Virtual Mobile Networking Using Always Best Connected Business Relationships

by

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Kevin David Shatzkamer

Submitted on January 29, 2015 to the Systems Design and Management Program in Partial Fulfillment of the Requirements for the Degree of Master of Science in Engineering and Management.

Abstract

With the advent of smartphones and tablets, mobile networks are no longer luxuries in the communications industry. Mobile networking is paramount to meeting the need of corporate users and the desires of consumers. These users consume mobile data to reach content and services deployed on the Internet by way of cloud computing. Mobile networks have undergone a number of iterations, with the current state – 4G Long Term Evolution (LTE) – providing a starting point for high speed, low latency mobile networking that meets the demands of bandwidth hungry applications and services.

Mobile Virtual Network Operators (MVNOs) have existed as a means to help Mobile Network Operators (MNOs) achieve meaningful market share in industry segments that have been harder, or more expensive, for the MNO to reach. In this way, MVNOs have remained niche providers to a highly segmented industry. In addition, a traditional 1:1 model of MVNO to MNO has left the MNO in dominant position to determine the extent to which the MVNO may be successful.

This thesis explores the trends that are forcing business model disruption in the MVNO industry and proposes a technical solution, built around the systems engineering System of Systems (SoS) principles that may be leveraged to help transform the mobile industry into a more competitive environment in which MVNO and MNO compete on level playing fields for subscribers.

Thesis Supervisor: Michael A M Davies

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1 Introduction

1.1 Context

This thesis lies at the intersection of many of the fascinating technology and business trends impacting the mobile industry. On the technology side, the introduction of virtualization, through the industry-standard Network Function Virtualization (NFV) architecture, and Software-Defined Networking (SDN) pave the way to rethink mobile network architecture. On the business side, the shifting consumer preferences towards Over-the-Top (OTT) services, enterprise Bring Your Own Device (BYOD) policies, and the Internet of Things (IoT) are driving new business models for mobile Service Providers with economics so significantly different from the status quo that new operating models are paramount to their future success.

Figure 1 is a simple causal loop diagram that illustrates the intersection of business and technology disruption. As operational economics deteriorate, there is increased opportunity for technology disruption. In the mobile industry, NFV and SDN represent that technology disruption. This technology disruption yields improved operational economics, which, in turn, creates opportunity for business model disruption. OTT consumption, BYOD, and IoT are some of many business model disruptions in the mobile industry.

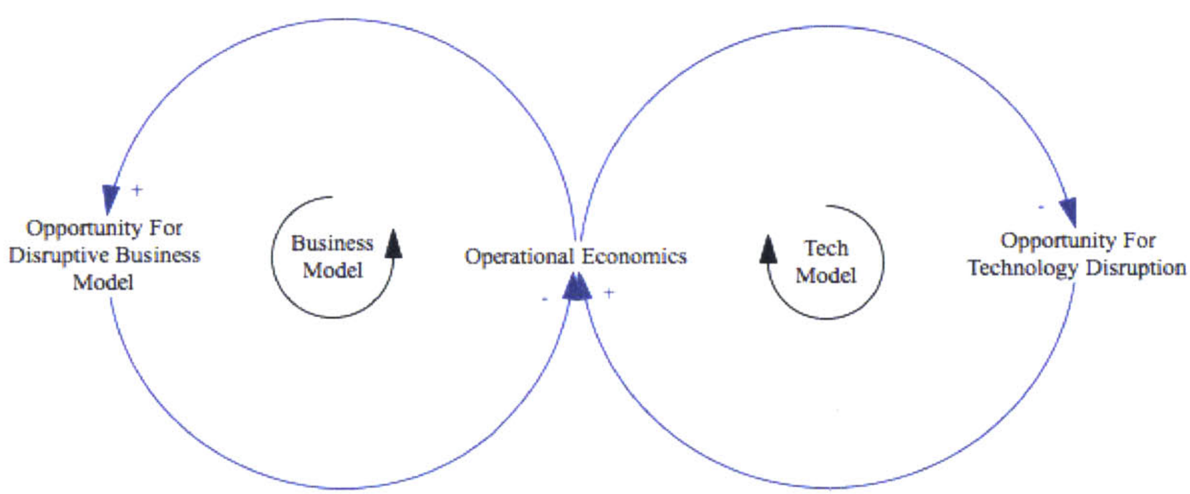

Figure 1: Business and Technology Disruption (Causal Loop)

One particular business model that has consistently generated interest in the mobile industry is that of the Mobile Virtual Network Operator (MVNO). MVNOs offer subscriber services for both voice and data, similar to those offered by traditional Mobile Network Operators (MNOs), but do so with a significantly different technology model. Unlike MNOs, MVNOs do not own the wireless network infrastructure over which they deliver services. For this reason, MVNOs are dependent on relationships with the MNOs for access to wireless access networks, and enter wholesale agreements with MNOs for bulk capacity - either voice minutes or data tonnage. In general, MVNO profitability is highly dependent on the rates negotiated in these wholesale agreements, with the underlying MNO often in a position of dominance.

The MVNO model, in general, is win-win opportunities for both the MVNO and MNO. In the case of the MVNO, lower barriers to entry (i.e., no spectrum costs) and reduced operating expenses (OpEx) allow these service providers to target underserved demographics and other lower-margin, niche market segments. For the MNO, increased subscribers without selling, general, and administrative expenses (SG&A), negative margin implications, or brand dilution is attractive.

1.2 Motivation

Regardless of the seemingly positive outcome for both all parties in MVNO models, there has been very limited success. From the early days of mobile voice services, MVNOs have consistently been niche players in the industry. Since 1997, when Telstra and Bellsouth signed an agreement allowing Telstra to use Bellsouth's GSM network, establishing the world's first MVNO in New Zealand[1], the MVNO market has had numerous waves of entrants and exits. To date, MVNOs have been relegated to competing in highly competitive market segments that MNOs have opted to avoid directly.

The landscape has shifted dramatically in the last 15 years, as new MVNOs serving niche markets have had varying degrees of success and longevity. As a thesis, it is the belief of the author that the business and technology disruptions discussed earlier have created an opportunity to reinvent the MVNO models - both technology and business - to ones in which the MVNOs are able to not just effectively compete for niche market segments, but also for the core market segment that the MNOs target directly.

[1] "Telstra, Bellsouth Sign Mobile Deal." *Telecompaper*. N.p., 5 Dec. 1997. Web.

1.3 Assumption of Knowledge

For the sake of brevity, this thesis makes a number of assumptions about the reader's initial level of understanding. These assumptions include:

- A basic understanding of networking functions, including routing and switching
- A basic understanding of the Open Systems Interconnect (OSI) networking framework
- A cursory understanding that Service Provider economics consists of a set of capital and operational expenses, and that profit margins are derived as the difference between revenue and these expenses
- At least some personal experience interacting with mobile devices, including smartphones and tablets, and requesting Internet content over wireless networks

1.4 Thesis Structure

This thesis will be structured to address the entire mobile system from both a business and technology perspective. The thesis may be broken into three distinct parts:

- The initial part of this thesis will provide the reader with context and understanding of mobile network architecture, mobile standards, and the demarcations within the mobile network architecture between MNO and MVNO. This part will also provide a historical perspective of MVNOs through 2014.
- The second part of this thesis will provide the reader with a framework for understanding the proposed solution. Included in this part are an overview the disruptions that are occurring on the Internet that are changing the long held assumptions upon which the MNO / MVNO business models are based and a System of Systems analysis of key stakeholder requirements and technology enablers for the propose solution.
- The final part of this thesis will propose a solution architecture based on the technology enablers and key stakeholder requirements. As with any proposed solution, assumptions

need to be made, and potential inhibitors need to be understood – and these are discussed in this part.

Mobile Industry Overview

The mobile industry has been a sustained area of growth and innovation for the last several decades. During this time, mobile technologies have matured and evolved from the delivery of analog voice services to the delivery of digital voice, video, and data services. Mobile devices, especially smartphones, have become integral to the typical consumer's lifestyle, allowing users to surf the Internet, access social networks, listen to music, watch video, check email, play games, and take and share photos. For this reason, it is no surprise that smartphones are the fastest adopted technology in human history[2].

According to Chetan Sharma Consulting, smartphones are not only the fastest adopted technology, but mobile is also the most pervasive technology (**Figure 2**)[3]. As of 2012, the number of people globally with mobile subscriptions broke the electricity barrier, and there are nearly two times as many mobile devices in use as there are bank accounts or credit cards. Similarly, mobile subscriptions outpace televisions and computers by 300%. With the pervasiveness of mobile technology, it is no surprise that there is a continuing upward trend in using cellular phones for ecommerce, video consumption, and Internet browsing.

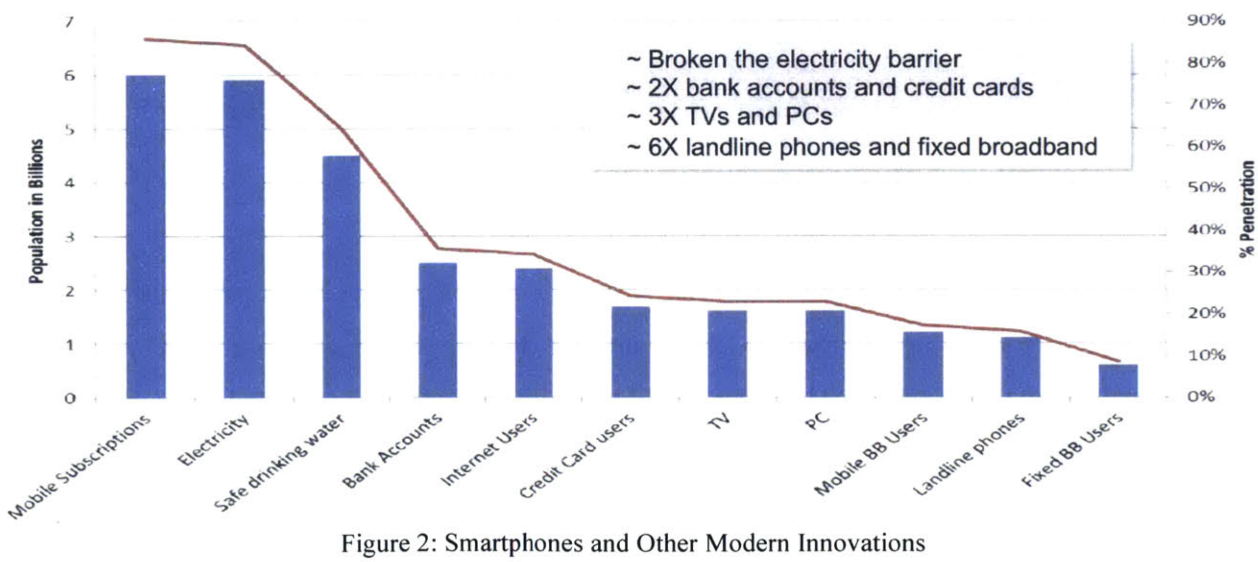

Figure 2: Smartphones and Other Modern Innovations

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[2] Mlot, Stephanie. "Smartphone Adoption Rate Fastest in Tech History." *PCMAG*. N.p., 27 Aug. 2012. Web.
[3] Sharma, Chetan. "Global Mobile Market Update." *Chetan Sharma: Technology & Strategy Consulting*. N.p., n.d. Web.

Even more important than adoption is the impact that the mobile industry has had on the global economy. According to the Groupe Speciale Mobile Association (GSMA), which focuses on standardization, deployment, and promotion of mobile technologies, the mobile industry represented 3.6% of global Gross Domestic Product (GDP) in 2013 and is expected to contribute approximately 5.1% of global GDP in 2020[4]. With all the attention focused on the "app" economy, social networking, content, and services, MNOs represent that single largest contributor to that GDP at 1.3% (**Figure 3**).

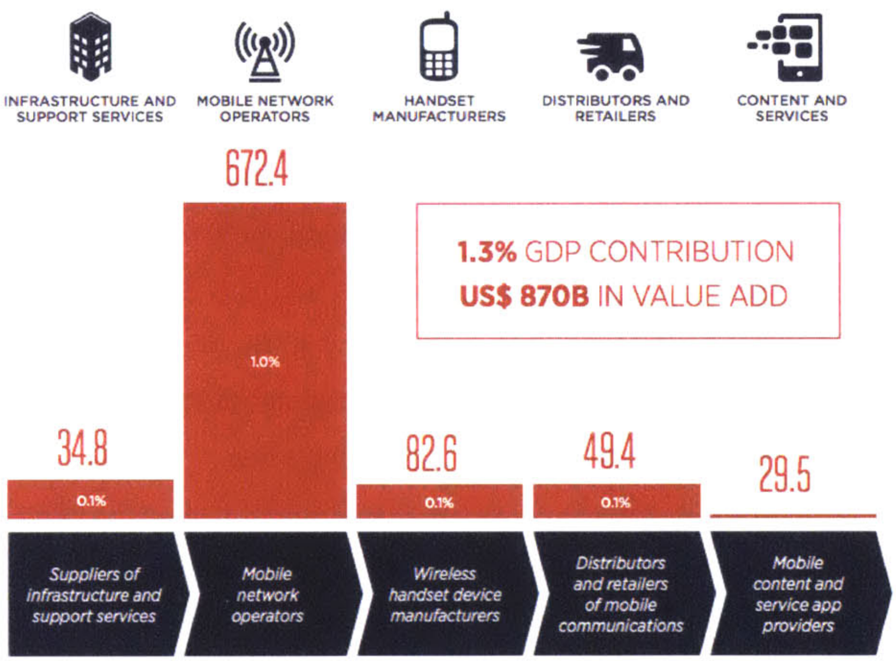

Figure 3: Mobile Industry Contribution to GDP

1.5 Current State of the Mobile Industry

The mobile industry can best be summarized by the rapid growth experienced, beginning with the launch of the modern day smartphone, characterized by both Apple's iPhone and Google's Android operating system, in 2007[5]. When combined with the increasing capability of mobile networks to deliver data and Internet services, the mobile industry experienced a rapid ascent in data usage at a time when voice usage was beginning to stagnate. In an analysis of mobile traffic growth between 2010 and 2014, Ericsson found that worldwide usage had grown from 200 petabytes/month globally to approximately 3200 petabytes/month (3.2 exabytes/month) in 2014,

[4] "The Mobile Economy 2014." GSMA Intelligence (2014): n. pag. *GSMA Mobile Economy*. GSMA Intelligence. Web.

representing a Cumulative Aggregate Growth Rate (CAGR) of 100%. Over the same period, however, voice traffic had stagnated completely. **Figure 4** illustrates these growth rates.

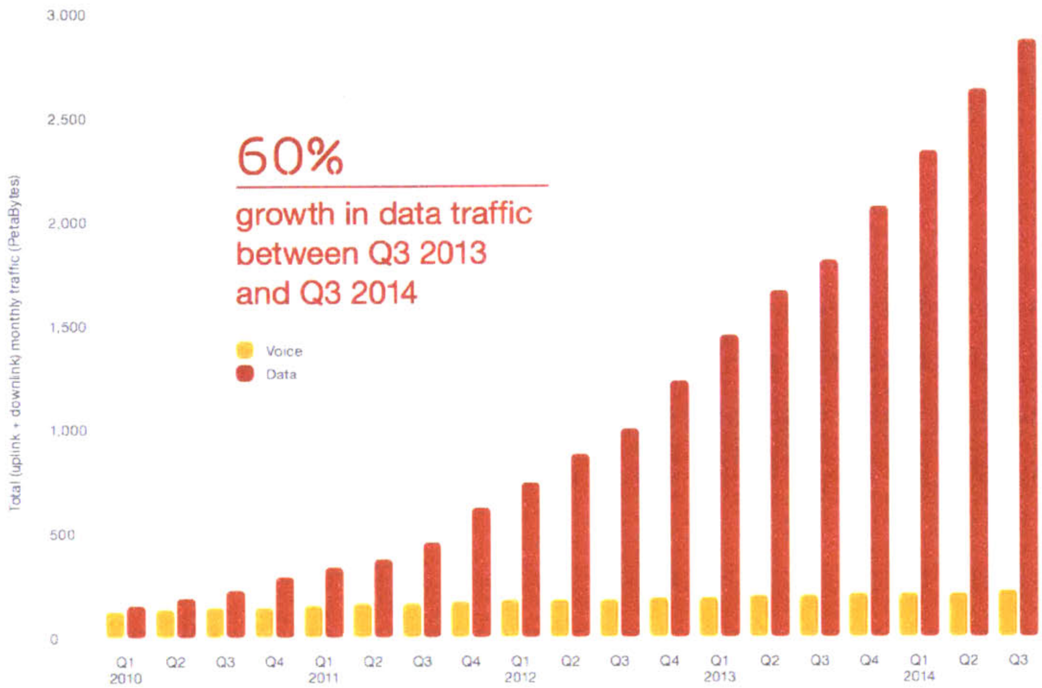

Figure 4: Mobile Traffic Growth (2010-2014)

The current state of the mobile industry is only one important data point when considering what future mobile networks and business models might look like. Over the next five years, mobile traffic is projected to grow at a CAGR of 40%, due to the combined growth in smartphone subscriptions (2014: 2.7B, 2020: 6.1B) and mobile traffic per subscription (2014: 900MB/mo., 2020: 3500MB/mo.) (**Figure 5**). The GSM Association predicts that global connection speeds between 2010 and 2017 will increase at a 54% CAGR, from 189 kilobits per second (kbps) to 3..9 Megabits per second (Mbps).

[5] "Timeline." *The iPhone Wiki*. N.p., n.d. Web.

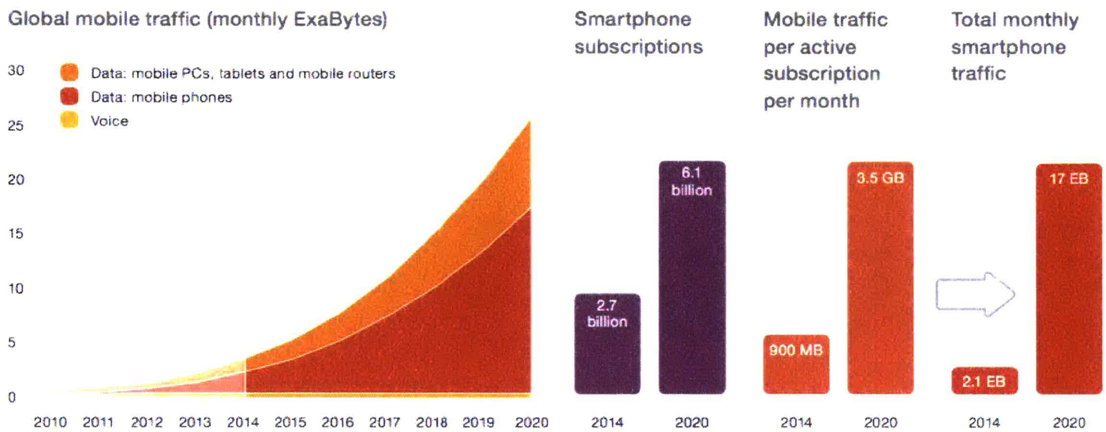

Figure 5: Mobile Growth (2014-2020)

Tremendous growth in consumer expectations has also forced Mobile Network Operators (MNOs) to increase their Capital Expenditures, although the investments in network infrastructure have been considerably slower than traffic growth rates. Globally, MNOs are expected to spend nearly $1.7 trillion on new network infrastructure by 2020, at a 4.7% CAGR (**Figure 6**).

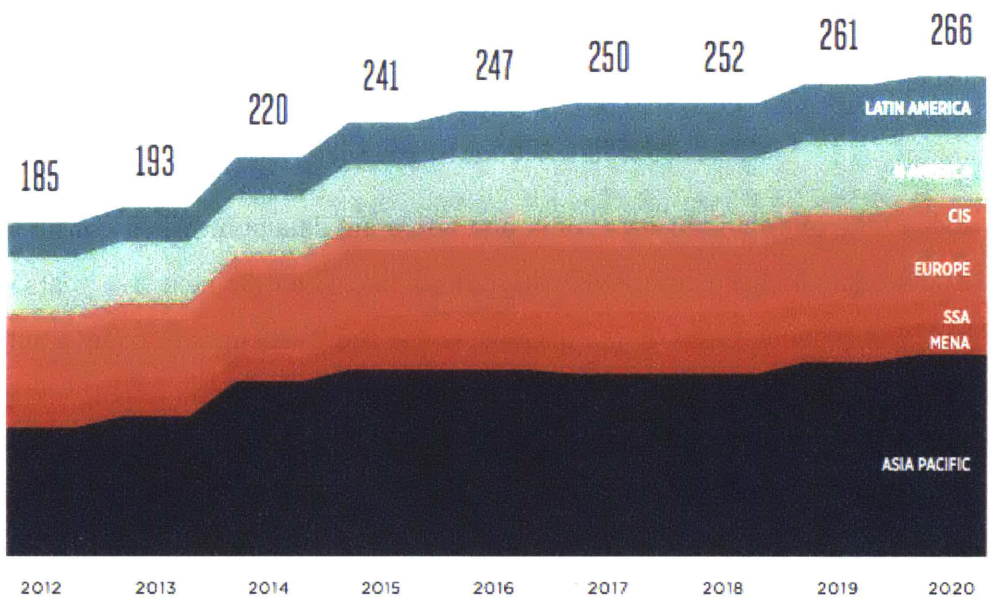

Figure 6: Total MNO Capex

1.6 Challenges Facing the Mobile Industry

This rapid growth has generated tremendous wealth in the mobile industry, from device manufacturers and "app" developers to MNOs and infrastructure vendors. MNOs, while attempting to support the data increase, are faced with a number of challenges that must be resolved. These challenges are economical, operation, and technical, in nature.

Economically, the impact of the transition from voice-driven traffic volume to data-driven traffic volume has been deflationary to the MNOs. **Figure 7**, for example, describes schematically the impact of the traffic mix shift on MNO revenue. The threshold at which network costs outstrip revenue may be considered theoretical, as such an inflection is not expected as long as the cost of capacity remains considerably lower than the initial cost of coverage, but the diagram can be used to understand industry dynamics. The impacts identified are driven by more than just increasing traffic volume, but also:

- Increase in infrastructure CAPEX and OPEX to support mobile data growth drives network costs higher
- Availability of services from 3rd parties as a replacement for MNO services leads to fewer revenue opportunities

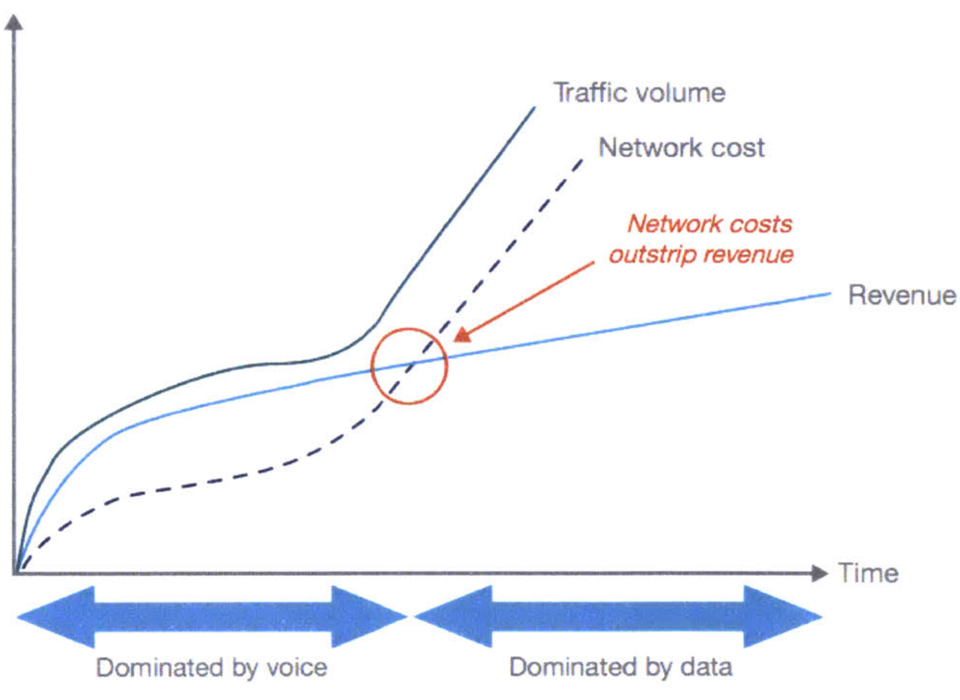

Figure 7: Impact of Data Dominated Networks (Analysys Mason, 2011)[6]

[6] "Building a Profitable Data Future." www.ericsson.com. *Ericsson*, n.d. Web.

