this context, a caching system would also allow the delivery of improved QoS content. As a result, new business models could be implemented including subsidies from third-parties (e.g. advertisers, content providers, analytic companies) in an extended value network.

6.2 Results Assessment

In the literature review, this thesis claims that the enablers of large-scale network capacity progressively connect underserved regions. And, in the bottleneck analysis, this also states that the bottleneck to the Internet diffusion is the delivered capacity to users in the last-mile. Although these conclusions might sound contradictory, both exemplify the existing gap between the large backbone capacity available to metropolitan areas (e.g. provided by terrestrial fiber) and the insufficient capacity delivered to users (e.g. provided by IEEE or 3GPP technologies). In other words, the demand for Internet broadband access is not satisfied by the current offered last-mile services.

From a purely technological point of view, the standardization cycles of wireless access technologies have consistently improved both bandwidth and coverage per base station. Consequently, shorter development cycles might accelerate the deployment of more efficient technologies and the delivery of both, more capacity and a larger coverage, in the last-mile (assuming the incremental improvement persists at each cycle). Therefore operators and alternative networks might consider the standardization cycle length of the technology with regard to their own deployment cycles when acquiring wireless access technology.

In parallel, the mentioned demand evolves driven by application developers with an even shorter development cycle associated with the software industry (e.g. Facebook, Youtube). As result, demand might remain unsatisfied unless both industries align requirements (e.g. the Facebook Zero application minimizes data usage). The convergence of the two mentioned industries driven by the benefits of cloud computing (e.g. Network Function Virtualization) might become crucial in this regard.

Independently of the wireless technology, the Return On Investment (ROI) assumed by access operators limits the capacity and the geographical coverage in relation to the expected revenue. In order to maximize the two first factors, one option is to reduce investments by sharing infrastructure with other operators (e.g. Open Access/Community Network) in the context of fair regulatory framework. A complementary option is to increase revenues by collaborating with partners in an extended value network (e.g. content providers, advertisers) that could benefit from a larger, shared customer base (e.g. to extend coverage to new users, to subsidize connecting costs of new users). The downside is that the value network could take advantage of the new revenue and close sponsored-consumers within walled-gardens.

To conclude, it can be observed that, the affordability of broadband Internet access is limited, in the first place, by the less scalable network technology along both the first and last mile (e.g. satellite technology) and costs of deployment and operation need to be minimized. Secondly, operators provide services via the deployed network technology constrained by market conditions which depend on the regulatory framework (e.g. fair market competition level) and profits need to be minimized as well. Finally, business models of operators might maximize subsidies to support connecting costs of users (e.g. from advertisers, governments, as a freemium model).

6.3 Future Research

To pursue a deeper understanding of the dynamics of the mobile broadband market a mathematical model could be developed to relate: subscription growth, market bottlenecks and, operator's cost structure. A system dynamics model would be a good candidate thanks to its flexibility describing forces and causal loops. Such a model could address both demand and supply by defining the interplay between consumer and supplier surplus.

The main challenge to approach the consumer problem is the socio-economic and cultural differences between users. In this thesis, the economic utility of consumers is roughly estimated through a unique MOS predictor to all consumers and assuming only the browsing experience into account. To overcome this limitation, particularities of each market could be included. For instance, the availability of suitable and local content derived from indicators such as the number of both Wikipedia articles and Internet domains defined in local languages.

Regarding the supplier problem, the model would need to expand the cost comparison between wireless technologies by introducing a detailed cost estimation model seeking maximization of operator efficiency. Moreover, different deployment strategies such as mobile small cells could be taken into account to reduce the cost of deployment of 3GPP technologies while reducing the scale of deployment. To this regard, the advent of Software Defined Networking and Network Function Virtualization might be assumed as a driver of cost reduction.

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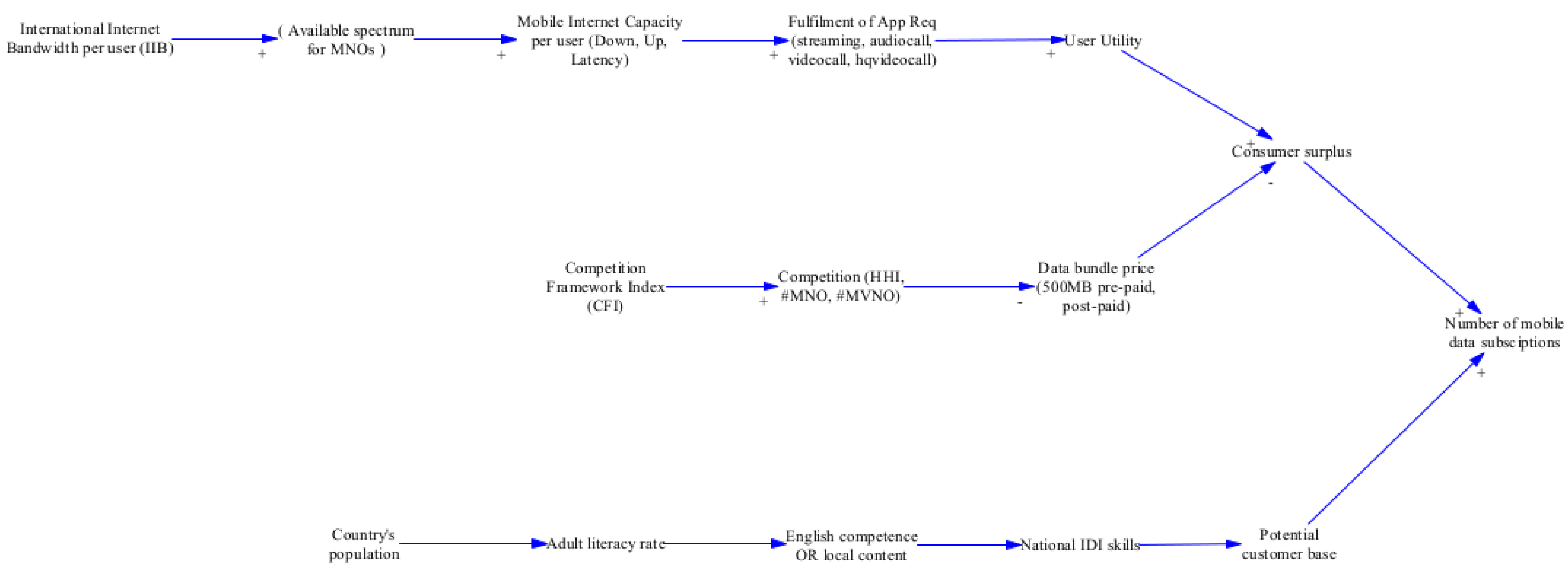
A Bottleneck chain diagram

Figure A1: Full bottleneck-chain



B Bottleneck prioritization table

Table B1: Summary of findings

	User competences			Pricing					Capacity			
City, Country	**Adult literacy rate**	**English c. OR local content**	**IDI skills**	**CFI**	**Market competition**	**mobile sub-basket prices**	**pre-paid data**	**post-paid data**	**IIB**	**Mobile Internet Capacity**	**App Req**	**data subs 100**
Tehran, Iran		X		X					**D**			1,3
Bangalore, India	X						X			**D**		5,3
Dar es Salam, Tanzania	X					**D**				X		8,8
Mexico City, Mexico			X		**D**						X	10,3
Jakarta, Indonesia		X						X		**D**		11,8
Sao Paulo, Brazil			X				**D**			X		47,2