Foreword

by David Chambers – Wireless Industry Analyst and founder of ThinkSmallCell

As the number of mobile connections overtakes our global population, we rely more than ever on our smartphones, tablets and other wireless devices as part of our daily life. Radio access networks in large cities and commercial areas are already feeling the strain, driving operators to find new ways to enhance coverage, capacity, and the quality of the mobile experience.

Heterogeneous networks (HetNets) evolve and expand the traditional approach by complementing existing macrocells with a layer of small cells using both 3G and LTE technology supplemented by carrier Wi-Fi. Sophisticated techniques are needed to manage the complexity and achieve high quality of service while maximizing efficient use of available spectrum.

The business case is strong — HetNets enhance the customer experience, improve retention, slash cost, and unlock new revenues — but adopting this new model is rife with challenge. Orchestrating a seamless service using multiple equipment vendors, introducing new features, software upgrades and configuration parameters all involve some risk.

Small Cells, Big Challenge takes an in-depth look at how operators can leverage the power of HetNets while minimizing the risk of the unknown. Inside, the wireless experts at Ixia explore HetNet market drivers and growth forecasts, business and technology benefits, deployment challenges. They provide a step-by-step approach of how to validate design and performance in the lab, both before and after deployment.
Why Read This Book?

The following chapters help fast-track and maximize the value of HetNet initiatives by exploring:

- How HetNets boost coverage, capacity, and quality
- HetNet market dynamics and growth forecasts
- Challenges to deploying HetNets
- Evolving best practices for validating and optimizing HetNet performance in the lab and in the field
- Detailed procedures for validating HetNets technologies and designs in the lab

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TABLE OF CONTENTS

CHAPTER 1
HetNets Improve Performance and Profitability .......................................................... 12
  1.1 What is a HetNet? .................................................................................................. 13
  1.2 How HetNets Improve Performance ..................................................................... 14
     1.2.1 Better Use of Spectrum ............................................................................... 14
     1.2.2 Improving Capacity, Service Quality in Urban Areas ..................................... 15
     1.2.3 Improving In-building Coverage / Coping with BYOD ............................... 17
     1.2.4 The Other “Growth” Factor: Rising Expectations for Quality ........................ 18

CHAPTER 2
HetNet Market Drivers: Rising to the Challenge of 1000x Growth .......................... 20
  2.1 HetNet Benefits to Mobile Operators ................................................................. 21
     2.1.1 Increased Revenues from Existing Services .................................................. 22
     2.1.2 Fast-tracking Delivery of Compelling New Services ................................. 22
     2.1.2.1 Managed Services on the Rise ................................................................. 23
     2.1.2.2 Targeted Offerings to Vertical Industries ............................................... 24
     2.1.2.3 Profitable Expansion to Rural Areas ......................................................... 24
     2.1.3 Increased Revenue per Customer .................................................................. 25
     2.1.4 Dual Capex and Opex Reductions ................................................................. 27
     2.1.5 Last but Not Least: A More Strategic Role in the Enterprise ....................... 28
  2.2 HetNet Benefits to the Enterprise: Higher Productivity at Reduced Cost .......... 28
     2.2.1 Capex and Opex Reduced ............................................................................. 29
     2.2.2 Increased Bargaining Leverage ..................................................................... 29
     2.2.3 Tighter Control / Security ......................................................................... 30
     2.3 How Soon Will We Get There? ......................................................................... 30

CHAPTER 3
HetNet Deployment Plans on the Rise ....................................................................... 32
  3.1 Total Units Deployed .......................................................................................... 33
  3.2 4G Deployments ................................................................................................ 33
  3.3 Outdoor Deployments ......................................................................................... 33
  3.4 Enterprise Deployments ..................................................................................... 34