In addition, consumer sentiment towards the role of MNOs has changed as a result of the shift from voice-centric service to data-centric service. In both landline and mobile voice services, there is an inherent acceptance of poor capacity that results in call failure. This acceptance leads consumers to attempt their voice calls at a later time. As evidence of this, voice capacity is modeled using Erlangs, which are unit representing continuous voice traffic. Although multiple different Erlang traffic models exist, MNOs use Erlang B, which models all blocked calls being cleared and reattempted later. In contract, a seldom-used Erlang C model assumes that voice calls are queued, and places a significantly higher burden on the mobile network infrastructure[7]. Although the Erlang model has been applied in the past to mobile data networks, consumers are less tolerant to poor capacity for mobile data. Although counter-intuitive, mobile data services, such as navigation and search, are generally more real-time than voice services, requiring continuity of coverage, contiguous capacity, and consistency[8].

The increase in indoor consumption of mobile data has led to both technical complications, as the cost of delivering cellular mobile data services to in-building subscribers is considerably more expensive due to attenuation, and economic complications, as in-building alternatives, such as WiFi, pose a competitive threat by delivering best-effort services at a fraction of the cost. According to Senza Fila Consulting, the cost of covering indoor subscribers via cellular networks is up to 8.74X more expensive than in-building WiFi[9]. As a result, MNOs are actively deploying in-building small cells to resolve the economics imbalance.

2 Mobile Networking 101

The thesis presumes a cursory understanding of the fundamental working of the Internet, the Internet Protocol (IP), and the Transmission Control Protocol (TCP) / IP networking stack. The most important aspect of this is that the Internet is not mobile, by default. In fact, when the IP protocol was first proposed (1975), "the problems of...mobility were many years off."[10] Before beginning to understand mobile network architectures, it is important to understand why IP breaks in a mobility environment, and how mobility is achieved over an IP network.

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[7] "What Is an Erlang?" Erlang.com. N.p., n.d. Web.

[8] Davies, Michael. *Endeavour Partners*. N.d. "The 5C's of Mobile Networking"

[9] Paolini, Monica. Cost Savings and Revenue Benefits from Next Generation Hotspot (NGH) Wi-Fi (n.d.): n. pag. *Wireless Broadband Alliance*, Senza Fila. Web.

[10] J. Day, Patterns in Network Architecture, Indianapolis, Indiana: Pearson Education; 2008.

2.1 The IP Mobility Challenge

As discussed in my previous publication, IP Design for Mobile Networks, in order for a network to identify and route traffic to a specific node, an addressing scheme – IP addressing – is used. The IP address uniquely identifies a node connected to the network, and all packets are sent across the network indicating both the source IP address and destination IP address. In addition, Transmission Control Protocol (TCP) which resides at Layer 4, the Session Layer, creates connections, identified by a 4-tuple (Source IP address, Source port, Destination IP address, Destination port), used to identify the transmission session.

If neither node is mobile, sending traffic from source to destination is trivial. Routers use the hierarchical structure of Internet addressing to locate a path from the source node to the destination node, and the packet is sent to the next hop in that path.

The IP address assigned to the node, in essence, serves two purposes. For TCP, the IP address serves as an endpoint identifier upon which sessions can be established and maintained. At the network layer, however, the IP address is used in making routing decisions. **Figure 8** illustrates how IP addresses are assigned and used at the network layer.

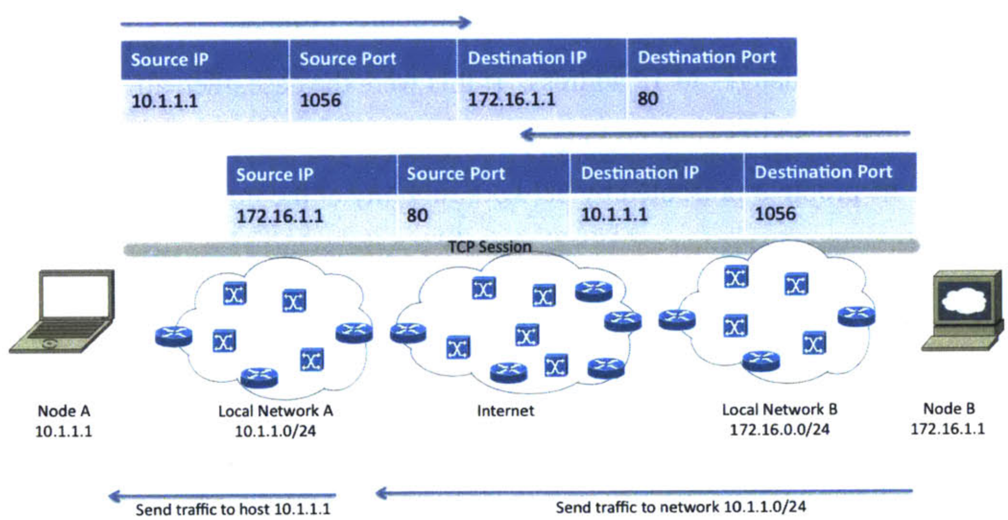

Figure 8: Network Layer Connectivity

For this reason, mobility presents a unique problem to the network. Layer 3 mobility refers to an end node that changes point-of-attachment. Layer 3 creates a two-dimensional challenge:

- The mobile node keeps its IP address. If this were the case, then the hierarchical structure of the Internet is broken, and the network cannot properly route to the mobile node. **Figure 9** illustrates the problem presented by mobility at the network layer.

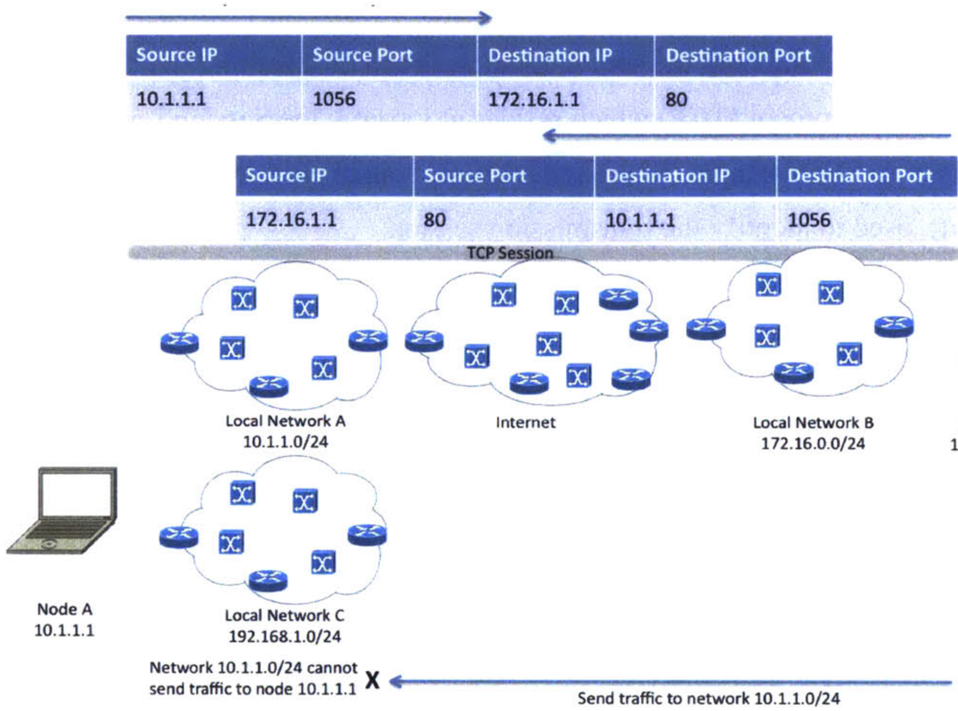

Figure 9: Network Layer Mobility Problem

- The mobile node changes its IP address. If this were the case, then all TCPs session built on the original IP address can no longer continue, and are broken. **Figure 10** illustrates the problem presented by network mobility at the transport layer.

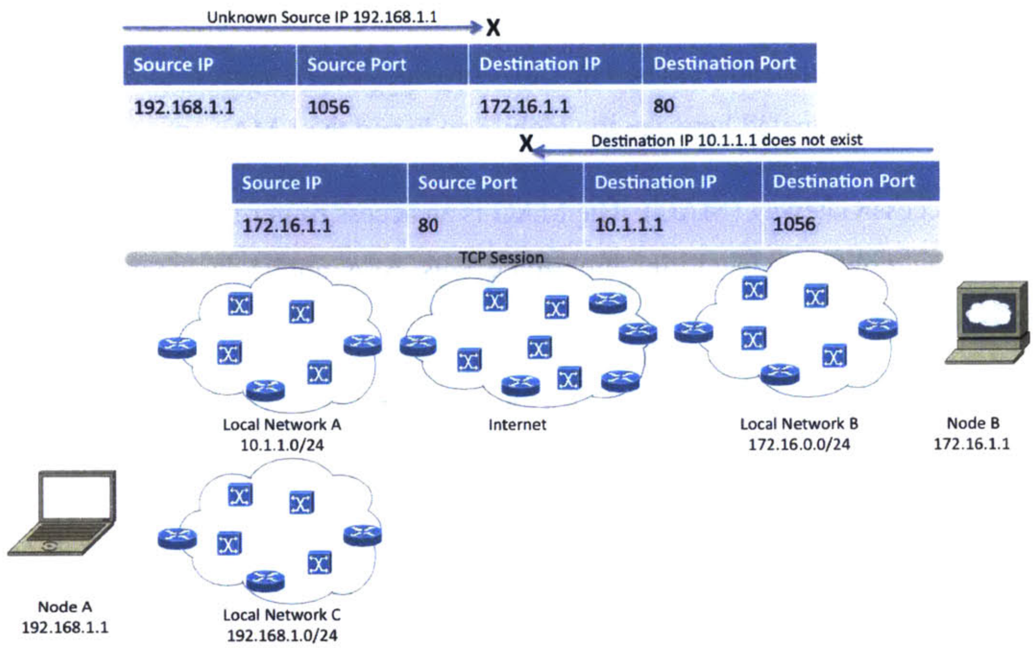

Figure 10: Transport Layer Mobility Problem

It is unreasonably complex to expect that the network routing decisions and topology can adapt to reflect the mobility of every node, it is necessary to preserve the node's original IP address, regardless of point-of-attachment. More specifically, it is necessary to preserve the node's original IP address, as perceived by the other node communicating over the established TCP session. Multiple protocols have been developed for this purpose, including Mobile IP and GPRS Tunneling Protocol (GTP).

All of these protocols resolve the mobility problem in essentially the same way, relying on IP in IP tunneling mechanisms to create separate location addresses, known as Care-Of Addresses (CoA), and identifier addresses. In this way, the IP address in the outside IP tunnel header denotes location, while the IP address in the inside IP packet header denotes identifier.

This work reappears across multiple standards developed by the Internet Engineering Task Force (IETF) Network-based Localized Mobility Management (NETLMM) working group[11]. Regardless of the protocol used, network mobility includes two core functions[12]:

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[11] IETF. "Charter." *Network-based Localized Mobility Management (netlmm).* N.p., n.d. Web.

[12] Gundavelli, S., Ed., Leung, K., Devarapalli, V., Chowdhury, K., and B. Patil, "Proxy Mobile IPv6", RFC5213, August 2008.

- Local Mobility Anchor (LMA): The LMA acts as the anchor point, topologically, for the mobile device network addresses. The LMA provides the IP address to the mobile device, and all traffic is tunneled between the mobile node and the LMA.

- Mobile Access Gateway (MAG): The MAG is an access router function responsible for tracking the mobile device during mobility events. As a mobile device moves between MAGs, the LMA remains consistent.

2.2 Mobile Network Architectures and Standards

There are many types of mobile networks in use today. Standardization takes place across a variety of organizations, with the predominant cellular standards organization being the Third Generation Partnership Project (3GPP)[13]. The 3GPP is an aggregate of six regional telecommunications standards development organizations (SDOs), known as "Organizational Partners" with a charter to promote interoperability of cellular equipment and networks. The six regional Organizational Partners are:

- Association of Radio Industries and Businesses (ARIB) and Telecommunication Technology Committee (TTC) in Japan

- Alliance for Telecommunications Industry Solutions (ATIS) in North America

- China Communications Standards Association (CCSA) in China

- European Telecommunication Standards Institute (ETSI) in Europe

- Telecommunications Technology Association (TTA) in Korea

While 3GPP defines the standards and architectures themselves, multiple organizations play a role. For instance, the Next Generation Mobile Networks (NGMN) organization provides both performance requirements and functional recommendations to 3GPP[14] and the IETF standardizes many of the protocols that are used in the 3GPP architecture.

[13] 3GPP. "About 3GPP." *3GPP.org*. N.p., n.d. Web.

[14] NGMN. "Vision and Mission." Next Generation Mobile Networks: Vision & Mission. N.p., n.d. Web.

Mobile network architectures are defined by generation, categorized by access technology and frequency bands. Each successive generation of access technology is typically non-backwards-compatible. Cellular access systems are currently on their 4th Generation (4G), with a Fifth Generation (5G) standard currently in a requirements gathering phase. **Table 1** provides the nomenclature, purpose and network types in the evolution of mobile networks[15], with the predominant access technology in each generation highlighted in bold[16].

Gen	Purpose	Predominant Network Type(s)
1G	Analog Voice (Circuit Switched)	**Advanced Mobile Phone System (AMPS)**
2G	Digital Voice (Circuit Switched)	**Global System for Mobile Communications (GSM)** Code Division Multiple Access (CDMA) Time Division Multiple Access (TDMA)
2.5G	Digital Data (Packet Switched)	**General Packet Radio Service (GPRS)** CDMA 1X
3G	High-Speed Data (Packet Switched)	**Universal Mobile Telecommunications System (UMTS)** CDMA Evolution - Data Only (EV-DO)
4G	High-Speed Data (All IP)	**Long Term Evolution (LTE)**

Table 1: Generations of Mobile Technology

As a general strategy, as new generations of mobile technology are released, MNOs tend to slow investment in previous generations. This allows MNOs to shift spend towards more efficient technologies, then repurpose spectrum towards those efficient networks. In addition, operationally, cellular architectures have continued to evolve from wide and sparse to narrow and dense. This densification of cell towers and other network elements has enabled MNOs to scale to meet increasing demand.

[15] "Understanding 1G vs. 2G vs. 3G vs. 4G." 4G Americas. N.p., n.d. Web.
[16] Qualcomm. "The Evolution of Mobile Technologies." (n.d.): n. pag. Qualcomm, June 2014. Web.

Figure 11: Infrastructure Evolution Over Time

In general, there are still many 2G, 2.5G, 3G and 4G networks in use today. In many instances, these networks are deployed in parallel, with 2G networks delivering voice services and a combination of 3G and 4G networks delivering data services[17]. Each standard consists of different network elements, protocols, authentication methods, roaming capabilities. This thesis will only provide a description of the LTE system for multiple reasons:

- Both 2G and 3G Networks will begin to experience decreasing global connections, beginning in 2015. The GSMA predicts that LTE connections will growth from 3% of total global connections in 2013 to 25% by 2020 (**Figure 12**).

[17] "Coverage Maps for AT&T, Verizon, Sprint, T-Mobile & More | OpenSignalMaps." - *OpenSignal*. N.p., n.d. Web.

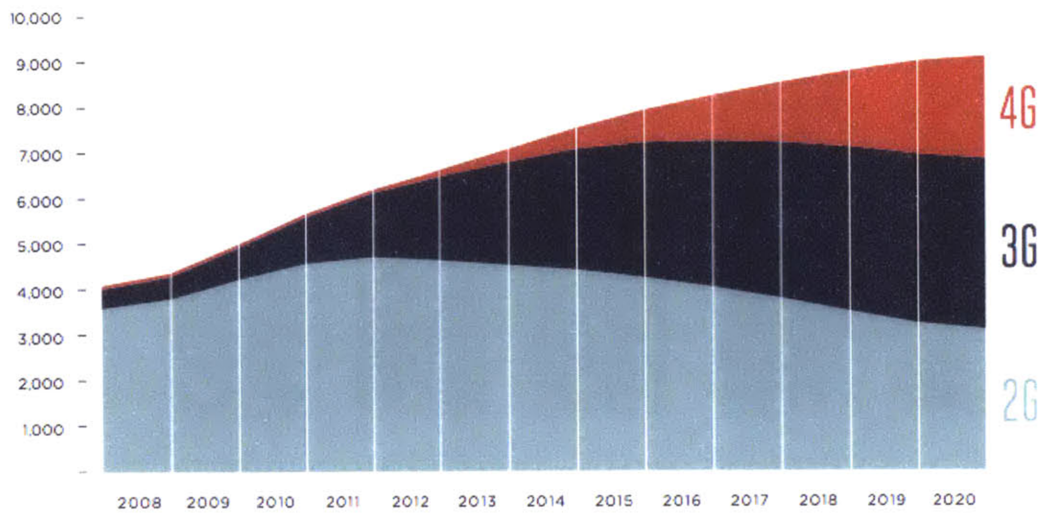

Figure 12: Global Connections by Technology (2008-2020)[18]

- LTE is the technology investment path from most mobile network operators globally, with over 300 LTE network commercially launched in 112 countries[19] (**Figure 13**). The GSMA predicts over 500 LTE networks across 128 countries by 2017[20].

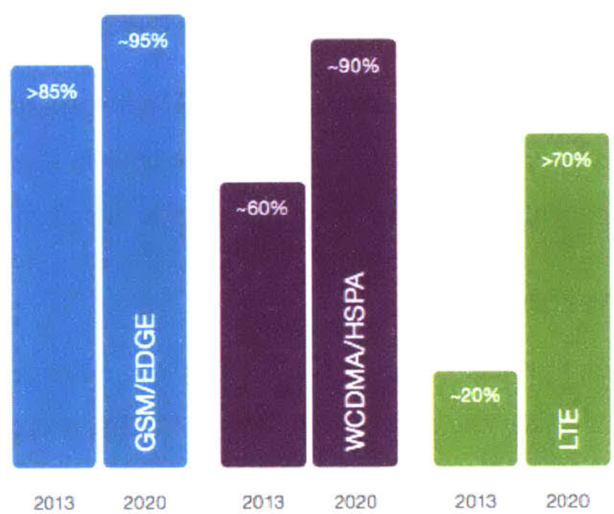

Figure 13: World Population Coverage by Technology (2013-2018)

- LTE is the network of choice for essentially all current and future 4G networks and subscribers (**Figure 14**)

[18] "The Mobile Economy 2014." GSMA Intelligence (2014): n. pag. *GSMA Mobile Economy*. GSMA Intelligence. Web.

[19] Ericsson. "Ericsson Mobility Report." *Ericsson Mobility Report* (n.d.): n. pag. Nov. 2014. Web.

[20] "The Mobile Economy 2014." GSMA Intelligence (2014): n. pag. *GSMA Mobile Economy*. GSMA Intelligence. Web.

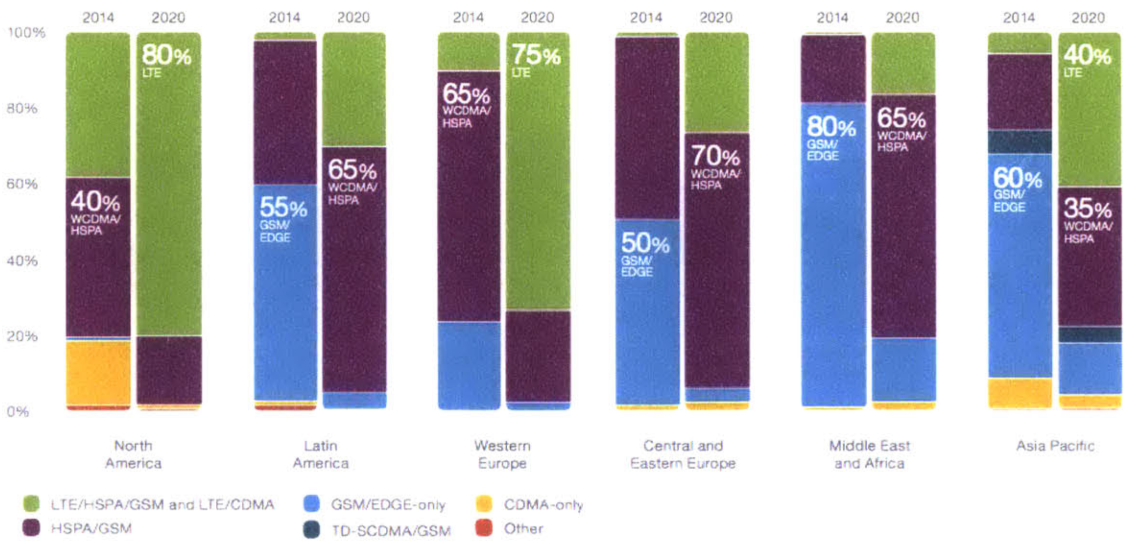

Figure 14: Mobile Subscribers by Region and Technology[21]

- LTE provides the most robust set of interoperability and roaming capabilities, both for other cellular access methods and for non-cellular access methods, such as WiFi.
- LTE is an inherent assumption in the solution offering proposed in this thesis.

This thesis does not detail the complete workings of the LTE network. Instead, sufficient context of the LTE network architecture, interfaces, and functional elements is provided to give the reader clarity into the subsequent MVNO architectures and functional splits.

2.2.1 LTE Network Architectures

The LTE network architecture project began in 3GPP in 2004 to enhance the UMTS architecture and optimize the radio air interface and access architecture[22]. What is commonly referred to as "LTE" today is actually standardized as the Evolved Packet System (EPS), consisting of two distinct architectures – the Evolved UMTS Terrestrial Radio Access Network (E-UTRAN) addressing the radio aspects, and the Evolved Packet Core (EPC) addressing the non-radio aspects. Together, the E-UTRAN and EPC provide the access system that enables mobile devices, or User Equipment (UE) to access various network operator and non-operator services, including voice, video, and Internet browsing.

[21] Ericsson. "Ericsson Mobility Report." Ericsson Mobility Report (n.d.): n. pag. Nov. 2014. Web.
[22] 3GPP. "LTE." 3GPP - The Mobile Broadband Standard. N.p., n.d. Web.

The architecture of the EPS is illustrated in **Figure 15**, with the logical split of the E-UTRAN functional elements and EPC functional elements denoted by a vertical dashed line[23].

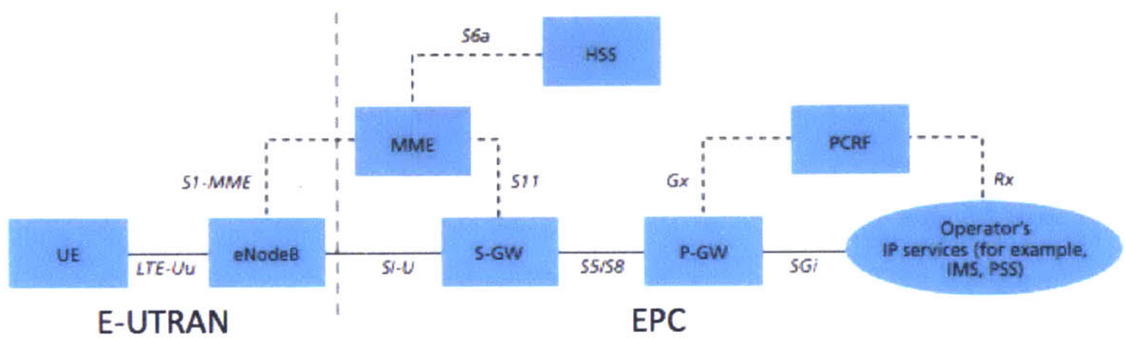

Figure 15: LTE EPS Architecture[24]

2.2.1.1 Functional Split

The functional split of the E-UTRAN and EPC are provided in **Figure 16**. Unlike previous generations of mobile standards, the LTE architecture is flat, with radio functions residing in the E-UTRAN (eNodeB) and non-radio functions residing in the EPC (a combination of the Mobility Management Entity [MME], the Serving Gateway [S-GW] and the Packet Data Node Gateway [P-GW]). The S1 interface is defined, which allows the E-UTRAN and EPC to transfer both control and bearer information between each other.

[23] Alcatel Lucent. "The LTE Network Architecture." (n.d.): n. pag. Web.

[24] 3GPP TS 23.401, "General Packet Radio Service (GPRS) Enhancements for Evolved Universal Terrestrial Radio Access Network (E-UTRAN): Overall Description; Stage 2."

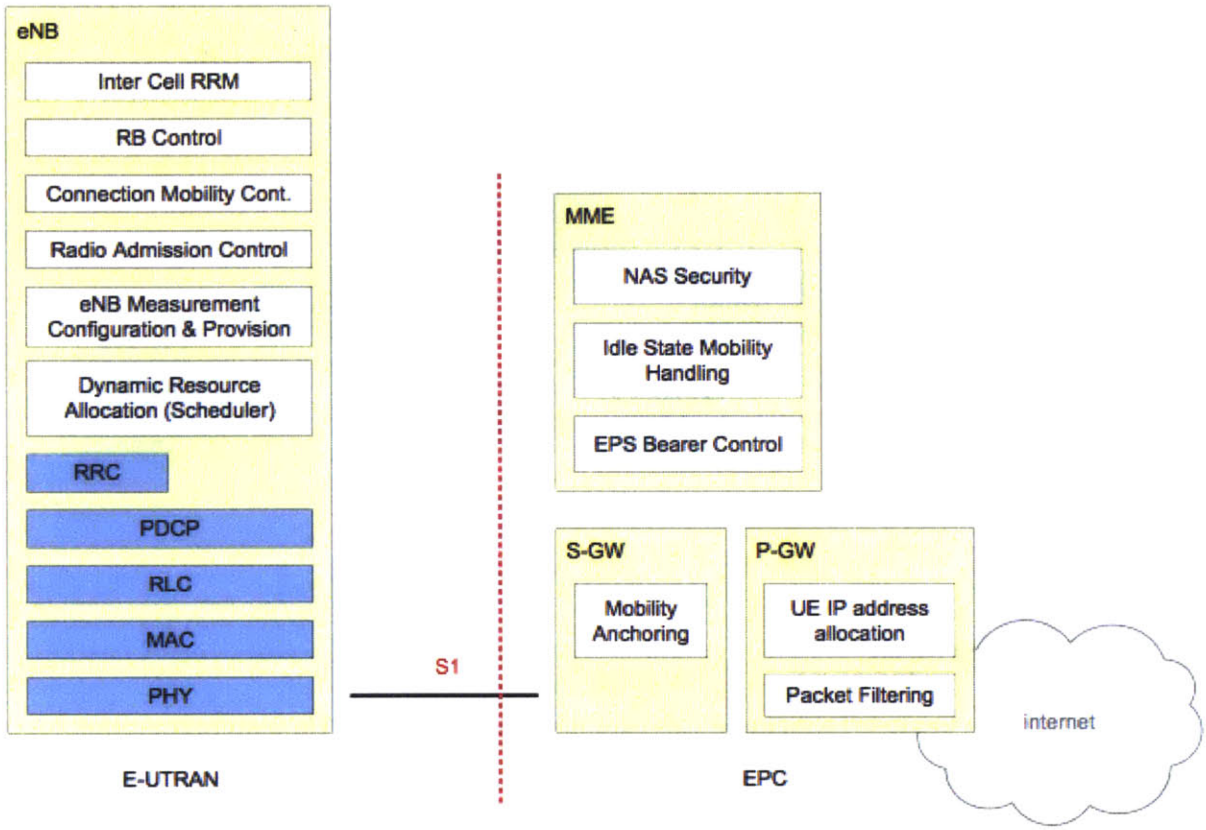

Figure 16: Functional Split of E-UTRAN and EPC[25]

2.2.1.2 E-UTRAN

The LTE E-UTRAN consists of two main functions – the UE and the eNodeB.

The UE is essentially the mobile terminal, allowing the user to have access to network services. Common UE devices include smartphones, tablets, sensors, modems, and mobile hotspots. The UE connects to the network via an air interface to the eNodeB.

The eNodeB is essentially the cellular radio, or access point. The E-UTRAN consists of many eNodeB's all connected to the EPC. The interface for this connection is the S1 interface, which is comprised of both a control plane (S1-MME) and bearer plane (S1-U).

Operationally, the cellular radio infrastructure has shifted from coverage-driven to capacity-driven. The LTE E-UTRAN is the first cellular architecture to pay special attention to this shift,

[25] 3GPP TS 36.300, "Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN) Access." Figure 4.1-1.

and has developed a hierarchical approach to cell deployment, optimized for aggregate capacity. As such, multiple eNodeB "types" have been defined, per **Table 2**. Smaller cell sites generally not only provide improved capacity versus traditional macrocells, but also provide more uniform coverage when deployed as an underlay, or in addition to, the macrocells.

LTE Cell "Type"	Typical Cell Range	Capacity (in Mbit/s per km^2)
Femtocell (Residential)	20m	40+ per household
Femtocell (Enterprise)	100m	1000+ (1Gbps)
Picocell (Indoor/Outdoor)	300-500m	260+
Microcell / Metrocell (Indoor/Outdoor)	700 -1500m	50+
Macrocell	800m – several km	24+ (Coverage limited)

Table 2: LTE EnodeB Terminology By Cell Type

In areas where large coverage gaps appear, such as stadiums and venues, distributed antenna systems (DAS) are also used. Unlike "small cells," DAS are smaller antennas that do not wholly contain the intelligent infrastructure of the eNodeB, but instead are physically connected, typically via fiber, back to existing eNodeB. Coverage is augmented with the additional antennas, but capacity is still determined by the number of carriers, or amount of spectrum, contained at the eNodeB. Although originally deployed for voice services, DAS continue to be the most economical way to provide uniform coverage for mobile data services[26].

2.2.1.3 EPC

The LTE EPC consists of four main functions – the MME, S-GW, P-GW, and Home Subscriber System (HSS), illustrated in **Figure 17**. The Policy Control and Charging Rules Function (PCRF) is also sometimes associated with the EPC, as per **Figure 15**.

[26] Davies, Michael. *Endeavour Partners*. N.d. "Uniform Coverage vs. Capacity"

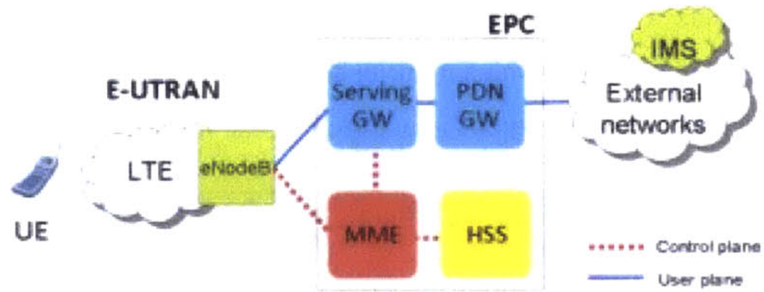

Figure 17: EPC Core Functions

The MME is the core control function in the EPC, responsible for the bearer activation and deactivation procedures, including user authentication and identity, location tracking, and S-GW / P-GW selection. The MME works in coordination with the HSS, which acts as the database and repository for the MME functions. This interface is defined as the S6a interface.

The S-GW provides the local mobility anchor for the UE during eNodeB handovers, the mobility anchor for roaming scenarios, and routing/forwarding functions to the LTE E-UTRAN. The S-GW contains the MAG functionality defined earlier. All IP packets to and from the UE are routed through the S-GW. The S-GW communicates with the MME via the S11 interface and with the eNodeB via the S1-U interface.

The P-GW is the IP point of attachment in the mobile network, acting as the mobility anchor point between LTE and non-3GPP access networks. The P-GW acts as the LMA defined earlier. The P-GW also provides IP address allocation and policy enforcement functions, such as filtering, charging, marking, rate enforcement, and lawful intercept. In this regard, the P-GW provides the Policy Control Enforcement Function (PCEF). The P-GW communications with the SGW via the S5 interface, and with the Internet and operator services via the SGi interface. The SGi interface represents the first point of un-tunneled IP bearer traffic in the mobile network.

The HSS contains the database of all subscriber data and is responsible for user authentication and access authorization. The HSS database includes call establishment data, such as session setup, and mobility management data, such as location tracking.

The PCRF acts as the policy decision point (PDP) for policy and charging control and is responsible for determining Quality of Service (QoS) and charging policies, as granular as per-flow.

2.2.2 LTE Network Identifiers

LTE also defines a number of identifiers for use in cellular networks. The most important identifiers are those that identify the user, the user subscription, and the device. These are defined as[27]:

- The International Mobile Subscriber Identity (IMSI), which identifies users. The IMSI is typically 15 digits long (although, it can be shorter), and consists of three components – the country code, network operator code, and mobile subscriber identity. This identity is stored on the Subscriber Identity Module (SIM) card in the mobile terminal, and is used to authenticate the user. In order to ensure privacy, the IMSI is rarely sent over the network. Instead, a Temporary Mobile Subscriber Identity (TMSI) is assigned by the HSS and used in all communications with the UE post-authentication. The relationship between the subscriber and the IMSI is permanent for the life of the SIM card.

- The Mobile Station International Subscriber Directory Number (MSISDN), identifying the country, network operator, and subscriber, is the phone number corresponding to the SIM card. The MSISDN associated with a SIM card may change, while the IMSI associated with the SIM card does not. The relationship between the subscriber and the MSISDN is semi-permanent, and may be changed upon subscriber request.

- The International Mobile Equipment Identifier (IMEI) identifies the mobile device itself. This identifier is specific to the hardware, and may be used by the mobile network to validate the mobile terminal itself. The IMEI has no relationship, either permanent or semi-permanent, to the subscriber. In some countries, the mobile network operator does, however, lock the relationship between the IMSI and the IMEI during the life of a subscriber contract.

[27] Grayson, Mark, Kevin Shatzkamer, and Klaas Wierenga. Building the Mobile Internet. Indianapolis, IN: Cisco, 2011. Print.

The nuances of identity management in mobile networks, and the various identifiers used, will be pertinent later in the final part of this thesis when discussing the potential solution for MVNOs.

2.2.3 LTE Roaming Architecture

The 3GPP LTE architecture specifies a roaming architecture[28] that allows a mobile subscriber to receive services when they are away from home. The roaming architecture technology is complemented by business relationships between MNOs, in which either unilateral or bilateral agreements are established for one MNO's subscribers to use the other MNO's network. This is especially relevant for international travelers.

The roaming architecture establishes the concept of a "home" network (Home Public Land Mobile Network [HPLMN]) and a "visited" network (VPLMN), in which the "home" network is the one to which the user is subscribed and the "visited" network is the one in which the user is connected. There are two architectures defined for roaming – one in which the P-GW is located in the home network, denoted as a Home Routed architecture (**Figure 18**), and one in which the P-GW is located in the visited network, denoted as a Local Breakout architecture (**Figure 19**).

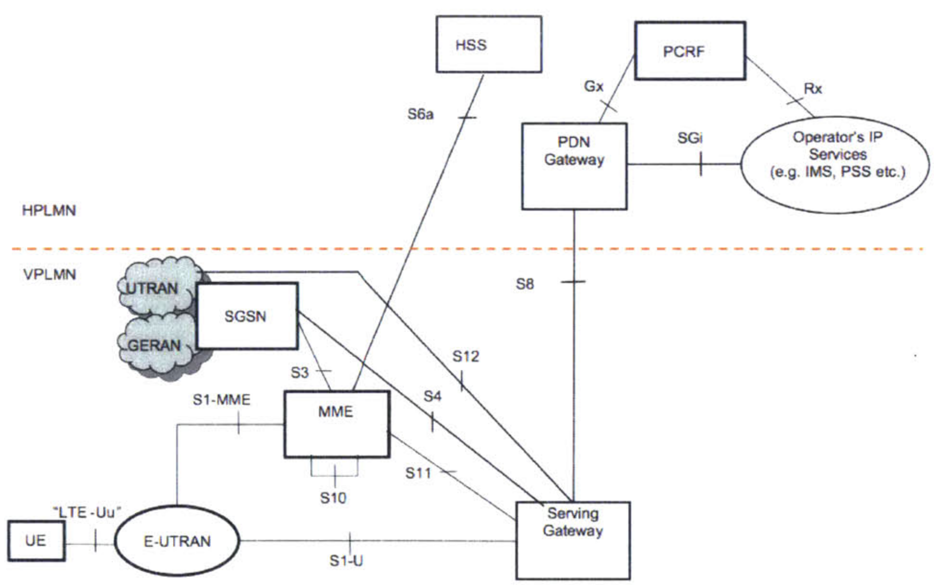

Figure 18: Home Routed Roaming Architecture[29]

[28] 3GPP TS 23.401, "General Packet Radio Service (GPRS) Enhancements for Evolved Universal Terrestrial Radio Access Network (E-UTRAN) Access"
[29] 3GPP TS 23.401, "General Packet Radio Service (GPRS) Enhancements for Evolved Universal Terrestrial Radio Access Network (E-UTRAN) Access." Figure 4.2.2-2

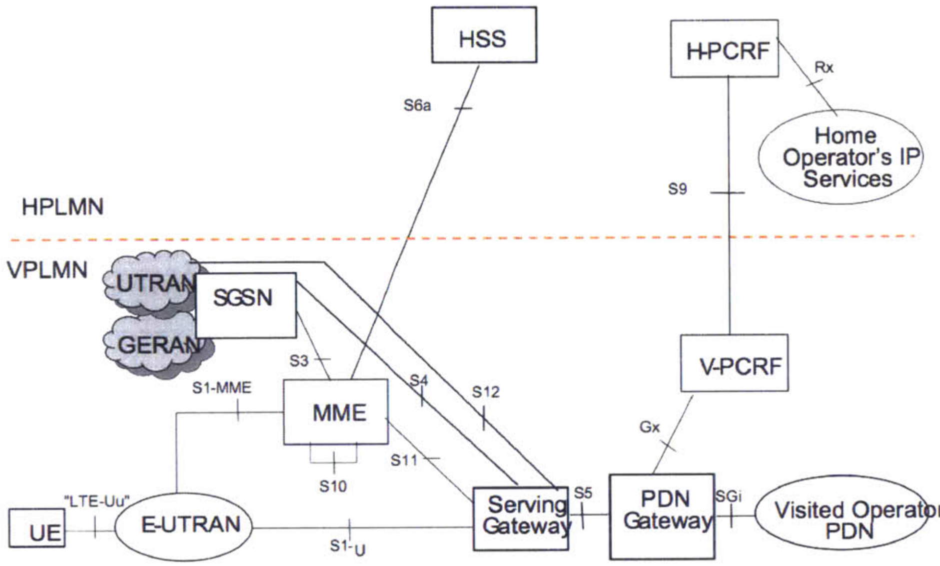

Figure 19: Local Breakout Roaming Architecture[30]

The nuances of these roaming architectures will be pertinent later in the final part of this thesis when discussing the potential solution for MVNOs.

2.2.4 LTE Interworking Architecture

The 3GPP LTE architecture specifies an interworking architecture (**Figure 20**), which enables communication between the LTE network and other non-LTE 3GPP networks (i.e., UMTS) or non-3GPP networks (i.e., WiFi). In this architecture, a new network element – the enhanced Packet Data Gateway (ePDG), is introduced. This function integrates untrusted non-3GPP networks into the LTE P-GW, allowing UEs connecting to these networks to tunnel their traffic, typically over IPSec, and access operator services. Since the session remains anchored at the P-GW, this supports mobility between non-3GPP untrusted networks and 3GPP networks. This scenario typically occurs when a mobile subscriber connects to a 3rd party WiFi network.

In addition, this architecture defines a trusted non-3GPP IP access network, in which direct integration with the P-GW is possible. This scenario typically occurs when a MNO offers WiFi access in conjunction with their LTE network.

[30] 3GPP TS 23.401, "General Packet Radio Service (GPRS) Enhancements for Evolved Universal Terrestrial Radio Access Network (E-UTRAN) Access." Figure 4.2.2-3

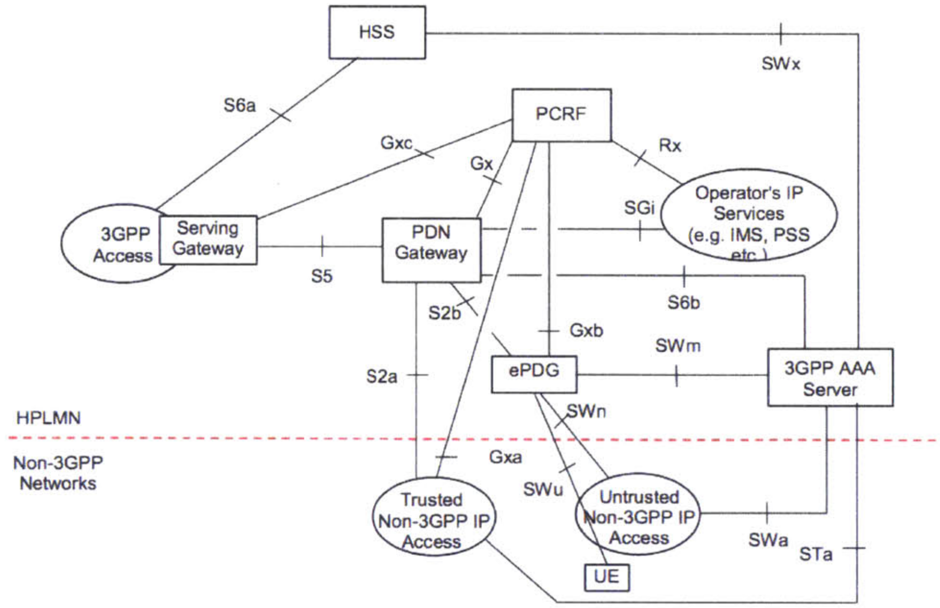

Figure 20: LTE Interworking Architecture[31]

The nuances of this interworking architecture will be pertinent in the final part of this thesis when discussing the potential solution for MVNOs.

3 History of MVNOs

Now that the basics of the mobile industry and mobile network architecture have been discussed, a closer look at how MVNOs have historically been structured, both in terms of their business models and technology architectures, will provide the remaining information required to explore potential solutions paths forward for MVNOs. This section will provide sufficient level of detail to explain the MVNOs, their business models, and how the functional demarcations between the MNO and the MVNO architecture.

Although the majority of this thesis will address North America, where the MVNO model has been only mildly successful, the author does recognize that the proposed solution extends beyond North America. In fact, Western Europe, which exhibits many of the same developed market characteristics as North America, accounts for the majority of MVNO launches (**Figure 21**).

[31] 3GPP TS 23.402, "Architecture Enhancements for non-3GPP Accesses." Figure 4.2.2-1

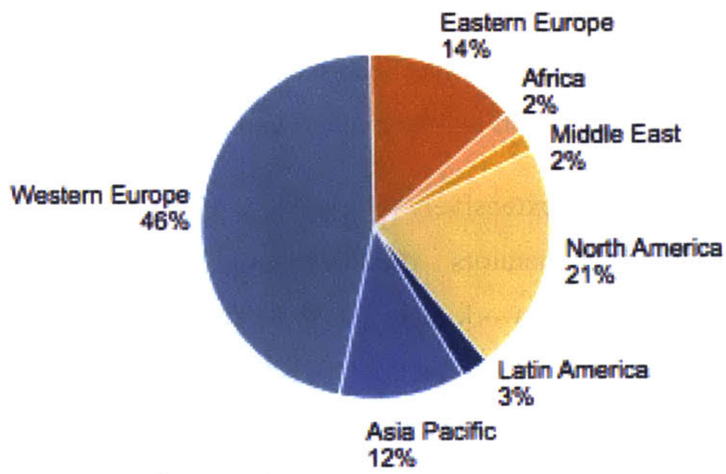

Figure 21: Global MVNO Launches, By Region[32]

3.1 MVNO Definition and Business Models

First and foremost, MVNO is a business model, not a technology model. The MVNO business is built around a wholesale relationship with one or more MNOs in which the MVNO purchases voice and/or data capacity and delivers the service. The basis of these relationships typically forms around mutually beneficial opportunities for the MNO to capture revenue from markets that they have chosen not to entre for a variety of reasons. Such reasons may include devalution of the MNO brand, inability to target specific demographics, Christian Borrman, on his MVNO blog, compares the MVNO/MNO relationship to a typical production environment[33]:

- The MNO is the manufacturer, and produces a product (the mobile network)
- The MVNO is the retailer, and sells the product through its channel on behalf of the manufacturer

Borrman further elaborates that, in immature markets, the manufacturer typically manages both production and supply chain. However, once markets mature and critical mass is achieved, a portion of supply chain management shifts to retailers and the manufacturer maximizes Return on Investment (ROI) by shifting to a wholesale model. The mobile industry, although having

[32] "The Future of MVNOs." *Informa Telecom and Media.* May 2012. Web.
[33] Borman, Christian. "Mobile Virtual Network Operator - MVNO: MVNO Explained." *http://www.mobile-virtual-network.com/.* N.p., 15 Oct. 2005. Web.

reached critical mass and almost 100% saturation in developed markets[34], has yet to shift to the typical wholesale supply chain model that has been seen in most other industries. It is important to keep this in mind, as this recognition is fundamental to the premise of this thesis.

Although the term MVNO is used extensively to describe a wide range of business models, there are actually three types of virtual operators – the MVNO, the Mobile Virtual Network Enabler (MVNE), and the Mobile Virtual Network Aggregator (MVNA). The major difference between these is whether the entity operating the infrastructure is the same as the entity offering the service. **Figure 22** illustrates these different virtual operators, and **Table 3** provides definitions[35]. This thesis will treat the concepts of MVNO, MVNE, and MVNA largely interchangeably, as the operating entity of the MVNO is not the focus of this thesis, but rather the potential business and technology realization. The author does note, however, that opportunity to differentiate and disrupt in the operating function is also possible.

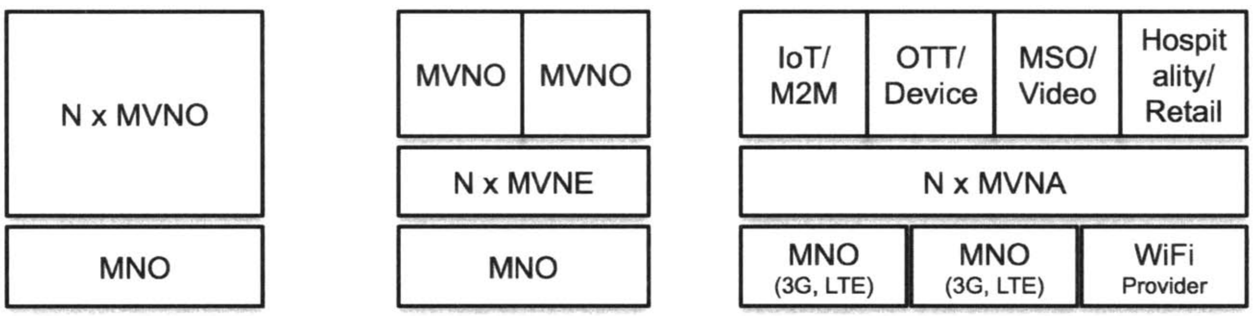

Figure 22: MVNO, MVNE, and MVNA Illustrated

Virtual Operator Type	Predominant Network Type(s)
MVNO	Mobile Virtual Network Operator (MVNO) is a mobile phone or device operator that does not own it's own radio spectrum or infrastructure, instead leveraging that of a Mobile Network Operator (MNO). The MVNO develops the consumer services (voice, video, social, etc.).

[34] "Market Saturation Slows Mobile Phone Growth." Worldwatch Institute. N.p., Oct. 2013. Web.
[35] Ghadialy, Zahid. "The 3G4G Blog." *MNO, MVNO, MVNA, MVNE.* 1 Apr. 2014. Web.

MVNE	A mobile virtual network enabler (MVNE) is the technical outsourcing partner, delivering all the components an MVNO requires in a single package, and finds best route to customer. The MVNE does NOT develop consumer services, but instead provides the foundational (or platform) functions required for the MVNO to offer services.
MVNA	A mobile virtual network aggregator (MVNA) is both a vertical (market segment) and horizontal (across multiple networks) representation of a MVNE that delivers unique and customized capabilities to the particular market.

Table 3: Virtual Operator Types and Definitions

The MVNO business model may range from simple (i.e., rebranding and reseller agreements) through complex (i.e., "Full" MVNO with more control over the offer, and associated heavier technology investment). At the simplest, the MVNO is responsible for marketing and sales, and at the most complex, the MVNO is responsible for many of the network infrastructure functions required to deliver mobile services. The spectrum in between the simplest and most complex includes responsibility for customer care, billing and operations, and applications and services. As the business model gets more complex for the MVNO, and increased value-add is provided, The range of potential business models translate directly into customer stickiness, including loyalty, upsell service opportunities, and brand recognition and awareness. A high level functional split, depending on the MVNO business model variant, is depicted in **Figure 23**, with further details and relation to the 3GPP standards provided in the MVNO Architecture and Demarcations section (Section **Error! Reference source not found.**).

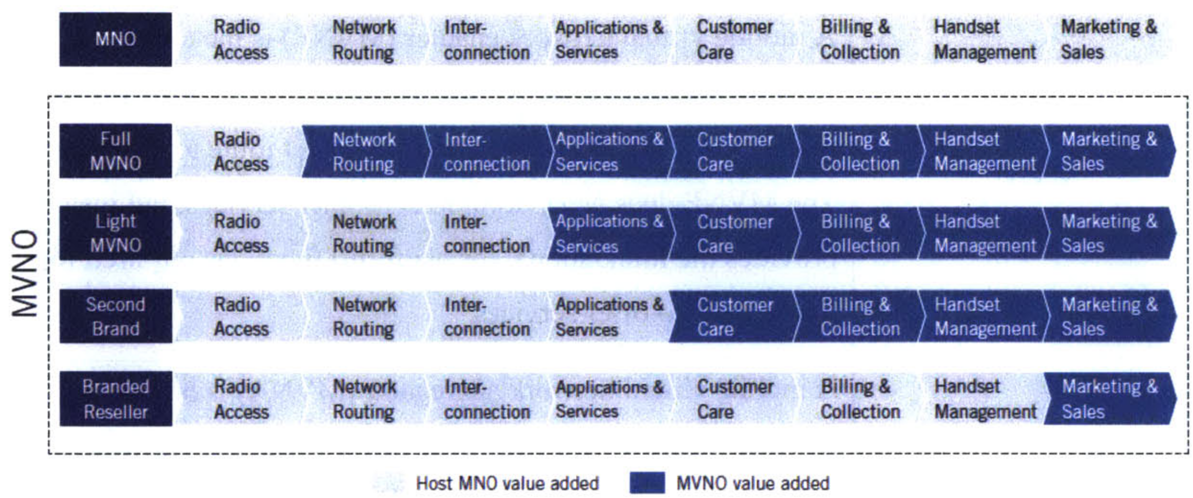

Figure 23: MVNO Business Model Variants[36]

Numerous MVNOs have attempted to compete effectively in the U.S. market over the last fifteen years. **Figure 24** illustrates the market entrants and exits into the U.S. MVNO market from 2000-2014, with entrants listed above the hype cycle line, and exits listed below the line. The data was compiled from numerous sources. The figure shows that the vast majority of MVNOs who entered the market in the early 2000s exited in less than ten years. The figure was intentionally illustrated using Gartner's Hype Cycle research methodology for industry maturity[37].

Applying the Gartner Hype Cycle terminology:

- The early 2000s marked the peak period, where inflated expectations drove a large number of brands to enter the MVNO market, and the number of failures dwarfed the number of success stories. This thesis will refer to this time period, and the MVNOs that launched during this time, as MVNO 1.0.
- Mid-2006 represents the Trough of Disillusionment, when the number of market exits questioned the validity of the MVNO business model in the U.S. MVNO data architectures will be discussed in Section 3.2.
- Early 2012 represents the beginning of a Slope of Enlightenment, where new MVNOs enter the market with unique business and technology models. This thesis will reference

[36] Ghadialy, Zahid. "The 3G4G Blog." *MNO, MVNO, MVNA, MVNE*. 1 Apr. 2014. Web.
[37] "Gartner Hype Cycle." *Hype Cycle Research Methodology*. Web.

this time period, and the MVNOs that launched during this time, as MVNO 2.0. MVNO 2.0 business and technology innovation will be discussed in Section 3.4.

- Going forward, the MVNO industry opportunistically represents a Slope of Productivity, in which mainstream adoption and successive innovations in both business and technology are likely to occur. This thesis will reference the future as MVNO 3.0, and will present requirements and an analysis of the opportunity in Section 5 and a potential solution in Section 6.

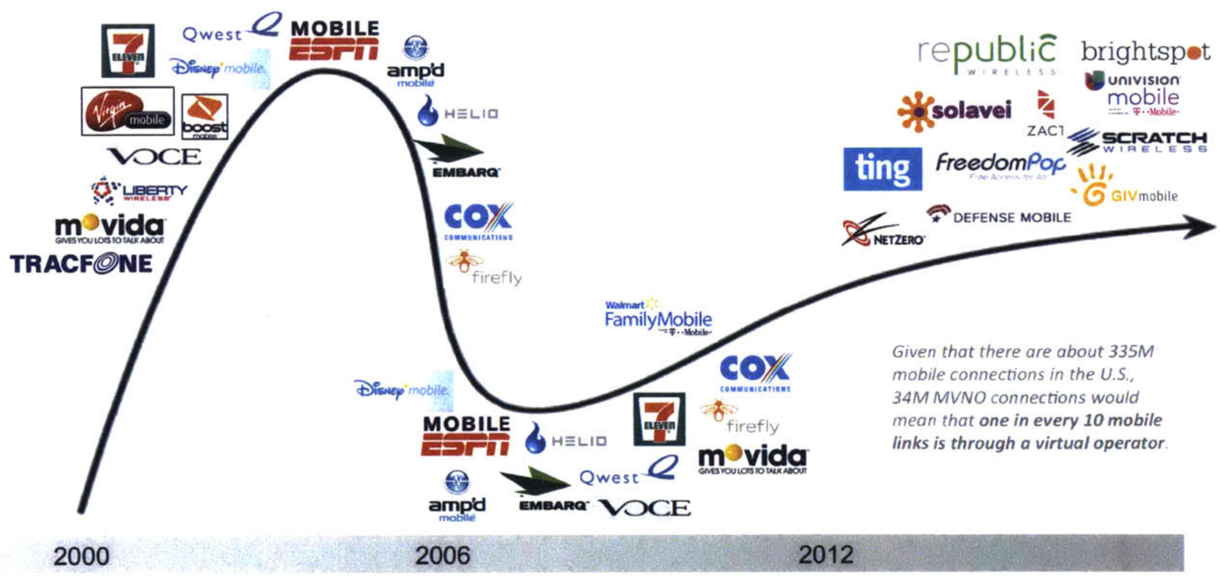

Figure 24: U.S. MVNO Market Entrants and Exits

One notable MVNO in **Figure 24** is TracFone Wireless, which has built a MVNO business aligned around a different set of operational and economic models than the other MVNOs identified. In particular, TracFone Wireless has reseller agreements with multiple MNOs (AT&T, Verizon Wireless, T-Mobile, Sprint) in the U.S. and operates multiple brands (TracFone, Net10, Straight Talk Wireless) simultaneously. In the TracFone Wireless model, the consumer's selection of a particular handset and the market in which the consumer resides determines which of the service networks is most economical to TracFone, and, therefore, which network the user is subscribed to[38].

[38] Bournique, Dennis. "How to Tell Which Network (AT&T, T-Mobile, Sprint or Verizon) a TracFone, NET10 or Straight Talk Phone Uses." *Prepaid Phone News*. N.p., 9 Aug. 2013. Web.

3.2 MVNO Keys to Success

As the growth in the MVNO opportunity becomes apparent, the natural influx of consultants to develop frameworks for success is inevitable. Informa Telecom and Media identifies nine stipulations for a successful MVNO[39], while McKinsey and Company identify five success factors[40]. Once these keys to success are understood, the author will then analyze whether the past (MVNO 1.0) or existing (MVNO 2.0) frameworks between the MNO and MVNO are sufficient to enable MVNO success.

Based on both the Informa and McKinsey studies, three tenets have been identified within the scope of this thesis for further exploration. In assessing the identified keys to success, the author will also present the implications on the MVNO 1.0 and 2.0 business models.

3.2.1 Lean Cost Base

MVNO costs are largely driven by their negotiated wholesale rates in the MNO and their customer acquisition costs. In contrast to MNOs, where expenses are a combination of Capital Expenditure (CAPEX) investments and infrastructure Operational Expenditures (OPEX), up to 85% of the MVNO cost structure is variable, resulting from wholesale capacity negotiations and customer acquisitions[41]. The dependence on wholesale rates from the MNOs typically leads MVNOs to complement the MNOs rather than compete directly.

3.2.2 Flexibility in Commercial and Technical Models

The ability for the MVNO to define business relationships and technology architectures that are agile enough to respond to changing market conditions, economic drivers, or industry trends, is a key ingredient for sustained success. In order to ensure such flexibility, MVNOs need to be in a position to modify any aspect of their business model, including retail distribution model, service offerings and pricing, provisioning and activation, and policy and identity rules. This flexibility

39 "The Multifaceted World of MVNOs." *Informa Telecom and Media*, 2013. Web.
40 Lehikoinen, J, Point, P, and Sent, Y. Virtually Mobile: What Drives MVNO Success. N.p.: *McKinsey and Company*. Web.
41 Lehikoinen, J, Point, P, and Sent, Y. Virtually Mobile: What Drives MVNO Success. N.p.: *McKinsey and Company*. Web.

tends to greatest in the Full MVNO model (As discussed in Section 3.3), when the MVNO has control of network infrastructure and subscriber data sessions.

3.2.3 Differentiation

The level of differentiation that the MVNO can offer, both against other MVNOs and also against the MNOs, is a key aspect for both short term (Customer acquisition) and long-term (Customer retention) success. MVNO capabilities to offer competitive differentiation directly relate to the business model (and technology architecture) they select. In the Reseller model, the extent of differentiation is branding and bundling. As the MVNO moves further downstream into the infrastructure, there is opportunity to differentiate with pricing models and unique service offerings tied to subscriber policy and identity. Finally, in the Full MVNO model, the MVNO has the opportunity to differentiate with session / service control functions and with services tied to visibility into the data traffic.

3.3 MVNO 1.0 Architecture and Demarcations

Architecturally, a MVNO typically resembles one of the 3GPP-defined roaming architectures. Extending the previous **Figure 23**, which defined the MVNO potential business models, **Figure 25** defines the technology and architecture implications of that selection:

- In the Reseller model, the MVNO only provides only retail distribution. In these cases, the MVNO leverages their brand and distribution channels as a differentiator and provides devices to mobile subscribers. In the Reseller model, the MVNO adopts a discounted rate for the MNO-defined services, pricing plans, and subscriber policies. The MVNO is also dependent on the MNO's activation and provisioning procedures. The MNO, on the other hand, has ownership of the entire infrastructure.

- In the Light MVNO model, the MVNO owns portions of the network infrastructure, up to and including the policy and identity infrastructure. Depending on which infrastructure the MVNO owns, the MVNO may be in control of service definition, pricing, provisioning and activation, and subscriber policy. The Light MVNO model, however, does not provide the MVNO with visibility into the data traffic. This model resembles architecturally the Local Breakout Roaming Architecture depicted in **Figure 19**.

- In the Full MVNO model, the MVNO owns portions of the network infrastructure, up to and including at least some portion of the LTE EPC. In most instances, the demarcation point between the Full MVNO and the MNO is the P-GW. Ownership of the P-GW allows the MVNO to not just determine the rules for the offering (services, pricing, and policies), but also to capture the subscriber data traffic, as well. This model resembles architecturally the Home Routed Roaming Architecture depicted in **Figure 18**.

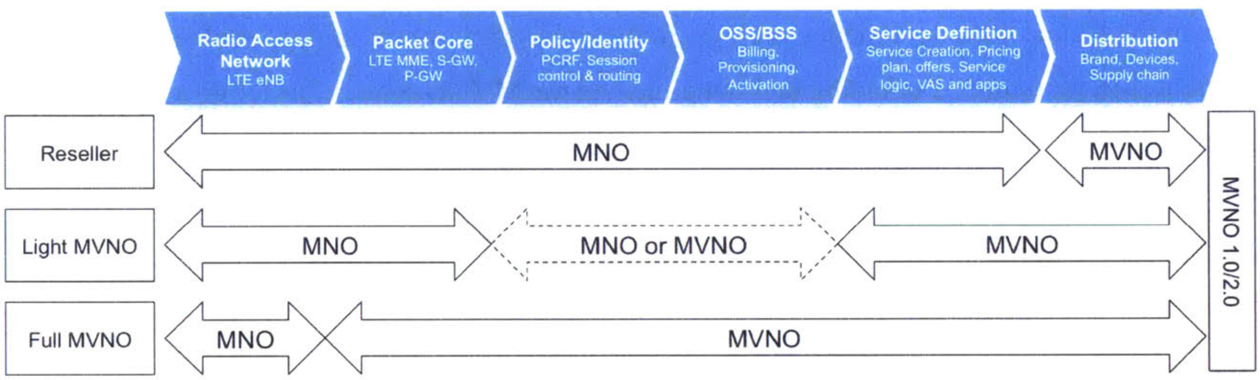

Figure 25: MVNO Technology Models

For the MNO, supporting multiple MVNO simultaneously presents integration challenges that might limit their ability to deliver economical wholesale solutions. Therefore, in any MVNO scenario, the MNO is incentivized to limit their integration costs to support a MVNO. As such, only a small handful of MVNOs adopt the Full MVNO technology model, instead opting to reuse existing technologies within the MNO that have been tested, certified, deployed, and proven technically and commercially. Returning to an understanding of the MVNO keys to success (Section 3.2), this creates a tension between the technology architecture that is in the best interest of the MNO and the technology architecture that is in the best interest of the MVNO.

Although there is a technology architecture for RAN sharing, in which multiple MNO or MVNO share the LTE eNodeB, those architectures are out of scope of this thesis. RAN sharing architectures are not built with the wholesale business model in mind. The thesis will instead focus on scenarios in which the MVNO purchases wholesale airtime from the MNO.

3.4 MVNO 2.0: Business and Technology Innovation

To summarize, the MVNO 1.0 model was constructed of strategic relationships with a single MNO in which 100% of the MVNO traffic was carried over the cellular infrastructure. While initially voice-centric, increasing demand for mobile data led to the inclusion of data traffic in the MVNO bundles. In order to avoid competition with the MNOs themselves, MVNOs settled for niche markets, accounting for lower Average Revenue Per User (ARPU) and margins. These niche markets also demanded significant changes in the pricing model, and MNOs leveraged MVNOs to compete in these market segments to avoid brand dilution. The technology architecture of these MVNOs was largely based on either the 3GPP Home Routed or Local Breakout Roaming architectures, discussed in Section 2.2.3.

In many ways, MVNO 2.0 expands on the market segmentation, pricing, and distribution innovations that marked the demise of MVNO 1.0. Figure 26 illustrates many of the virtual operators innovating in these ways. MVNO 2.0 operators are not only innovating through business models, however, but also introducing technology innovations that alter the competitive landscape. Republic Wireless, for instance, has developed technology that allows a mobile phone to seamlessly handoff a voice call from a WiFi network to a circuit switched mobile telephony network.

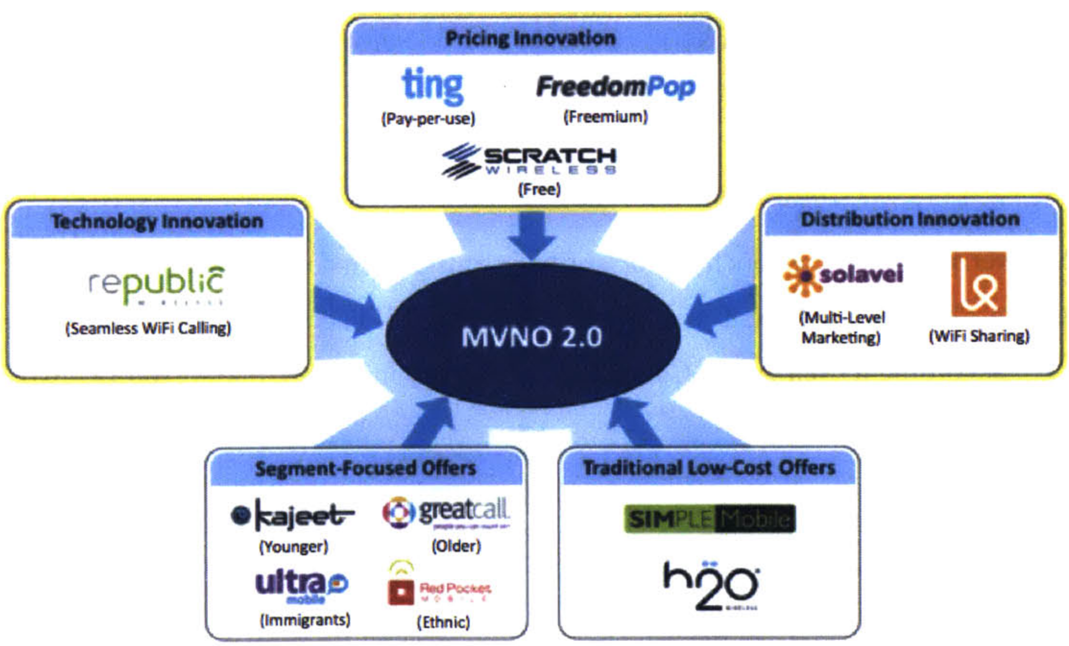

Figure 26: MVNO 2.0 Examples in the U.S.

MVNO 2.0 technology innovation is largely led by the emergence of unlicensed technologies, such as WiFi, as a primary access network for the delivery of mobile services. In a WiFi-first MVNO, mobile devices connect primarily to available WiFi networks, both public and private, for both voice and data. In this regard, the cellular network is used as a coverage network between WiFi hotspots, and the macro cellular network becomes the network of last resort. As a result, MNOs began to lose much of their pricing power and competitive advantage against the MVNOs, resulting not only in pricing wars against the MVNOs, but also between MNOs[42]. **Table 4** provides a comparison of MVNO 1.0 and MVNO 2.0.

MVNO 1.0	MVNO 2.0
100% Cellular Single MNO Single Homed	WiFi-First (~30% Cellular) Single MNO Single Homed
Voice-Centric Subscription Billing Low ARPU/Margin	Voice/Data-Centric Consumption Billing Low ARPU/Margin
Lower End Devices Narrow Focus (Market) Pricing Innovation	Higher-End Devices (Limited) Narrow Focus (Market) Technology Innovation

Table 4: MVNO 1.0 vs. MVNO 2.0

For the MVNO, offloading as much as 70% of their traffic from cellular to WiFi represents significant margin improvement, as the cost of wholesale WiFi access is up to 10X cheaper than that of LTE, according to Senza Fila Consulting[43]. In many instances, public WiFi networks are offered for free.

[42] "How Low Can It Go? Wireless Price War to Escalate in 2015." *Mind Of The Geek*. N.p., 17 Dec. 2014. Web.
[43] Paolini, Monica. "The Economics of Small Cells and Wi-Fi Offload." (n.d.): n. pag. Senza Fila Consulting, 2012. Web.

3.4.1 MVNO 2.0 Technical Innovations

Technologically, WiFi-first MVNOs rely on a combination of the 3GPP Home Routed Roaming architecture and the 3GPP interworking architecture (Section 2.2.4), predominantly leveraging untrusted WiFi (Untrusted non-3GPP IP Access) to connect to the Internet and their own IP-based voice services. Realization of MVNO 2.0 required the integration of multiple different technology innovations, across multiple standards organizations. These technology innovations are summarized in **Table 5**.

Innovation	Standard	Impact
Hotspot 2.0	WiFi Alliance	Defines an architecture that allows mobile devices to discover, select, and authenticate to WiFi networks securely, without subscriber intervention
Extensible Authentication Protocol (EAP)	IETF (RFC 3748)	Specifies a protocol that allows IP networks (such as WiFi) to carry secure authentication messages between the mobile device and the authentication system (such as the mobile HSS)
Hotspot Discovery and Selection	IEEE (802.11u)	Defines an interface between the WiFi network and MNO network, allowing WiFi providers to advertise the availability of the network to MNO subscribers, and allowing MNO subscribers to discover, select, and authenticate to roaming partner WiFi networks

Table 5: MVNO 2.0 Innovations

4 The Future of MVNOs

According to Informa Telecom and Media, the global MVNO market is expected to grow at approximately twice the pace of the traditional mobile market. **Figure 27** highlights that the MVNO market will grow from 1.9% of the overall mobile industry to 3.1% between 2012 and 2018, representing MVNO operator CAGR of 17% compared to only 7.8% for the mobile operators[44]. This overall growth is due to a number of factors, including lower barriers to entry for MVNOs driven by cloud technologies, the increasing number of enablement (MVNE, MVNA) platforms, and new online support functions for distribution and customer care.

[44] "The Multifaceted World of MVNOs." *Informa Telecom and Media*, 2013. Web.

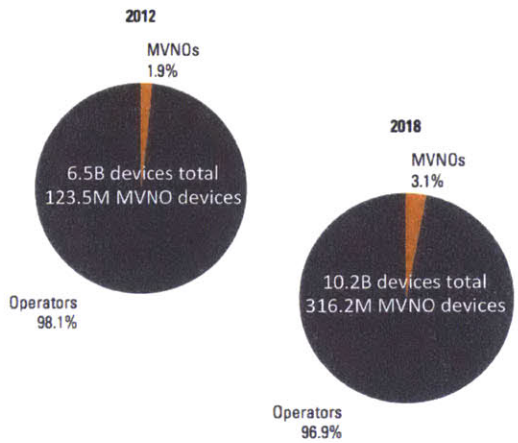

Figure 27: MVNO vs. MNO Subscription Growth Rates

4.1 Rethinking the MVNO Assumptions

MVNO 2.0 has led a number of industry experts to question the validity of many of the earliest MVNO business and technology model assumptions to determine the future MVNO opportunity. In general, the MVNO model was built on three core assumptions[45]:

1. High-segmented markets for reselling MNO services is attractive
2. Vertical integration of Access and Services is desirable to subscribers
3. User-Network Relationships are long-lived and persistent

Each of these assumptions will be revisited to disprove the ongoing validity of these assumptions.

4.1.1 Market Segmentation for MVNOs

As discussed earlier, the mobile industry, especially in developed markets, has become highly competitive. The increasing cost of offering network services coupled with the declining ARPU has also led to industry consolidation[46] and concentration. For instance, in the United States, the four Tier 1 MNOs (Verizon, AT&T, T-Mobile, Sprint) account for over 95% of the total

[45] M.P.de Leon, A.Adhikari "A User Centric Always Best Connected Service Business Model for MVNO", ICIN2010 proceedings

[46] GSMA Intelligence. "Market Consolidation Aims to Address Rising Investment Costs for European Operators." *GSMA Intelligence*. N.p., n.d. Web.

subscribers[47]. As a result, smaller MNOs prefer to take advantage of MVNOs to reduce their own costs in targeting specific market segments. These MNOs can, therefore, be selective about which MVNOs they allow to use their networks. An analysis of the current U.S. MVNOs and their MNO affiliations found that 62% of MVNOs are affiliated with the Sprint and T-Mobile networks, while only 38% of MVNOs are affiliated with the Verizon and AT&T networks. These factors combined lead to two logical conclusions:

1. Hyper-segmented, demographics-based markets are less attractive than the past due to low margin and smaller total addressable market.
2. Proportional lack of dominant MNO participation limits the coverage and capacity that MVNOs can offer to the equivalent of lesser MNOs

In addition, the industry consolidation has shifted greater power to the MNOs in establishing favorable wholesale contracts. In a recent petition to the FCC by T-Mobile USA[48], the FCC's former Chief Economist, Dr. Joseph Farrell, notes that "pockets of monopoly give some carriers a degree of market power in wholesale data roaming markets" and that a MNO "with market power in a region may charge a rate substantially above the price that would prevail in a more competitive environment." In other words, MNOs are able to set network lease prices unnaturally high to increase barriers to entry. According to the filing, MVNOs on T-Mobile's network are paying an average of $0.03 per MB, or $30 per GB. These agreements are static, established well in advance, based on expected mobile data growth. As consumption of mobile data increases, MVNOs are under considerable margin pressure due to these unfavorable contracts.

In MVNO 3.0, then, it is imperative for MVNOs to consider models that provide better leverage against the MNOs, including the potential to target the core mobile subscriber base and introduce competition and pricing pressure into the wholesale roaming agreement negotiations.

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[47] Goldstein, Phil. "FCC Report Fails to Find U.S. Wireless Industry Competitive, Highlights Consolidation." *Fierce Wireless*. N.p., 19 Dec. 2014. Web. 05 Jan. 2015.

[48] "Filing by T-Mobile USA, Inc. in 05-265 on 2014-05-27." *FCC Electronic Comment Filing System*. N.p., 27 May 2014. Web.

4.1.2 Network and Services Value Chain

Also discussed earlier was the trend towards consuming 3rd party service delivered "Over-the-Top." The original assumption that subscribers would leverage services offered by their mobile provider has been under pressure since the launch of the modern day smartphone. As Internet services and "apps" became widely available, consumers have been consuming services from various other entities, including cloud providers, social networking providers, and social sharing communities.

As an example, in a November 2012 research note[49], GSMA Intelligence highlights the pressure on Short Message Service (SMS) due to messaging services that are delivered in one of three ways:

- Directly integrated into the Operating System, such as Apple iMessage
- Independently, such as WhatsApp
- Integrated with social networks, such as Facebook Messenger

The launch of these services has directly impacted SMS revenue (**Figure 28**) by providing alternative messaging options to consumers. These services are not tied to the cellular infrastructure like SMS, either, but instead offered over any IP-based network, including WiFi. Further, the low cost (or free) nature of these messaging services has impacted the rates that mobile providers can charge for SMS, directly resulting in declining ARPU (**Figure 29**). In a 2013 report on mobile messaging, Strategy Analytics noted that MNOs could lose more than $3B in mobile messaging revenues over the next five years[50], reversing the upward trend of one of the most profitable mobile data services.

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[49] GSMA Intelligence. "SMS and the Challenge of Over-the-top Messaging." *Wireless Intelligence* (n.d.): n. pag. Print.

[50] Lewis, David. "In an Over-the-Top World, Mobile Operators Must Evolve to Survive." *Wired Innovation Insights*. N.p., 30 Aug. 2013. Web. 05 Jan. 2015.

Figure 28: SMS Revenue Decline

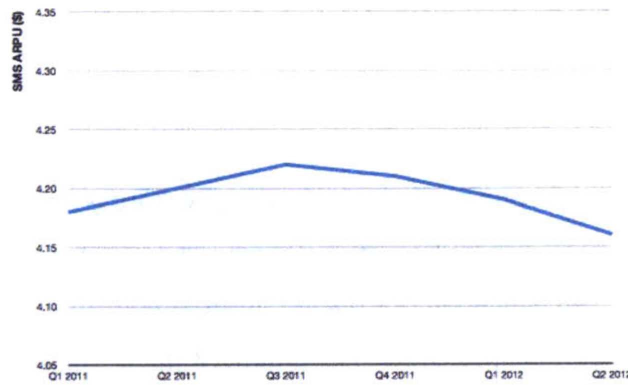

Figure 29: SMS ARPU Decline

GSMA also correlates the downward trend with increasing smartphone penetration, noting that OTT messaging services are dependent on smartphones. As smartphone penetration increases, the number of SMS decreases (**Figure 30**).

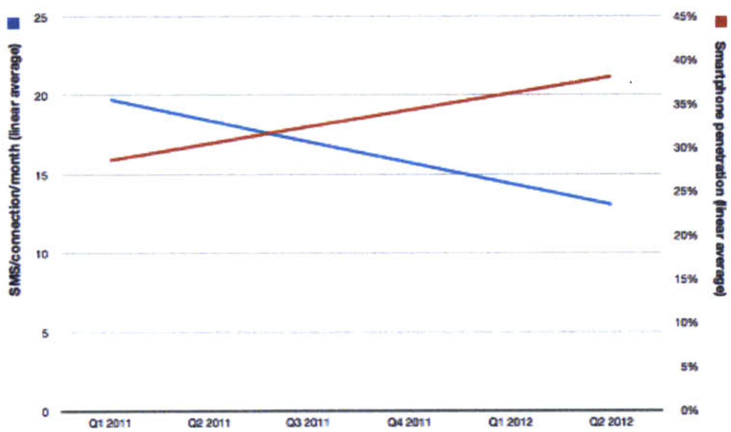

Figure 30: SMS Volume vs. Smartphone Penetration

The trend towards "Over-the-Top" services extends far beyond messaging to include file sharing, contact list synchronization, video (streaming, sharing, calling), social networking, and gaming. As a result, both MNOs, and to a larger degree, MVNOs are forced to leverage cost leadership as a mechanism for competition in lieu of service differentiation. The indication, therefore, is that MVNOs cannot rely on vertical integration of services with the MNO infrastructure as a mechanism to deliver value-added services, and, within a MVNO 3.0 environment, deliver services that are independent of the access networks.

4.1.3 Sustained User-Network Relationships

Both MNO and MVNO business models have historically been built on a model of long-lived relationships. As such, many of the important metrics in the mobile industry – subscriber acquisition cost (dubbed "Cost Per Gross Addition"), subscriber growth, subscriber lifetime value, subscriber retention rate ("Churn"), subscriber retention costs ("Cash Cost Per User"), etc. – are dependent on the assumption that subscribers and network providers maintain these long-lived relationships. The length of these relationships has helped accelerate smartphone adoption, since mobile providers can subsidize the cost of the smartphone in exchange for high margin service plan commitments.

These subsidies impact mobile profitability initially, as highlighted in **Figure 31**, which illustrates AT&T and Verizon profit quarterly profit margins. Specifically, the quarters subsequent to new iPhone releases (Q4 2011, Q4 2012, etc.) identifies significant declines in profit margin due to up front subsidy expenses.

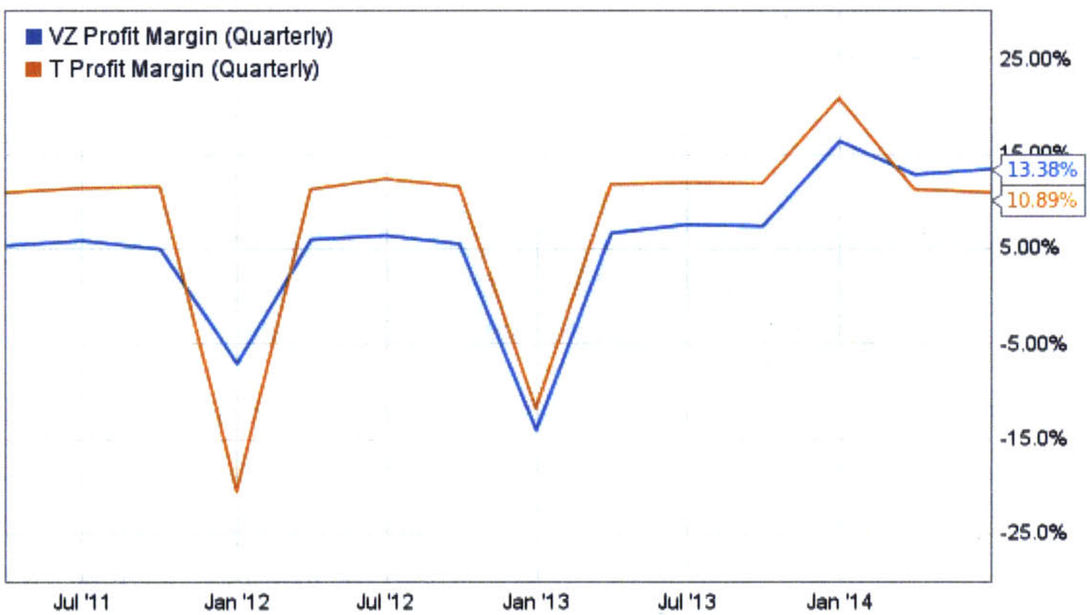

Figure 31; AT&T / VZ Subsidies for iPhones

Figure 32 also illustrates one example of how the subsidy model works.

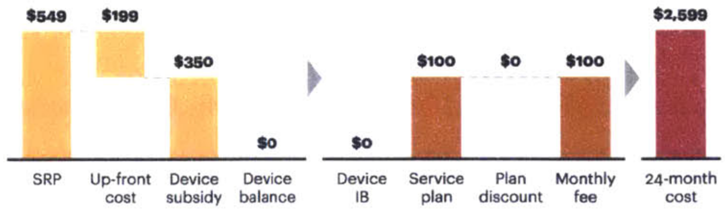

Figure 32: Device Subsidy Exchange For Service Plan Commitment[51]

The impact of device subsidies has evidenced itself in the limited number of high-end smartphones available by MVNOs. Going forward, the convergence of cellular network towards LTE, and the pending launch of Voice over LTE (VoLTE), will allow MVNOs to transition towards a Bring Your Own Device (BYOD) policy and leverage 3rd parties who can provide device financing.

In addition to the multi-year relationship assumed by the mobile industry, there is also an implicit assumption that a mobile device will connect to the same mobile network for long periods of time. In other words, the mobile industry relies on a model that includes a primary access network, and multiple secondary access networks, leveraged in series. MVNO 1.0 assumed the primary access network was cellular, and secondary access networks were WiFi. In many instance, MVNO 2.0 assumed the primary access network was WiFi, and the secondary access network was cellular. In either scenario, the mobile device was unable to leverage multiple cellular networks or to leverage primary and secondary networks in parallel.

4.2 The Potential Emergence of MVNO 3.0

Section 4.1 (Page 48) provided perspectives on some of the original assumptions that MVNOs were based upon, and defined some requirements for future MVNO success, including:

- Targeting the core mobile subscriber base instead of only niche markets
- Introducing pricing competition in wholesale roaming negotiations
- Delivering value-added services independent of access networks
- Transitioning towards BYOD with 3rd party device financing options

[51] "Wrestling the Subsidy Challenge." *Communications Media & Technology*. A.T Kearney, n.d. Web.

- Multi-Homing devices to take advantage of multiple available MNOs simultaneously

This thesis defines these future MVNOS as MVNO 3.0, in which a fundamentally new business model, facilitated by advances in technology that change the operational model for MVNOs. **Table 6** provides a comparison of MVNO 2.0, based on the previous assumptions, with MVNO 3.0, in which those assumptions are removed[52].

MVNO 2.0	MVNO 3.0
WiFi-First (~30% Cellular) Single MNO Single Homed	WiFi-First (<20% Cellular) Multi MNO Multi Homed
Voice/Data-Centric Consumption Billing Low ARPU/Margin	Data-Centric (Voice as App) Alternative Billing (ex. Ad Funded) High(er) ARPU/Margin
Higher-End Devices (Limited) Narrow Focus (Market) Technology Innovation	MVNO or Consumer BYOD Broad Focus (Core Market Segment) Experience Innovation

Table 6: MVNO 2.0 vs. MVNO 3.0

MVNO 3.0 also incorporates Endeavour Partners' 5C model discussed previously to provide a uniform and continuous coverage and capacity model. By homing to multiple MNOs simultaneously, MVNO 3.0 architectures are able to smooth out the peaks and troughs across different MNO access networks. **Figure 33** illustrates this capability, highlighting four example MNOs and their associated coverage models over a given geographic area. In the figure, a baseline subscriber experience, regardless of network provider, is predetermined. An average experience and experience range are calculated based on the aggregated peaks and troughs in

[52] Gabriel, Caroline. "Over-the-top and Wi-Fi First Will Change the Definition of the MVNO." *4G Trends*. Maravedis-Rethink, 31 July 2014. Web.

network coverage and capacity. In general, it is not in the economic interest of an individual MNO to provide an experience above the baseline, as additional investments for variable demand is expensive to both build and operate. The dominant MNOs in any given market are responsible for setting, and delivering, the baseline subscriber experience, while the remaining MNOs provide an experience below the baseline. With all MNOs participating in MVNO 3.0, however, the MVNO is able to provide a higher average subscriber experience (above the baseline) with a narrower range. This constitutes a more uniform experience to the consumer and more predictable network behavior for application and service providers.

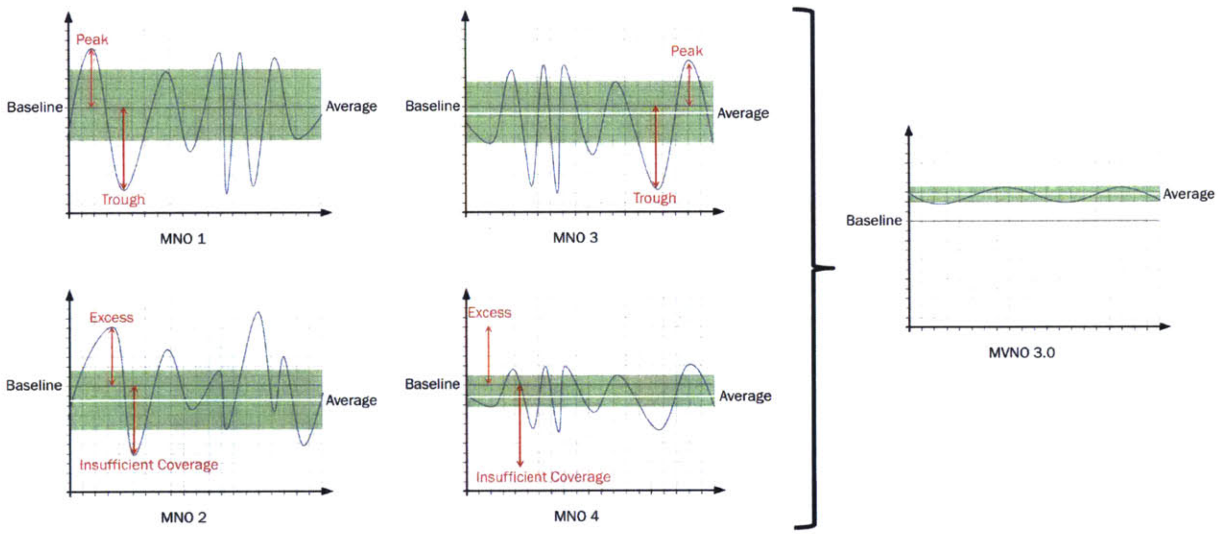

Figure 33: Uniformity of MVNO 3.0 Coverage and Capacity

An important consideration in this model is the need for all four MNOs in **Figure 33** to participate in order to deliver the highest average subscriber experience. In any particular market, however, it is not in the interest of the dominant MNO to participate in the MVNO model, and instead continues to leverage subscriber "flight towards quality," in which subscribers eventually all migrate towards that network. In the United States, Verizon Wireless and AT&T are examples of this.

Even without the dominant MNOs participating, however, MVNOs may still provide an average subscriber experience above the baseline by aggregating network capacity and coverage from the remaining network operators. This aggregation function establishes a new baseline, forcing dominant MNOs to either increase their own network investment or join the MVNO. In other words, investments by non-dominant MNOs to build, improve, support, and sustain MVNO 3.0 operators may be a viable model, in lieu of regulatory challenges of mergers and acquisitions to defend market share against the dominant MNOs.

According to Maravedis Research, there is tremendous opportunity for new organizations, such as cable providers (or "Multiple-System Operators" [MSOs]), "Over-the-Top" brands, device manufacturers, and retailers to offer their on MVNO, with the most significant opportunity belonging to the "Over-the-Top" brands (**Figure 34**). By 2018, these "Over-the-Tops" could represent over 20% of the MVNO market. These organizations would benefit greatly by adopting the MVNO 3.0 model to improve subscriber experience and mitigate variable costs.

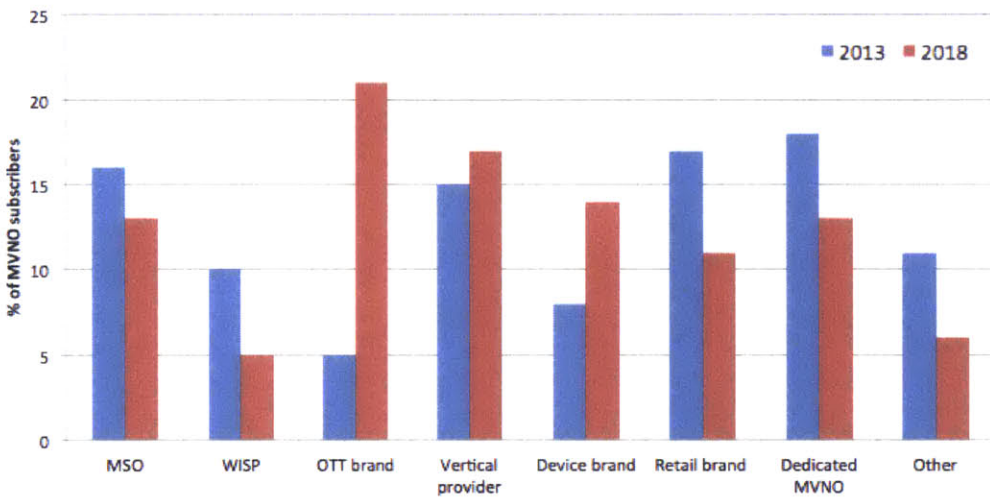

Figure 34: Types of MVNO by % of MVNO Subscriber Base

5 MVNO 3.0 System of Systems (SoS) Analysis

5.1 Systems Engineering Applied to Mobile Telecommunications

According to the NASA Systems Engineering Handbook, a system is a "construct or collection of different elements that together produce results not obtainable by the elements alone. The elements, or parts, can include people, hardware, software, facilities, policies and documents; that is, all things required to produce system-level results."[53] As such, while individual elements of the system have distinctive properties, functions, and performance, so, too, does the system comprised of these elements. Systems engineering seeks to find a logical way to think about

[53] National Aeronautics and Space Administration. *NASA Systems Engineering Handbook*. N.p.: CreateSpace Independent Platform, n.d. Print. NASA/SP-2007-6105 Rev 1.

stakeholders, their needs, and the subsequent functional, operational, and performance requirements based on those needs.

In applying this same set of parameters to the mobile network architecture, the "system" is comprised of the E-UTRAN and EPS. Each of these is composed of network elements, and these network elements consist of software functions (eNodeB, MME, SGW, PGW, HSS, and PCRF) and hardware functions (compute, memory, storage, and network adaptors). Individually, the network elements defined in the LTE architecture have specific functions, performance characteristics, and limiting hardware resources. **Table 7** describes the system elements by characteristics and limiting resources.

System Element	Performance Characteristics	Limiting Resources
eNodeB	Simultaneous Users Number of sectors Number of carriers	Spectrum
MME[54]	State Management Call setup rates Authentication rates Idle/Active transition rates Mobility events Subscriber Capacity	Memory Resources
S-GW[55]	Throughput Call transaction rates Packet processing Session State Management Micro-mobility Events Subscriber Capacity	Compute Resources Memory Resources

[54] "Cisco MME Mobility Management Entity - Products & Services." *Cisco*. N.p., n.d. Web

[55] "Cisco SGW Serving Gateway - Products & Services." *Cisco*. N.p., n.d. Web.

P-GW[56]	Throughput Call transaction rates Packet processing Session Anchoring Macro-mobility Events Subscriber Capacity	Network Resources
HSS[57]	Identity Management Call setup rates Authentication rates Idle/Active transition rates Mobility events Subscriber Capacity	Memory Resources
PCRF	Call transaction rates Registration transaction rates Concurrent sessions TCP connections	Memory Resources

Table 7: LTE System Elements and Characteristics

Further, each MNO system not only consists of these hardware resources and software functions, but also of multiple vendors, operations teams, physical facilities, and policies (QoS, Information Security, operational, redundancy, etc.). To illustrate this, it is simplest to first depict the 3GPP LTE network path for traffic originating from a UE and destined for the Internet. This network path and the associated LTE functional model is illustrated in **Figure 35**.

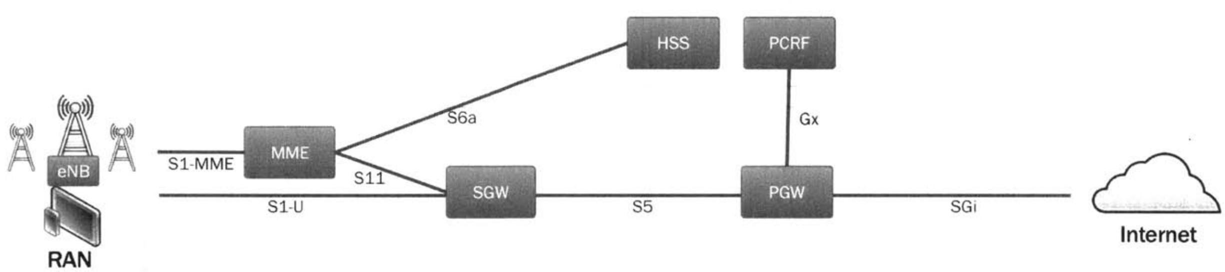

Figure 35: LTE Functional Model

[56] "Cisco PGW Packet Data Network Gateway - Products & Services." *Cisco*. N.p., n.d. Web.
[57] "HP I-HSS Data Sheet." *HP*. N.p., n.d. Web.

While network traffic appears to pass systematically between the 3GPP LTE network elements linearly for control (eNB➔MME➔HSS) and bearer (eNB➔SGW➔PGW➔Internet) traffic, actual paths are significantly different. In practice, the deployment and operational model of a LTE network looks more like **Figure 36**. Note that the deployment model is actually quite different, with the inclusion of additional network elements (routers, switches, firewalls, and load balancers), each with their own functions, performance characteristics, and hardware resource limitations. Mobile networks also deploy services inline with the LTE EPC for functions such as Deep Packet Inspection (DPI), video optimization, Network Address Translation (NAT), and application proxies.

To further complicate the mobile system, each of these network elements may be procured from different vendors, with proprietary functions and different performance characteristics. An important consideration of this heterogeneous environment is the tight coupling of system functional boundaries to system physical boundaries, disallowing physical resource pooling by system functions.

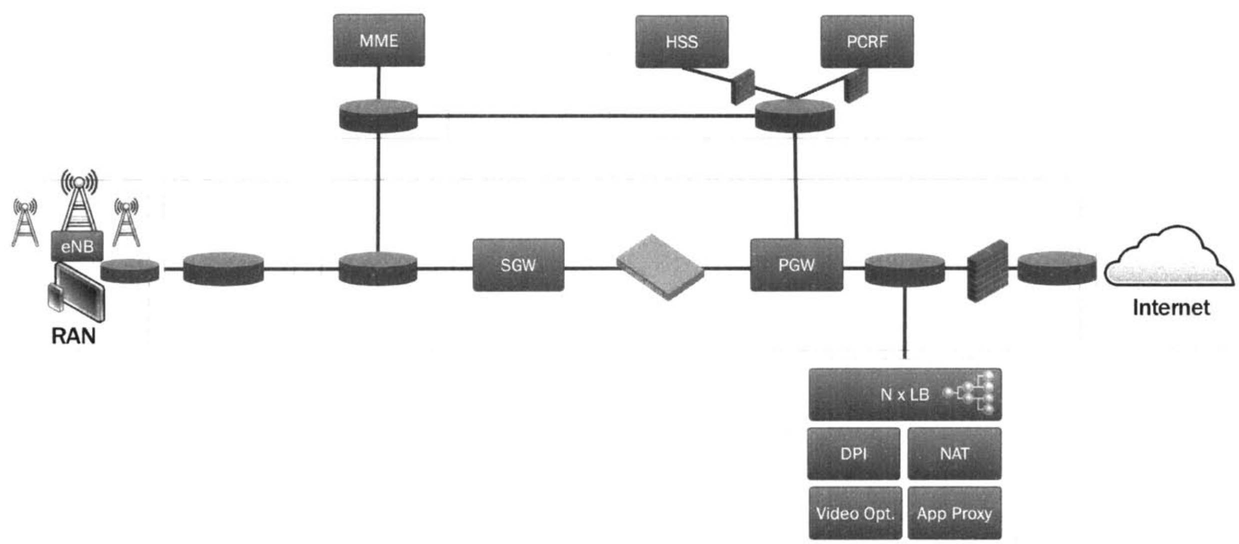

Figure 36: LTE Functional Deployment Model

Lastly, the physical deployment model of the MNO is hierarchical (**Figure 37**), providing multiple layers of aggregation. In general, the MNO physical deployment model resembles closely the Cisco hierarchical network design model[58], consisting of an access network, distribution network, and core network:

- Tens of millions of UE connect to cell sites for transmission of their wireless communications. These cell sites vary in size (measured in coverage radius) and capacity, as discussed in Section 2.2.1.2.

- Tens of thousands of cell sites are backhauled via multiple different transport technologies to pre-aggregation facilities. The transport technologies may be wired or wireless, and may be leased or owned by the MNO.

- Thousands of pre-aggregation facilities provide transport aggregation of the multiple transport technologies originating from the cell site onto a higher-bandwidth transport network.

- Hundreds of Mobile Telephone Switching Offices (MTSOs) provide bearer termination of the UE-originated traffic. This bearer termination includes the LTE S-GW and P-GW functions. The MTSO provide Internet access to allow bearer traffic to reach their respective destinations.

- Two types of data centers exist within the MNO, one housing the LTE control plane functional elements and the other housing the operations and maintenance functions, such as element management systems (EMS), operations support systems (OSS), and billing functions. These data centers may be physically or logically diverse.

[58] Dinocolo, Dan. "Understanding Network Models - The Cisco Network Design Model." *Network Newz*. N.p., 6 Feb. 2004.

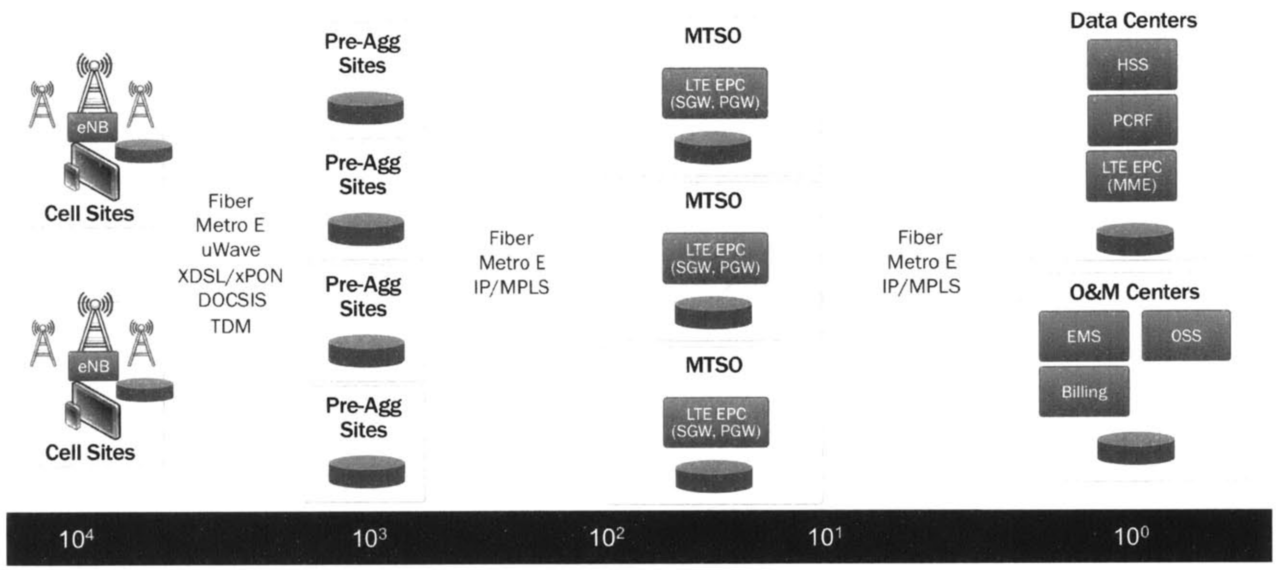

Figure 37: LTE Physical Deployment Model

Within the MNO, the principles of systems engineering are required in order to perform many tasks, with the primary objective being the integration, interoperability, and optimization of the system elements for the benefit of the system itself. The tasks and associated stakeholders include:

- Capacity Planning: Systems engineers model anticipated capacity across the entire mobile system to identify performance bottlenecks in individual system elements and plan for their expansion or upgrade. Systems engineers are responsible for understanding the needs of new mobile devices and new mobile services in order to determine system capacity requirements.

- Service Planning: System engineers model anticipated service functions or features across the entire mobile system to identify functional, capacity or performance impacts resulting from the enablement of these functions or features and plan for either system-level or element-level enhancements. Systems engineers are responsible for understanding the needs of their consumer and enterprise customers in order to determine system performance requirements.

- Operational Planning: System engineers use the capacity and service planning models to create operational planning models. Operationally, MNOs are typically divided into multiple organizations on either geographic or functional boundaries. The operational planning models include the activation and provisioning of new network elements within an operations organization, changes in scale that might impact another operations organization, and changes in scale of network elements that might impact cross-organization EMS or OSS systems.

5.2 SoS Thinking Applied to MVNO 3.0

System of Systems thinking extends the concepts defined by systems engineers for complex systems to include those systems in which the underlying system elements are complex systems themselves. The International Council on Systems Engineering (INCOSE) Systems Engineering Handbook illustrates the complexity of these systems of interest through hierarchy (**Figure 38**)[59].

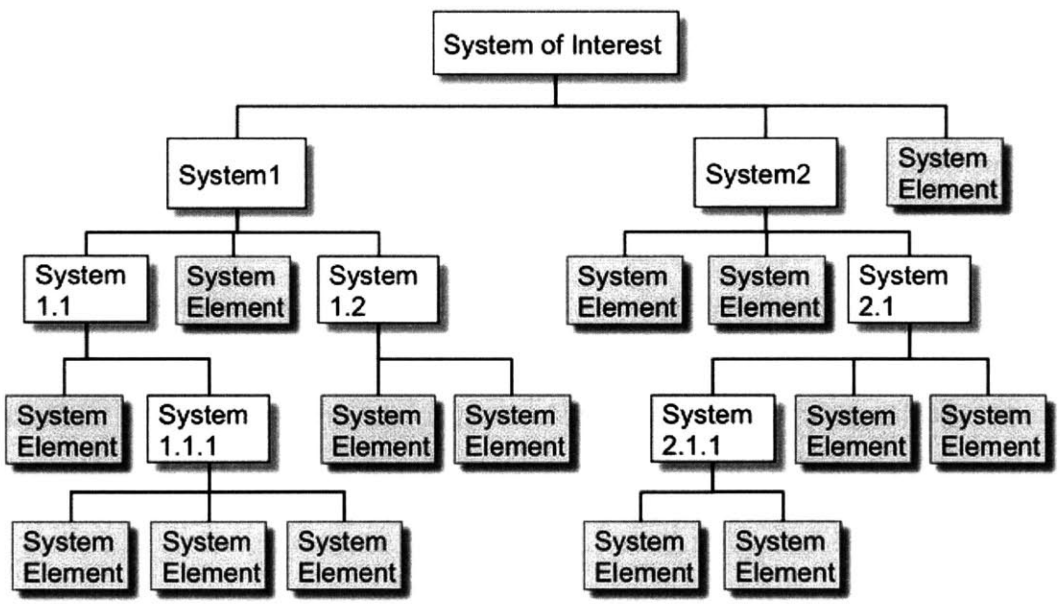

Figure 38: Hierarchy Within a System

SoS thinking for complex systems in the technology field has a long history. In 1997, Hewlett Packard's (HP) Computer Systems Laboratory had defined System of Systems as "large-scale concurrent and distributed systems that components of which are complex systems themselves."[60] In the HP paper "Systems of Systems as Communicating Structures," Vadim

[59] Haskins, Cecilia. *Incose Systems Engineeriing Handbook*. Version 3.2.2. a Guide for Life Cycle Processes and Activities. Place of Publication Not Identified: Incose, n.d. Print.

[60] Kotov, Vadim. *Systems of Systems as Communicating Structures*. Palo Alto, Calif.: Hewlett Packard Laboratories, 1997. Hewlett Packard, Oct. 1997. Web.

Kotov describes Communicating Structures as "hierarchical structures that represent SoS in a uniform, systematic way as composition of a small number of basic system objects."[61]

While MNOs may be described as systems, MVNOs that overlay these systems, and provide integration, interoperability, and optimization of multiple MNOs may be described as systems of systems. **Figure 39** illustrates the LTE physical deployment model for MVNO 1.0 / MVNO 2.0, based on the Full MVNO model, in which a technical and business relationship exists between one MVNO and one MNO. As can be seen in the diagram, the MVNO Data Center replicates many of the functions that the MNO already engineers into their system, and creates new operational integration points for both the MNO and MVNO. These integration points include:

- MVNO IP Network to MNO IP Network for traffic routing
- MVNO P-GW interface to the MNO S-GW for mobility management
- MVNO PCRF policy-peered to the MNO PCRF for policy establishment
- MVNO HSS interface to MNO MME for mobile authentication / authorization
- MVNO Billing system interface to MNO billing system to validate subscriber records
- MVNO EMS interface to MNO EMS for maintenance and management

[61] Kotov, Vadim. *Systems of Systems as Communicating Structures*. Palo Alto, Calif.: Hewlett Packard Laboratories, 1997. Hewlett Packard, Oct. 1997. Web.

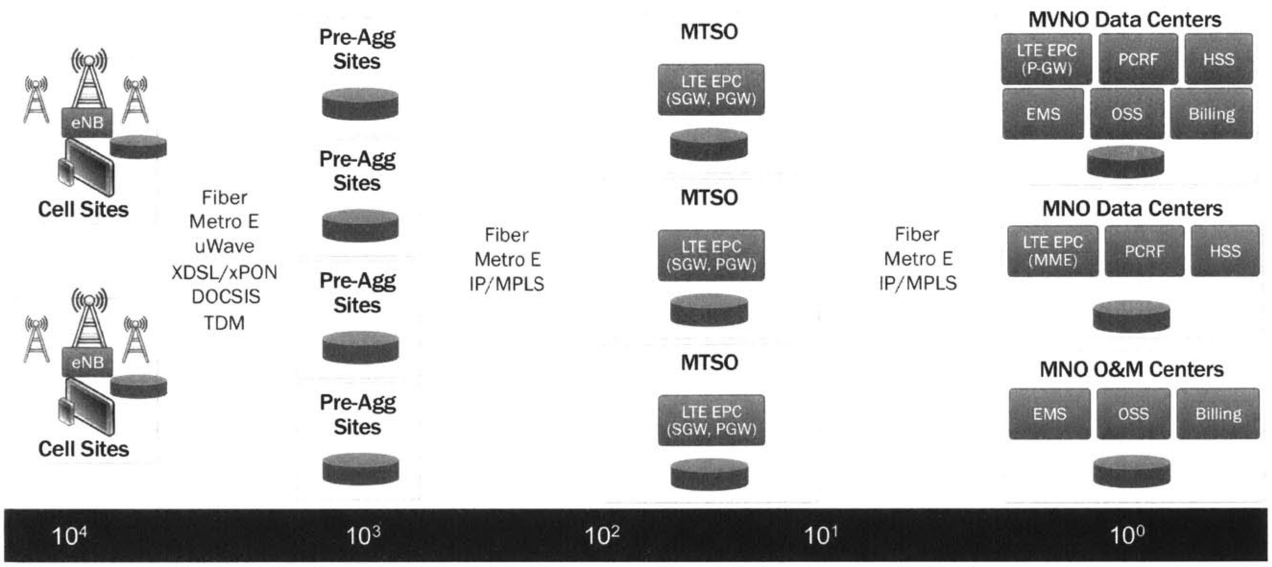

Figure 39: LTE MVNO Physical Deployment Model

MVNO 3.0 increases this complexity by enabling technical and business relationships between one MVNO and multiple MNO. As a result of this, the 1:1 interface complexity described for MVNO 1.0 / MVNO 2.0 is exacerbated, becoming 1:many. MVNO 3.0 SoS exhibit many of the behaviors of the complex systems discussed in Section 5.1, while also requiring resolution to combinational complexity, such as:

- Heterogeneity in the operational models and external interfaces of the underlying MNO systems, resulting in different interoperability paradigms that the MVNO must design for.

- Managerial independence of the underlying MNO systems, resulting in different scalability, quality, and reliability, requiring the MVNO to coordinate service only as good as the poorest-performing MNO.

- Managerial hierarchy of the underlying MNO systems introduces complexity in scheduling, requirements coordination, budgets, etc.

- Operational independence of the underlying MNO systems, resulting in different evolutionary paths and lifecycles, forcing the MVNO to deliver capabilities only as good as the least-capable MNO.

Heterogeneity, hierarchy, managerial independence, and operational independence of the underlying MNO complex systems are amongst the many behaviors of the MVNO 3.0 system that must be accounted for in defining stakeholders and system requirements. The remainder of this thesis will look at this combinational complexity across various stakeholders to develop a set of requirements and propose a potential solution for MVNO 3.0.

5.3 MVNO 3.0 Stakeholders and Needs

In designing a solution to support MVNO 3.0, it is important to first understand the key stakeholders, their needs, and derive an initial set of requirements for the development of the MVNO 3.0 system. **Figure 40** identifies six stakeholders and their relative importance – Device manufacturers, government and regulatory agencies, standards organizations, network infrastructure vendors, MNOs, MVNOs, and consumers of the MVNO 3.0 service. The importance of each of these stakeholders is discussed in the subsequent sections.

		System of Systems Stakeholders							Scores	Ranks
		Device Manufacturers	Government and Regulatory Agencies	Standards Orgs.	Network Infrastructure Vendors	Mobile Network Operator (MNO)	Mobile Virtual Network Operator (MVNO)	Consumers of the System		
	Importance (1-4)	2	3	2	3	4	4	4		
NEEDS	Interoperability	4	3	4	5	4	5	3	88	1
	Open / Standards Compliance	1	2	5	5	3	5	3	77	5
	Security & Privacy	2	5	3	1	4	5	5	84	3
	Maintainability	1	4	4	1	5	5	2	73	6
	Scalability	2	2	4	1	5	5	5	81	4
	Quality / Reliability	2	4	3	1	5	5	5	85	2

Figure 40: MVNO 3.0 Stakeholders and Needs

Six primary needs of all stakeholders are evaluated for each stakeholder, and weighted against the stakeholder importance to derive a cross-stakeholder score. The ranking of the relative importance of each need across all stakeholders is also included. From this analysis, the MVNO 3.0 needs, in order of importance, are as follows:

- Interoperability refers to external interfaces, APIs, and protocols between the stakeholders and other entities
- Quality / Reliability refers to the availability of the system to continuously deliver service

- Security and Privacy refers to the ability of the system to protect itself and confidential information in transit across the system or stored within the system
- Scalability refers to the ability of the system to meet increasing demand with minimal effort
- Open / Standards Compliance refers to the internal interfaces of the system, especially between the MNO and MVNO
- Maintainability refers to the ability to manage and monitor the system

5.3.1 Device Manufacturers

Device manufactures, including those who develop smartphones, tablets, PCs, and sensors that connect to the mobile infrastructure, have multiple needs in the development of the MVNO 3.0 system. Of primary importance to the device manufacturers is the ability to develop mobile devices as platforms from both a hardware and software perspective, enabling a single device platform to be extensible to as many different networks – both MNO and MVNO – as possible. In order to do so, device manufactures seek to minimize the number of unique interfaces required for interoperability with the network.

5.3.2 Government and Regulatory Agencies

In most markets, the mobile telecommunications industry is regulated. This regulation includes the treatment of network traffic ("net neutrality"), the use of licensed spectrum, interference requirements for unlicensed spectrum, tools to lawfully intercept network traffic (Communications Assistance for Law Enforcement Act [CALEA]), and inclusion of public safety capabilities (i.e., enhanced 911 services). Government and Regulatory agencies seek to minimize the integration points with MNOs and MVNOs, guarantee consumer privacy, and ensure availability of public safety services. In order to monitor these functions and regulate the industry, strong management and reporting tools that provide the agencies with compliance data are important.

5.3.3 Standards Organizations

A standard provides "requirements, specifications, guidelines, or characteristics that can be used consistently to ensure that materials, products, processes and services are fit for their purpose."[62] Standards organizations maintain their relevancy not only by creating these standards, but also in the industry adoption of their standards. In MVNO 1.0 and MVNO 2.0, 3GPP was the predominant standards organization, defining interworking and roaming architectures, with protocol-specific help from IETF and requirements contributions from NGMN. In MVNO 3.0, the same standards organizations will look to ensure their relevancy through the adoption of MVNO standards. These standards will continue to define the interoperability, maintainability, and scalability of the mobile system.

5.3.4 Network Infrastructure Vendors

Much like device manufacturers, network infrastructure vendors seek to minimize the number of iterations of their hardware and software products, and ensure broad applicability of their solutions without significant customization. Interoperable solutions based on standards compliance have historically been the avenue to meet this need.

When providing infrastructure to MNOs, needs such as maintainability, scalability, quality / reliability, and security and privacy are already addressed. MVNO 3.0 does not introduce significant additional capabilities beyond those already provided to the MNO and for MVNO 1.0 / MVNO 2.0. These needs are of low importance to the network infrastructure vendor within the context of MVNO 3.0.

5.3.5 MNOs

For MNOs, MVNO 3.0 represents the largest change in both operating and business model. MVNO 3.0 eliminates much of the competitive advantage and dominant position that the MNOs had over MVNOs in MVNO 1.0 / MVNO 2.0. Prior to the MVNO 3.0 model, MNOs did not compete against each other beyond initial contract to carry network traffic. MVNO 3.0 changes this – allowing the MVNO to select networks dynamically. As such, MNOs need to minimize their integration costs while also providing unique value in order to be attractive from a network

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[62] "Standards." *International Organization for Standardization (ISO)*. N.p., n.d. Web.

selection perspective. In addition, any scalability, quality, or maintainability problems experienced by the MVNO will also impact the MNO. Priorities for the MNO are therefore almost identical to those of the MVNO.

5.3.6 MVNOs

As the stakeholder offering services to consumers, MVNOs have the most needs from system of any stakeholder. The MVNOs seek to offer a high quality service to consumers at attractive margins to their owners while being compliant with regulations, maximizing the device selection on their network, and signing favorable carriage relationships with MNOs. The need to interface with all other stakeholders means that other stakeholder priorities become MVNO priorities.

5.3.7 Consumers of the System

Whether it is an individual, enterprise organization, cloud provider, MSO, or other entity, the paying consumer must have their needs met in order to purchase a service. Without delivering to the consumers' expectations, the MVNO does not generate profits, and those profits cannot be shared with the other stakeholders. For the consumers, the system needs to be reliable enough to meet their needs and scalable enough to deliver the services they request. In addition, the system needs to provide protection of their confidential or personal information.

5.4 Generation of SoS Requirements

Based on the needs of the key stakeholders defined previously, requirements can be developed for each of the needs identified. Based on the author's own industry expertise and relationships with both MNOs and MVNOs, an initial set of requirements was generated. This set of requirements serves as a baseline for the technical and operational realization of MVNO 3.0. The requirements are not intended to be exhaustive for full system deployment and operation, but instead to serve as an example of the functions and performance characteristics of individual system elements that are required for the MVNO SoS to be viable. In fact, as with most SoS in early Development Stage, the requirements are slightly ambiguous. These requirements can be found in **Appendix A: Abridged Requirements For MVNO 3.0**, with recognition that the SoS systems engineering will be iterative and continuous, accounting for "changes in the various system element life cycles, such as new technologies that impact one or more system elements, and normal system replacement due to pre-planned product improvements."[63]

6 Proposed MVNO 3.0 Solution

The proposed MVNO 3.0 Solution is based on significant research in the area of Always Best Connected (ABC) mobile networking. First introduced in 2003 by Eva Gustafsson and Annika Jonsson at Ericsson Research, ABC mobile networking is based on the premise that the user or service provider, not the access network operator, decides the best access network for the delivery of content and services[64]. Within the context of ABC, five "actors" are identified:

- ABC User or subscriber to the service
- Access Network Operator that provides the ABC user with a public or private access network at any point in time
- ABC Service Provider that offers the ABC Service
- Application Service Provider (ASP) that provides the ABC user with content or services
- A Corporation, representing a special type of ASP, for corporate services that must remain highly secure

In the context of the MVNO 3.0 solution, the MVNO plays the role of the ABC Service Provider. The functions of the ABC Service Provider include access discovery, access selection, mobility management, authentication / authorization. Unlike MVNO 1.0 / MVNO 2.0 business models, this model requires that the MVNO provides a Full MVNO offering, including, at the bare minimum, the LTE EPC P-GW, PCRF, and HSS.

As noted in **Figure 34** (Page 56), the future MVNO landscape is expected to be diverse, with offerings from many non-traditional mobile service providers. **Figure 41** illustrates these future MVNOs, and the various combinations of ABC Actors that might exist as a result of their entrance into the MVNO 3.0 market. There are potentially five combinations, each of which

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[63] Haskins, Cecilia. "Section 2.6." *Incose Systems Engineeriing Handbook. Version 3.2.2. a Guide for Life Cycle Processes and Activities*. Place of Publication Not Identified: Incose, n.d. N. pag. Print.

represent an opportunity for a new entrant into the MVNO market:

- Dedicated MVNO, in which the MVNO 3.0 provider acts solely as the ABC Service Provider. A business relationship exists between the Dedicated MVNO and the ABC User, and between the Dedicated MVNO and multiple MNO.

- Vertical Wireless Internet Service Provider (WISP), in which the MVNO 3.0 provider acts as both the ABC Service Provider and Access Network Operator. A business relationship exists between the Vertical WISP and the ABC User, and between the Vertical WISP and multiple MNO.

- OTT Brand WISP, in which the MVNO 3.0 provider acts as both the Application Service Provider and ABC Service Provider. A business relationship exists between the OTT WISP and the ABC User, and between the OTT WISP and multiple MNO.

- MSO WISP, in which the MVNO 3.0 provider acts as the Application Service Provider, ABC Service Provider, and Access Network Operator. A business relationship exists between the MSO WISP and the ABC User, and between the MSO WISP and multiple MNO.

- Enterprise IT WISP, in which the MVNO 3.0 provider acts as the Corporation, the Application Service Provider, and the ABC Service Provider. An employment relationship exists between the Enterprise IT WISP and the ABC User, and a business relationship exists between the Enterprise IT WISP and multiple MNO.

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[64] M.P.de Leon, A.Adhikari "A User Centric Always Best Connected Service Business Model for MVNO", ICIN2010 proceedings

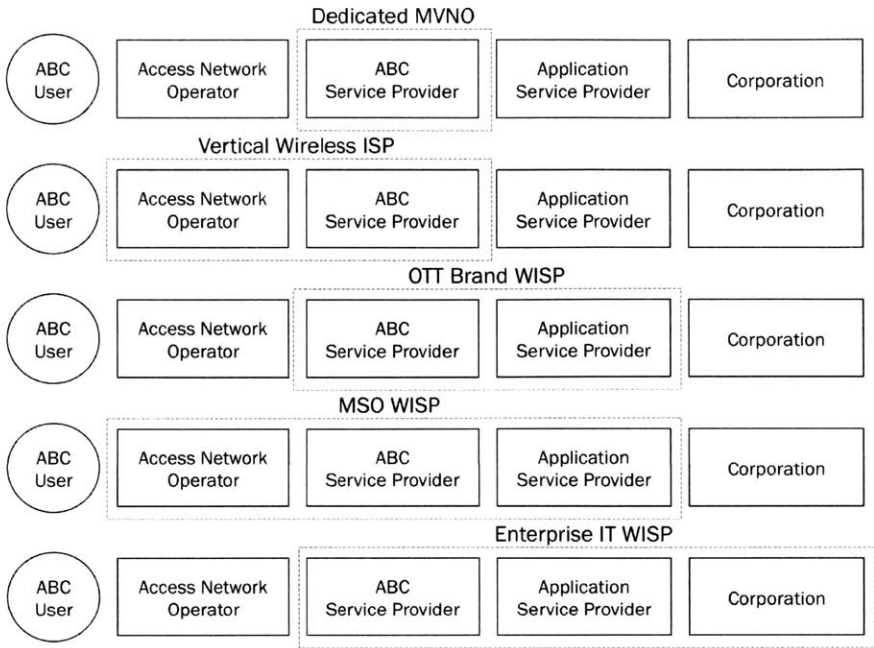

Figure 41: Future MVNOs as ABC Actors

The proposed solution for MVNO 3.0 allows any variant of the above business models to be realized. In addition to the technical requirements defined in Section 5.4, the MVNO 3.0 solution consists of functional and operational enablers that allow MVNOs to deliver information seamlessly across access networks with limited user interaction, at the right economics.

At the functional level, the MVNO system does not differ significantly from those of MVNO 1.0 / MVNO 2.0, based on the 3GPP roaming and interworking architectures. The MVNO 3.0 platform includes the LTE EPC P-GW, ePDG, PCRF, HSS and ANDSF functions defined previously, and a number of value-added services, including DPI, NAT, Video Optimization, and application proxy. In order to meet the requirements defined in Appendix A, the proposed MVNO 3.0 solution includes an API platform that exposes information from system elements in an open / standardized manner using an enhanced version of GSMA OneAPI and a portal function that allows 3rd parties to provision and modify subscriptions, services, and system functions. For reference, the proposed MVNO functional solution, with seven new system elements (discussed in Section 6.1 and Section 6.2), is depicted in **Figure 42**.

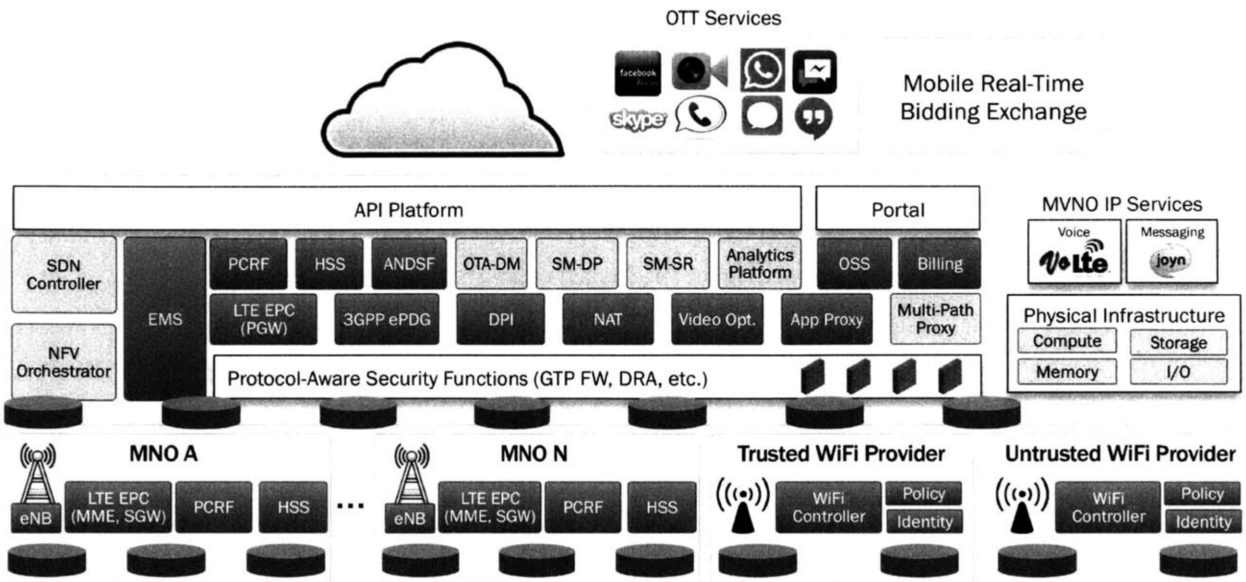

Figure 42: Proposed MVNO 3.0 Solution (Functional)

6.1 Functional Enablers

Table 5 (Page 47) defined innovations that have facilitated the deployment and operation of MVNO 2.0 systems. In some instances, these functions are embedded in existing system elements (i.e., the UE capabilities for 802.11u, the AAA capabilities for EAP). In other instances, these functions result in the development of an entirely new system element (i.e., the ANDSF for access network selection). In order to support business models reliant on detecting, selecting, and authenticating to multiple cellular and WiFi networks dynamically, the capabilities developed for MVNO 2.0 are insufficient.

Apple proposed one example of such as system in 2006, in their US Patent and Trademark Office filing entitled "Dynamic Carrier Selection,"[65] depicted in **Figure 43**, in which the MVNO server sends the mobile device a list of preferred network operators with the ability to dynamically alter the list based on network operators bidding for carriage based on price or network quality.

[65] Apple, Inc. "United States Patent Application: 0110130140." *United States Patent and Trademark Office (USPTO)*. N.p., n.d. Web.

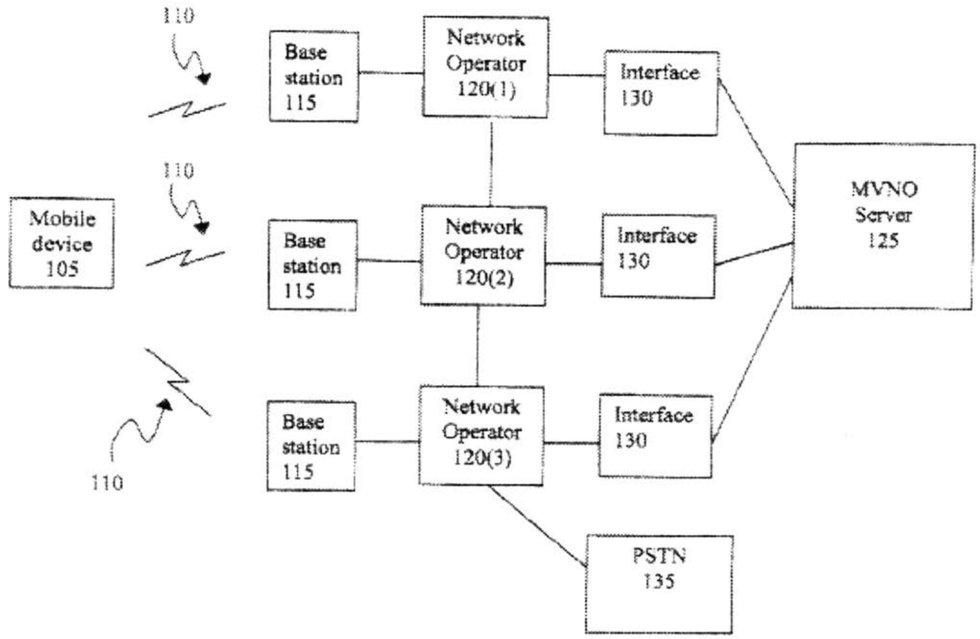

Figure 43: Apple Dynamic Carrier Selection Patent Filing

In order for MVNO 3.0 to be successful, the MVNO needs to have the capability to dynamically re-provision the mobile device with the information necessary to help discover and connect to these multiple cellular and WiFi networks, either in parallel or in series. A number of emerging technologies, when integrated, provide MVNOs with this capability. The functional enablers described in this section follow similar paradigms to the innovations in MVNO 2.0, with some functions embedded in existing system elements and others requiring new system elements:

- Mobile Embedded SIM Cards
  - UE functions for embedded SIM cards
  - Introduction of new system elements for remote provisioning (SM-DP, SM-SR)
- Coordinated Selective IP Traffic Offload
  - UE functions supporting traffic offload
  - Introduction of new system elements for remote provisioning (OTA-DM)
- Multipath Capabilities

- UE functions supporting multipath
- Introduction of new system element for supporting multipath in legacy environments (Multipath Proxy)

- Access Network Selection Algorithms
  - UE functions supporting access network selection
  - Introduction of new system element for determining access network selection algorithms (Analytics Platform)
  - Introduction of new system elements for remote provisioning (OTA-DM)
- Real-Time Bidding Exchanges
  - Extended functionality in SM-DP and SM-SR to provision and enable new MNO
  - Extended functionality in OTA-DM for remote provisioning of offload policies
  - Extended functionality in Analytics Platform for access network selection policies

6.1.1 Mobile Embedded SIM

As discussed in Section 2.2.2 (Page 33), the removable SIM card is currently the basis for authentication of the mobile user based on IMSI and related security keys. Each MNO provisions a SIM card, tied to a subscriber account, open subscriber request. This SIM card contains all the credentials that a subscriber needs to authenticate both with the subscribed MNO and roaming MNOs. To do so, the credentials on the SIM are transported securely to the HSS in the subscribed MNO network. For MVNO 1.0 / MVNO 2.0, the HSS typically resides within its network, so, for all intents and purposes, the MVNO subscriber is considered a roaming subscriber within the associated MNO. Until recently, only MNO were allowed to issue SIM cards, and these SIMs were not reprogrammable. As a result, should a subscriber wish to switch MNO (or MVNO), a new SIM was required[66].

[66] "The Endangered SIM Card." *The Economist*. The Economist Newspaper, 22 Nov. 2014. Web.

In December 2013, GSMA introduced a standard for reprogrammable SIM cards called the embedded Universal Integrated Circuit Card (eUICC), which combines with a remote provisioning system to increase the flexibility of business models associated with SIM cards[67]. For handset manufacturers, adoption of the eUICC specification by MNO and MVNO allows for devices to be more standardized. eUICC also enables consumers to switch MNO and MVNO subscriptions more readily. Most importantly, eUICC allows multiple operator profiles to be provisioned simultaneously.

At present, both the specification and industry adoption of eUICC has been limited to Machine to Machine (M2M) modules, where the complexity and cost of including physical SIMs is prohibitive. The specification, however, is extensible to any mobile device. According to Smart Insights, "eUICC will change the way SIM card vendors and mobile telecommunications players, third parties and, finally, end users interact with each other. Moreover, such a reshape prescribes the introduction of new roles and the arrival of new entrants as well."[68]

The eUICC specification from GSMA enables both over the air provisioning/deletion and enablement/disablement of operator profiles. At any point in time, a mobile device may have multiple operator profiles provisioned, but only one may be active. For MVNO 3.0, this allows for mobile devices to be rapidly re-provisioned as new MNO relationships are forged, and for dynamic selection of networks based on MVNO decision criteria. To perform these functions, two new network elements have been specified:

- Subscription Manager – Data Preparation
- Subscription Manager – Secure Routing

For the MVNO 3.0 Solution in **Figure 42**, the UE is enhanced to support the eUICC specifications, and the MVNO system includes the SM-DP and SM-SR functions.

[67] "Benefits Analysis of GSMA Embedded SIM Specification on the Mobile Enabled M2M Industry." (n.d.): n. pag. Beecham Research, Sept. 2014. Web.
[68] "EUICC, a Disruption in the SIM Market." Smart Insights, n.d. Web.

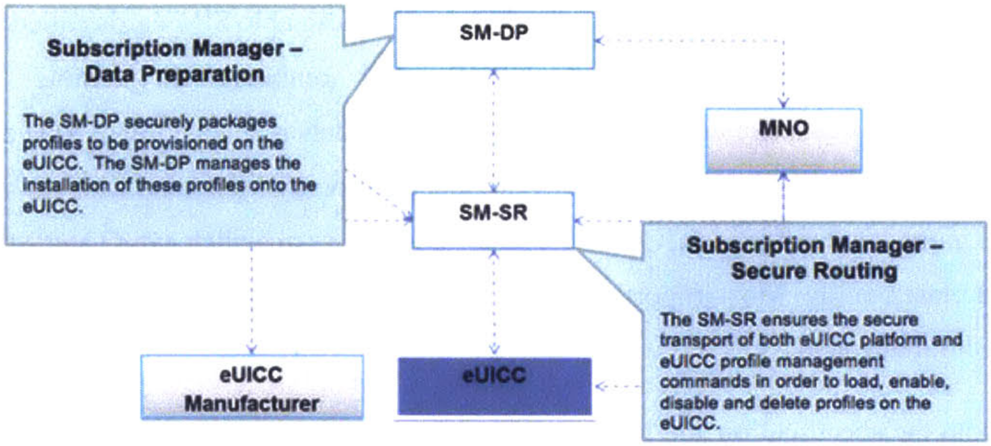

Figure 44: GSMA eUICC Architecture

6.1.2 Coordinated Selective IP Traffic Offload

Coordinated Selective IP Traffic Offload (CSIPTO) is a 3GPP System Architecture (SA) Work Item, analyzing how the network and UE can coordinate changes in point of attachment (LTE P-GW). This Work Item is an enhancement to previous work done for SIPTO (3GPP R10), in which the network decided point of attachment unilaterally. **Figure 45** illustrates the 3GPP CSIPTO architecture allowing the network and UE to coordinate relocation of network flows to minimize service disruption.

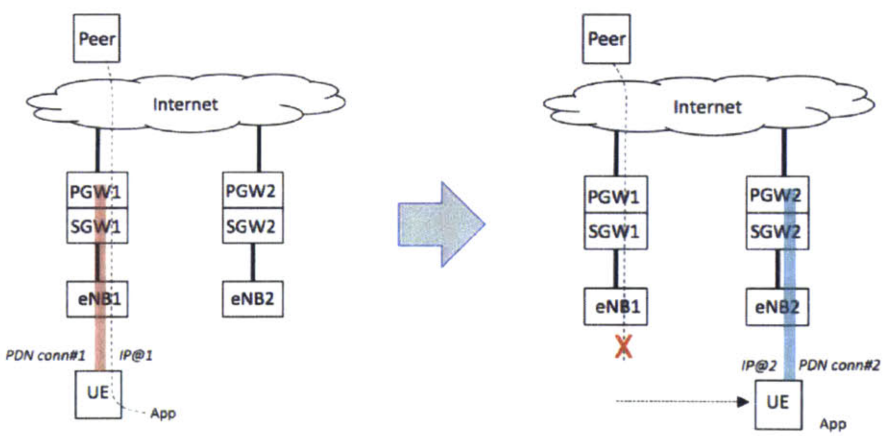

Figure 45: 3GPP CSIPTO[69]

[69] Yegin, Alper. "3GPP CSIPTO." *IETF 90*. Samsung Electronics. Web.

The proposed MVNO 3.0 system leverages the 3GPP CSIPTO functionality for multiple purposes:

- Relocation of network flows across redundant public or private data centers allows the MVNO to leverage multiple hosting providers
- Relocation of network flows when the subscriber connects to a new MNO, allowing for localization of point of attachment during mobility events
- Relocation of P-GW when content is accessible from a closer cache point in a public Content Delivery Network (CDN) or public cloud provides benefit for the OTT VISP.
- Establishment of network flows across multiple P-GWs provides continuity for services that require IP address preservation

6.1.3 Multipath Capabilities

Multipath refers to the capability of a device, such as a mobile device, to send and receive requests over diverse paths, either in serial or parallel. Multipath capabilities have historically been used to provide load balancing, fault tolerance, and higher aggregate bandwidth through functions such as route resiliency and congestion avoidance[70]. In mobile networks, multipath may be realized at multiple different layers of the OSI stack, including the physical layer, network layer, or transport layer.

Layer	Name	Capability
Physical	CoMP MiMo	Functions such Coordinated Multipoint (CoMP) and Multiple-Input, Multiple-Output (MiMo) allows coordinated transmission and reception of wireless signals across different antenna arrays and different eNBs essentially creating a virtual antenna array. With these technologies, the UE may transmit

[70] Mueller, Stephen, Rose P. Tsang, and Dipak Ghosal. *Multipath Routing in Mobile Ad Hoc Networks: Issues and Challenges* (n.d.): n. pag. Department of Computer Science, University of California, Davis. Web.

		information to multiple destination receivers, where the signals are combined, or may receive information from multiple source senders and combine the signals itself.
Network	MP Routing	Multipath Routing allows the network to split traffic over multiple paths to the destination. Multipath routing may be used to avoid any network congestion or link failures. The communicating nodes, such as the UE and Internet application, are unaware that the traffic took diverse paths through the infrastructure.
Transport	MP-TCP SCTP	Transport layer functions such as Multipath TCP (MP-TCP) and Session Control Transmission Protocol (SCTP) allow end devices to ensure communications continuity in the event of an IP point of attachment change. These protocols also allow communicating nodes to agree to send and receive session traffic on one or more network interfaces simultaneously.

Table 8: Multipath Technologies

The proposed MVNO 3.0 solution leverages multipath capabilities at all layers. While CoMP and MiMo are functions within the constituent systems (the MNOs), the solution includes the addition of a multipath gateway that terminates either MP-TCP or SCTP traffic from the UE. This multipath gateway allows the UEs to take advantage of multiple different MNO and WiFi networks in parallel for sending and receiving traffic while providing interworking functionality for Internet services that do not support these protocols. While the eUICC standardized solution includes new servers (SM-DP, SM-SR) for communicating SIM provisioning information, these same servers are today not capable of providing CSIPTO information (decisions, criteria, networks, etc.) to the UE. The MVNO 3.0 solution introduces an Over the Air Device Management (OTA-DM) system that can be used to communicate multiple types of policies to the mobile device, including CSIPTO policies.

With the combined capabilities of CSIPTO and multipath, the MVNO 3.0 solution provides soft handover functionality. Soft handover functionality allows a single UE to be simultaneously connected to two base stations during mobility events. Essentially, soft handover is a "make before break" technology, in which the new channel is established and determined to be reliable before the old channel is released. Hard handover, alternatively, is a "break before make" technology, in which the new old channel is released before the new channel is established. Soft handover functionality was inherent in 3G systems, but was eliminated from the LTE flat architecture[71] due to the loss of radio network control functions. Combining CSIPTO and multipath capabilities allows the UE IP address to change when the point of attachment (LTE P-GW) is changed without impacting network flows, thus providing function similar to soft handover. **Figure 46** illustrates multipath soft handover.

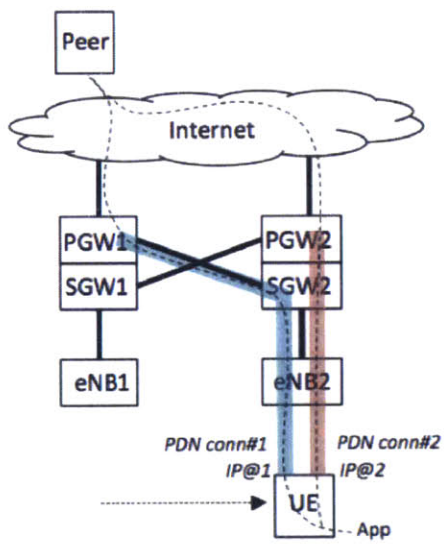

Figure 46: Multipath Soft Handover[72]

6.1.4 Access Selection Algorithms for Heterogeneous Networks

As the number of potential radio access network options increases for MVNO 3.0 subscribers, the ability to selectively determine which access network to connect to at any given time or location. Modern technological breakthroughs in the areas of big data and machine learning have created the opportunity for such access network selection to be algorithm-driven, based on a

[71] "Why No Soft Handover in LTE." *3G LTE INFO*. N.p., 23 May 2014. Web.

[72] Yegin, Alper. "3GPP CSIPTO." *IETF 90*. Samsung Electronics. Web.

combination of MVNO requirements, subscriber requirements, service QoS requirements, and link conditions. In the MVNO 3.0 solution, the access selection algorithm is embedded in an analytics platform.

The access selection algorithm combines profile information on the subscriber (identity, demographics, interests, devices, subscription plan, etc.), applications (QoS and latency requirements, protocol type, content type, etc.) and underlying MNO network (bandwidth, access types, IP pools, topology / routes / path, policy rule sets, network value-added service capabilities, etc.) with real-time profiling information to determine which access network is best suited for servicing the request. The real-time information retrieved may include subscriber mobility patterns or usage trends, application consumption data or popularity, and network performance or quality data.

Initially, the access selection criteria might be simple, focused only on optimizing the cost of service deliver for the MVNO. Such access selection criteria would include the bulk cost of data across each of the constituent MNOs and the remaining wholesale capacity purchased. With such a basic algorithm, the MVNO may select the MNO that provides a combination of best wholesale data rates for each given market. Long-term, however, the goal of such an algorithm is to match the profiles, or sets of requirements, to the capabilities, in real-time, of the constituent MNO systems, allowing the MVNO 3.0 solution to notify the UE of the best network to service the particular request. **Figure 47** provides one example of the types of information that would be factored in to the access selection algorithm for a video session.

	Profile	Profiling
User Analytics	Identity (Persistent) Demographics Explicit profile (interests, etc.) Device(s) and capabilities Billing / Subscription plan	Device sensor data Persistent Location / Presence Behavioral / Search / Social Purchasing / Payments Mobility patterns Usage data (from device)
Content Analytics	Catalog / Title Topic / Keywords CA / Rights management Encryption / DRM Format(s) / Aspect ratio(s) Resolution(s) / Frame rate(s)	Consumption data Content reach Asset popularity / revenue Distribution/Retention/Archival Search / Discover / Recommend Usage Data (from content source)
Network Analytics	Bandwidth and latency Access types IP pools Routes / topology / Path QoS / Policy Rulesets Network Service Capabilities	Active subscriber demographics Crowdsourced data Geographic segmentation Network Performance / Quality Network sensor data (IoT/M2M) Usage (from DPI)

Figure 47: Access Selection Criteria, Video Example

Today, the ANDSF deployed in mobile networks is a static element, leveraging a database of neighbor relationships to determine which networks to connect to. The ANDSF is not aware of real-time capabilities of the mobile networks or the requirements of the services and applications. For these reasons, the OTA-DM server in the MVNO 3.0 solution is operable not only to provide the CSIPTO policies discussed previously, but also access selection policies based on the access selection algorithm.

6.1.5 Real-Time Bidding Exchanges

John Maynard Keynes, a predominant UK economist in the early 1900s, developed an economic school of thought known as demand side economics with the premise that aggregate demand was the most important force driving any market[73]. This economic model can be seen in the wholesale mobile data market, where MNOs establish wholesale pricing models to MVNOs based on MVNO demand. This was discussed in Section 4.1 (Page 48), with supporting data from the FCC's Chief Economist. Demand side economics remain a significant business hurdle for MVNO 3.0 providers.

The demand side economics model has persisted in the MVNO market because MVNOs were unable to establish a free market across multiple MNOs due to the technical infeasibility. MVNO 2.0 introduced the first resolution – WiFi first – and this has changed the economics for MVNOs by limiting the amount of data delivered via cellular networks. With the MVNO 3.0 capabilities to algorithmically select access networks, maintain service continuity and subscriber experience across constituent MNOs with multipath, offload traffic with CSIPTO, and re-provision SIM cards dynamically, the full set of technical capabilities are available to MVNO providers to shift the wholesale mobile data market from demand-side economics to a free market economy.

Previously (Section 4.1.3, Page 52), this thesis established that long-lived relationships between networks and subscribers were increasingly less likely, and that transient subscriber/network relationships would be the dominant connectivity model in the future. With this in mind, the toolkit within the MVNO 3.0 solution also enables the introduction of bid-based mobile networking. The introduction of real-time bidding (RTB) has already been a dominant force in

[73] "What Are Demand Side Economics? Definition and Meaning." *BusinessDictionary.com*. N.p., n.d. Web.

changing the economics of advertising[74], including mobile advertising, and can provide a catalyst to MVNO margins, as well. RTB in the wholesale mobile data market would operate as per **Figure 48**:

- MVNO would provide real-time session requirements (QoS, latency, bandwidth, etc.) and current location to a mobile data exchange, who would be responsible for holding an auction, during which MNOs and WiFi providers will place a big to carry the data session.
- The value of the bid is based on the value of the session to the MNO, as determined by the MNO's parameters. For instance, if the MNO network is largely idle, the MNO might bid low as the cost to carry the additional traffic is low; however, if the MNO network is constrained, the MNO might bid high, or not bid at all.
- The bidding process ensures that the session is delivered at the minimum cost to the MVNO, while also maximizing MNO margins. In today's advertising networks, RTB happens in milliseconds. Further optimization of the RTB process, and the limited size of the MVNO industry compared to the advertising industry, would enable the RTB process to happen in less than 1ms.
- Once the bidding is complete, the winner is chosen and the session is assigned to that network. To do so, any combination of eUICC re-provisioning, CSIPTO, or multipath technologies may be used.

[74] "Infographic: Everything You Need To Know About Real Time Bidding For Display Ads." *Marketing Land.* N.p., 08 May 2014. Web.

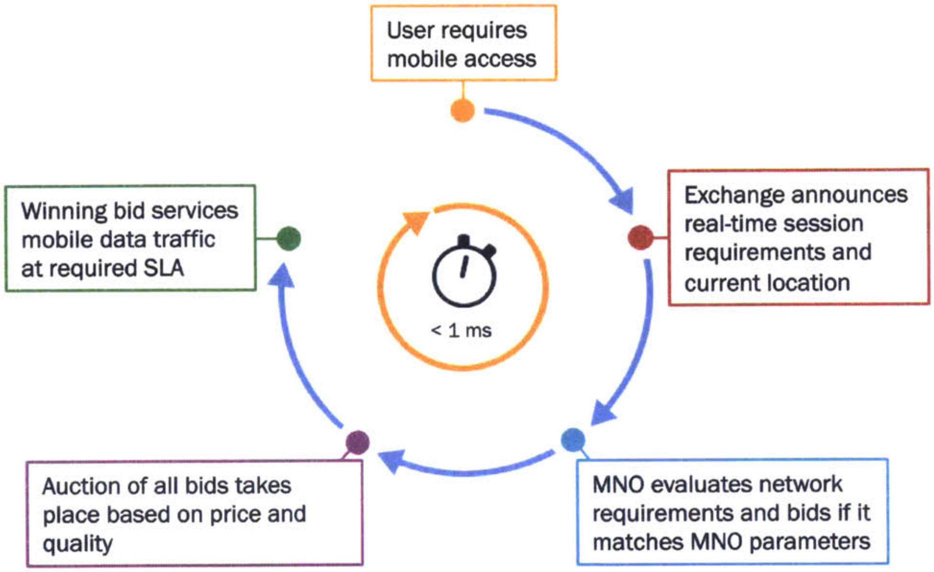

Figure 48: RTB For Mobile Data Access

The introduction of RTB to the MVNO industry as part of the MVNO 3.0 solution poses significant risk to MNOs, and is likely to be met with skepticism and resistance. There is no expectation that RTB will be a viable business model in the near-term, but the opportunity for RTB-based mobile access in the future is a significant area for further study.

6.2 Operational Enablers

Section 5.1 defined system elements as including "people, hardware, software, facilities, policies and documents; that is, all things required to produce system-level results."[75] In analyzing the mobile system, 3GPP functions such as MME, S-GW and P-GW, and non-3GPP functions, such as routers, DPI, NAT, and application proxies, were defined as system elements, each deployed as its own functional, operational, and performance capabilities. The mobile systems consisted of these system elements, each comprised of hardware, software, and documentation; each with uniquely defined operational and security policies; each with uniquely identified operations personnel. As a result, mobile systems have been vertically integrated into silos, limiting the reuse of subsystem capabilities. Such an integration model is not optimized for MVNO business models.

[75] National Aeronautics and Space Administration. *NASA Systems Engineering Handbook*. N.p.: CreateSpace Independent Platform, n.d. Print. NASA/SP-2007-6105 Rev 1.

Within the last ten years, the networking industry has paid specific attention to the changing economics of service providers. The industry is in the midst of a transition from vertical integration to horizontal integration, in which the creation of an underlying platform enables communication between multiple subsystems. At present, two core operational enablers have been promoted to resolve these challenges[76] – Software-Defined Networking (SDN) and Network Function Virtualization (NFV). These operational enablers provide the platform upon which the proposed MVNO 3.0 solution is built. SDN and NFV also represent additional complex systems integrated in the MVNO 3.0 System of Systems.

6.2.1 Software Defined Networking (SDN)

SDN, at its simplest level, is the exposure of the programmability of network software to external controllers via Application Programming Interfaces (APIs). SDN enables the control and management of network elements to shift from the vertical, proprietary software bundled on the network elements themselves to horizontal, open software disaggregated from the physical network element. The system functions may be as low-level as flow or routing tables, or as high-level as DPI or Firewall contexts. SDN has been at the forefront of the networking industry for only a short time – approximately three years, since the creation of the Open Networking Foundation (ONF). ONF was established to assist in the standardization of a protocol (OpenFlow) for communicating between a network controller and a network element[77]. Since for the formation of ONF, multiple standards organizations, including IETF SDN Working Group[78] and the OpenDaylight Consortium[79] have developed in support of SDN.

SDN is driven by the same disruptions occurring in the mobile industry and prompting the development of this thesis and proposal for MVNO 3.0[80]:

[76] Although SDN and NFV are publicized in the industry as technology enablers, this thesis treats the functions as operational enablers. Neither SDN nor NFV deliver new service capabilities to the network, but instead provide a new mechanism to program and operate the infrastructure.
[77] Evans, Steve. "The History of OpenFlow." *Computer Weekly*. N.p., n.d. Web.
[78] Nadeau, Thomas D. "IETF SDN Standards Emerge: Southbound Protocols, NFV, Service Chains." *TechTarget*. Brocade, n.d. Web.
[79] "OpenDaylight" *OpenDaylight | A Linux Foundation Collaborative Project*. N.p., n.d. Web.
[80] Open Networking Foundation (ONF). "Software-Defined Networking: The New Norm for Networks." (n.d.): n. pag. 13 Apr. 2013. Web.

- Changing traffic patterns resulting from subscriber connectivity via any device, from any location, over any network
- The rise of cloud services leading to an increase in network traffic, and the criticality of connectivity for both business and consumer applications
- The inability to scale to support or enforce policies dynamically for new subscriber or application requirements,

According to the ONF, the "SDN architectures support a set of APIs that make it possible to implement common network services, including routing, multicast, security, access control, bandwidth management, traffic engineering, quality of service, processor and storage optimization, energy usage, and all forms of policy management."[81] The OpenFlow controller in the ONF architecture is strikingly similar to the 3GPP PCRF, which provides "dynamic policy and control over bearer sessions, including flow detection, gating control, quality of service, bandwidth management, traffic mapping, and event monitoring."[82] **Figure 49** illustrates the similarity of these architectures side-by-side.

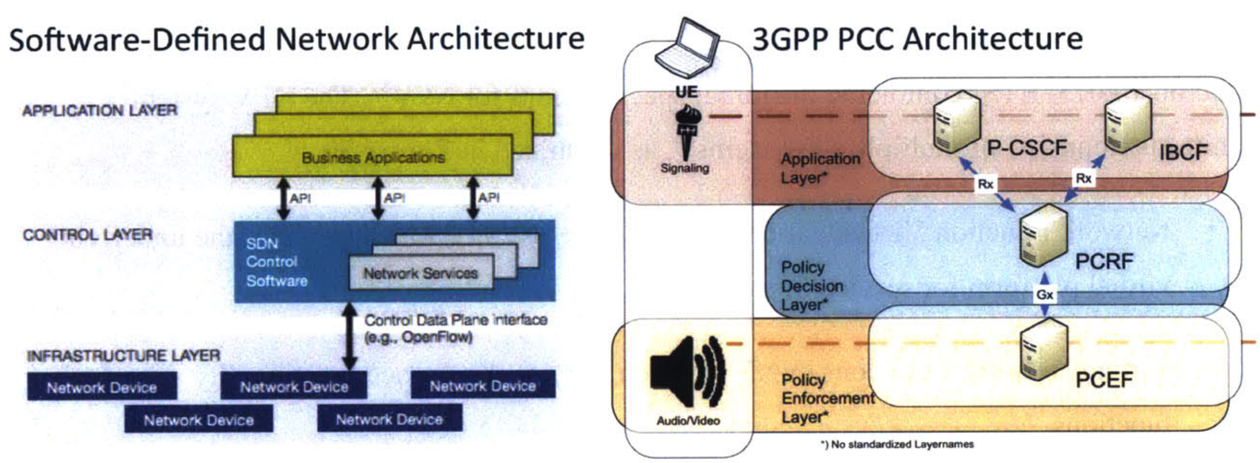

Figure 49: SDN Architecture and 3GPP PCC Architecture Compared

The MVNO 3.0 solution introduces SDN capabilities into the mobile control plane and the mobile data plane. The SDN Controller illustrated in **Figure 42** (Page 72), represents one functional entity in the MVNO 3.0 platform and provides the MVNO with programmability and

[81] Open Networking Foundation (ONF). "Software-Defined Networking: The New Norm for Networks." (n.d.): n. pag. 13 Apr. 2013. Web.

visibility into constituent MNO systems, and allows 3rd parties to program and view the MVNO system. These capabilities interface with EMS tools for discovery, provisioning, monitoring, and troubleshooting of system elements, and with OSS systems for fulfillment, service assurance, and customer care. For the MVNO, the ability to interoperate via open / standards-compliant SDN interfaces improves maintainability, scalability, and reliability of the overall system with lower investment.

6.2.2 Network Function Virtualization (NFV)

NFV originated via a whitepaper authored and made available by multiple service providers at the SDN and OpenFlow World Congress in October 2012[83] and later organized in the European Telecommunications Standards Institute (ETSI) NFV Working Group[84]. While SDN proposed that network functions be generally available via API and programmed by external controllers, NFV technology provides the decoupling of network services from proprietary hardware. With this decoupling, NFV helps service providers reduce infrastructure costs, increase resource reuse, and improve oversubscription models by creating a platform derived of general purpose compute and horizontally-available functions. Mobile networking, including the virtualization of the LTE EPC, was amongst the initial use cases that NFV sought to address.

In October 2013, ETSI completed the initial specifications for NFV[85]. The NFV system architecture consists of multiple subsystems[86], as illustrated in **Figure 50**:

- Network Function Virtualization Infrastructure (NFVI), which provides the underlying virtual platform for service functions
- Virtual Network Functions (VNFs), which provide the service functionality as virtual functions
- NFV Management and Orchestration (NFV M&O), which provides the lifecycle management, orchestration, and automation of both the NFVI and VNFs

[82] 3GPP TS 23.203, "Policy and Charging Control Architecture."
[83] "Network Functions Virtualization." (2012): n. pag. *ETSI*. 22 Oct. 2012. Web.
[84] "Network Functions Virtualisation." *ETSI*. ETSI, n.d. Web.
[85] "ETSI - ETSI Publishes First Specifications for Network Functions Virtualisation." 14. ETSI Headquarters, Oct. 2013. Web.
[86] "Network Functions Virtualisation (NFV): Network Operator Perspectives on Industry Progress." (n.d.): n. pag. *ETSI*, 15 Oct. 2013. Web.

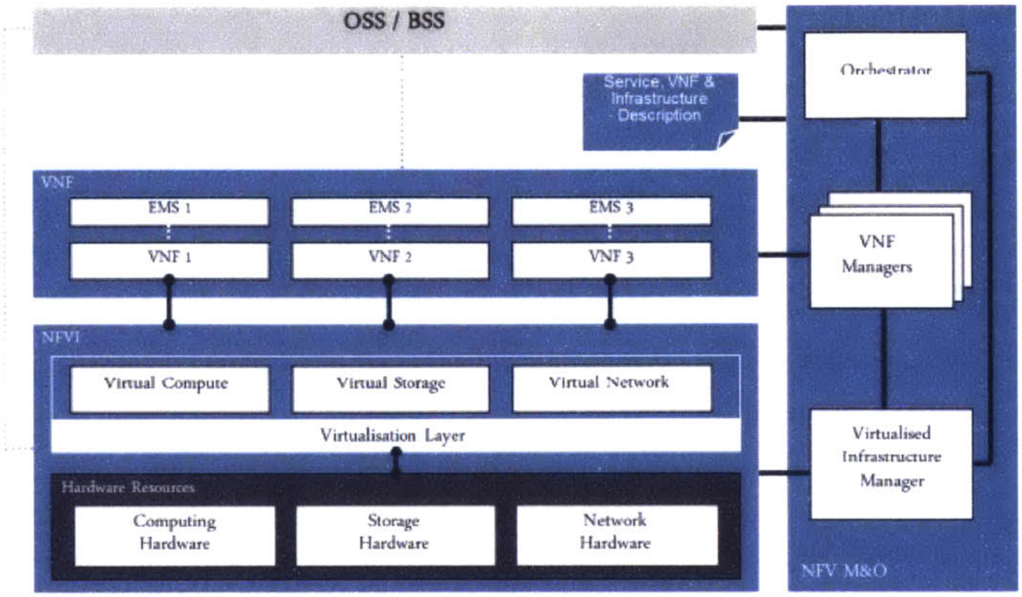

Figure 50: NFV System Architecture

The NFV capabilities are integrated into the proposed MVNO 3.0 system in a number of ways:

- A new functional entity, the NFV Orchestrator, is added, providing the functionality defined in NFV M&O.
- The functional entities in the MVNO 3.0 solution, including the PCRF, HSS, ANDSF, OTA-DM, SM-DP, SM-SR, Analytics Platform, OSS, Billing, LTE EPC, 3GPP ePDG, DPI, NAT, Video Optimization, DPI function, application proxy and multi-path proxy are realized as software-only functions, with the physical infrastructure decoupled.
- The NFVI is deployed as the MVNO 3.0 platform, with capabilities to virtualize physical infrastructure, including storage, compute, and network functions.
- ETSI NFV-compliant logical interfaces between the NFV M&O and the NFVI are used to communicate resource requirements to the underlying platform.

7 Conclusion

With the rate of innovation occurring in the mobile industry, especially with regard to technology, it is important that business models are developed that can leverage these innovations. This thesis presented a MVNO 3.0 solution that transforms the mobile industry from its current state to one in which MVNOs can successfully compete against traditional MNOs. By leveraging a SoS model of requirements generation and system development, the MVNO 3.0 solution leverages the functions developed in multiple standards organizations across multiple constituent systems to develop an integrated, platform-centric approach to the problem space.

Further development in this area, either in academia or industry, is highly likely as the mobile industry continues to transform to meet customer expectations and service requirements. In addition, it is worth paying special attention to the strategic decision-making (game theory) of dominant and non-dominant MNOs, and their respective participatory roles in MVNO 3.0, in establishing and resetting baseline subscriber experience expectations. Such a collusive approach to mobile networks has implications to the entire landscape of the mobile industry, especially regulatory and consumer protection positions regarding mergers and acquisitions in the mobile industry.

Appendix A: Abridged Requirements For MVNO 3.0

Stakeholder Need	Requirements
Interoperability	The system shall support communications flows between applications and mobile devices without requiring knowledge of the communication system technology or topology
	The system shall be capable of accommodating a variety of different access systems simultaneously thus providing a multi-access system environment
	The system shall be capable of accommodating a variety of different operational entities simultaneously, each associated with one or more access systems, thus providing a multi-operator system environment
	The system shall provide mobility functionality within and across the different access systems. Mobility functionality shall be optimized meaning that it offers minimal signaling overhead, minimal handover interruption time, secure handover procedure and local breakout
	The system shall support event-based (push), request-based (pull), periodic, asynchronous, and continuous communications models simultaneously.
	The system shall support "always on" mobile devices, which are operable to send and receiving information at all times
	The system shall support seamless mobility of devices across multiple access networks
	The system shall support both inbound and outbound roaming scenarios
	The system shall support seamless authentication of mobile devices on any access network
	The system shall support seamless re-authentication of mobile devices upon change of access network
	The system shall support location tracking for devices that support either nomadic or seamless mobility
	The system shall support mobile devices that have compute, power, and communications performance constraints
	The system shall support unicast, multicast, and broadcast communications modes
	The system shall support heterogeneous networking, in which a mobile node connects to multiple access networks in series
	The system shall support multi-homing, in which a mobile node connects to multiple access networks in parallel
	The system shall support the transport of any application-layer protocol negotiated between the mobile device and the application
	The system shall support delivery of value added services (VAS) independent of access network

	The system shall support interoperable naming and addressing across all access networks for both multi-homing and heterogeneous networking
	The system must support group-based communications
	The system must support peer-to-peer and mobile-to-mobile communications
	The system will be extensible for future technologies
Open / Standards Compliance	The system shall support Open Platforms defined by the following open source projects: OpenStack, OPNFV, OpenDaylight, and OpenFlow
	The system shall provide Open APIs for provisioning, authentication, rating, billing, and reporting
	The system shall support Open APIs compliant with GSMA OneAPI
	The system shall provide APIs for Quality of Service and Policy
	The system shall provide, at minimum, an API that is equivalent to that provided by the underlying operational entities and access systems
	The system shall support Hotspot 2.0 as specified by the WiFi Alliance
	The system shall support both IPv4 and IPv6 connectivity
	The system shall support 3GPP standard interfaces to external systems as defined for the E-UTRAN and EPS
	The system shall support 3GPP Home Routed and Local Breakout Architectures defined in 3GPP TS 23.401
	The system shall support 3GPP LTE Interworking Architecture defined in 3GPP TS 23.402
	The system shall support 3GPP supplementary services
	The system shall support charging models defined in 3GPP TS 22.115
	The system shall support IEEE 802.11u
	The system must support northbound APIs via Representational State Transfer (REST) for all functions
	The system must provide support for 3rd parties to insert services into a 3GPP-defined service chain
	The system must publish any APIs that are proprietary to the system
	The system should support Publish-Subscribe model for API access
	The system should support an aggregate API for QoS and Policy thus allowing a 3rd party to request end-to-end QoS in lieu of per-operational entity or per-access system QoS
	The system will support 3GPP Service Chains defined by Flexible Mobile Service Steering in 3GPP R13
Security & Privacy	The system shall provide a means to allow mobile devices and applications to send and receive information anonymously
	The system shall support confidentiality and data integrity validation
	The system shall support mutual authentication/re-authentication of mobile devices and communications system
	The system shall allow mobile devices and authentication systems to transmit information securely

	The system shall protect individual endpoints from unauthorized access
	The system shall ensure integrity of hardware, firmware, operating system, and executable code within the network infrastructure
	The system shall encrypt all data, both stored within the system and transported across the system
	The system shall use encryption based on Advanced Encryption Standard (AES, RIPS-PUB-197) with state of the art keys
	The system shall support IETF RFC 3748 for carrying secure authentication messages
	The system shall provide information immediately when needed
	The system should protect against malware, viruses and threats
	The system should have redundant infrastructure to support high security systems
Maintainability	The system shall support real-time monitoring of all network resources
	The system shall have mechanisms to ensure data is accurate, authentic, timely and complete (data integrity for system maintainability)
	The system shall provide for efficient use of system resources, especially the E-UTRAN
	The system shall support activation and provisioning of mobile devices Over the Air (OTA)
	The system shall support continuous monitoring of itself in order detect and report failures to infrastructure and links
	The system shall support continuous monitoring of itself in order optimize resource utilization, invoke dynamic policies, and correct errors
	The system shall support monitoring and reporting of: Cell Site ID, Call Type, Calling / Called Parties, Call Time / Duration, Calling / Called Party Location
	The system shall be capable of storing historical and statistical information for all logs for a minimum of 60 months
	The system should publish APIs that allow 3rd parties to provide maintenance functions
Scalability	The system shall support high speed data service (up to 10Gbps) for mobile devices
	The system shall support a minimum of 10Mbps data service for mobile devices
	The system shall support a minimum of two different access systems (LTE and WiFi)
	The system should support carrier aggregation functions thus allowing a single device to simultaneously connect to multiple access systems either within or between operational entities
	The system shall support identification and addressing schemes that support a huge number of mobile devices (~ 6-10 mobile devices per

	individual subscriber)
	The system shall support scalability on multiple dimensions to account for differing deployment models, application requirements (storage, compute), and performance and reliability characteristics.
	The system shall be aware of the acceptable delay for particular application/sensor communications and schedule resources to guarantee performance.
	The system shall support optimization of media streams consistent with constrained resources
	The system shall support large scale deployments in the order of million endpoints over a large area of 'x' square miles.
	The system shall incur low communication overhead
	The system will allow for automation using software or devices, allowing new classes of services
Quality / Reliability	The system shall support Service Level Agreements (SLAs) related to mobility, handoff, and connectivity
	The system shall have mechanism to recover from intermittent packet loss quickly via packet retransmission or it must report a message failure to the application
	The system shall support Quality of Service enforcement across the entire system based on the constraints in the radio air link and mobile backhaul network
	The system shall support all nine QoS Class Identifiers defined by 3GPP
	The system shall be capable of enforcing all nine QoS Class Identifiers on any operational entity or access system thus providing imperceptibly similar subscriber experiences independent of point of attachment.
	The system shall support path selection and access network selection based on static profiles. The path selection and access network selection functions shall support any operational entity or access system.
	The system shall support path selection and access network selection based on network conditions
	The system should use redundant facilities and paths, within a single operational entity and access system, within a single operational entity and between access systems, and between operational entities and access systems, attained cost-effectively, to achieve SLAs
	The system should provide APIs for monitoring of all SLAs related to mobility, handoff, and connectivity

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