CHAPTER 4
HetNet Technology ..................................................................................................... 36
  4.1 Overview ............................................................................................................. 36
CHAPTER 5
Small Cell Technology ........................................................................................................... 41
5.1 Radios and Base Stations ................................................................................................. 41
5.1.1 Femtocells, picocells and microcells ........................................................................... 41
5.1.2 Femtocells .................................................................................................................... 42
5.1.3 Picocells ......................................................................................................................... 43
5.1.4 Microcells ....................................................................................................................... 45
5.1.5 Distributed Antenna System (DAS) ......................................................................... 45
5.1.6 Cloud RAN and Remote Radio Heads ....................................................................... 46
5.1.7 Carrier Wi-Fi ................................................................................................................. 47
5.2 Self-Organizing Networks ............................................................................................... 50
5.2.1 Self-configuration ....................................................................................................... 51
5.2.2 Self-optimization ....................................................................................................... 52
5.2.3 Self-healing ................................................................................................................... 54
5.3 Interference Compensation ............................................................................................. 55
5.4 Mobility ............................................................................................................................ 61
5.5 Backhaul ............................................................................................................................ 63
5.5.1 Millimeter wave: 60, 70-80 GHz ................................................................................. 66
5.5.2 Microwave: 6-60 GHz ................................................................................................. 66
5.5.3 Sub-6 GHz licensed bands ........................................................................................ 67
5.5.4 Sub-6 GHz unlicensed bands ..................................................................................... 67
5.5.5 Satellite ......................................................................................................................... 67
5.5.6 Television white space ............................................................................................... 68
5.5.7 Timing Considerations ............................................................................................... 68
5.5.8 The Role of Carrier Ethernet in Mobile Backhaul ...................................................... 70
5.6 Subscriber Quality of Experience .................................................................................. 72
5.6.1 Using QoS and Policy Management to Limit Congestion and Enhance Service Quality .......................................................................................................................... 73
5.6.2 3GPP’s Vision for QoS/Policy Management in LTE ................................................ 75
5.6.3 Service Data Flows ...................................................................................................... 78
5.7 Security ............................................................................................................................. 78

CHAPTER 6
Small Cell Deployment Challenges ...................................................................................... 80
6.1 Design Considerations .................................................................................................... 80
6.2 Physical Placement ......................................................................................................... 81
6.3 Installation ........................................................................................................................ 81
6.4 Operations ........................................................................................................................ 82
6.5 Interoperability ............................................................................................................... 83
CHAPTER 7
Validating HetNets .......................................................... 86
7.1 Risks of Insufficient Validation ............................................. 86
7.2 Challenges to Validating HetNets ........................................... 87
7.3 Critical Test Capabilities ..................................................... 88
7.3.1 Emulation ........................................................................ 88
7.3.2 Realism ........................................................................... 88
7.3.2.1 Subscriber Modeling .................................................... 89
7.3.2.1 Specific Deployments .................................................. 90
7.3.3 Flexibility ....................................................................... 91
7.3.4 Scalability ...................................................................... 91
7.3.5 QoS / Service Validation .................................................. 91
7.3.6 Actionable Metrics ........................................................... 92
7.3.7 Replication of Field Issues .............................................. 93
7.3.8 Experience ..................................................................... 93
7.4 Scope of Testing .................................................................. 94

CHAPTER 8
Validating Heterogeneous Networks – Test Cases ......................... 96
8.1 Testing SON Features ......................................................... 97
8.1.1 Interference: eICIC features .............................................. 97
8.1.2 Automatic Neighbor Relations (ANR) ................................ 99
8.1.3 Mobility Load Balancing – Initiated by DUT ...................... 102
8.1.4 Mobility Load Balancing – Initiated by Simulated eNodeBs ... 105
8.1.5 Robustness Optimization .................................................. 107
8.1.6 RACH Optimization – UE report based optimizations .......... 109
8.1.8 PCI selection .................................................................. 111
8.2 Testing Network Performance ............................................... 113
8.2.1 Home eNodeB (HeNB) Gateway Performance .................. 114
8.2.2 Home eNodeB (HeNB) Gateway as MME Proxy Performance .... 116
8.2.3 Security Gateway Performance ......................................... 118
8.2.4 HeNB Security under Attack ............................................ 120
8.3 Testing Wi-Fi Performance ................................................... 122
8.3.1 Wi-Fi Offload Gateway Performance ............................... 122
8.3.2 Wi-Fi ANDSF Server Performance ................................... 124
8.3.3 Wi-Fi Hotspot 2.0 Performance ......................................... 126
8.3.4 Wi-Fi Maximum Client Capacity ....................................... 128
8.3.5 Wi-Fi Mixed Mode Throughput ......................................... 130
8.3.6 Wi-Fi Triple-Play Throughput ............................................ 132
8.4 Validating Backhaul Performance ......................................... 134
Preface

Mobile Access at a Crossroads

We’re hooked on mobility and there’s no going back. Mobile broadband connections are growing at a faster rate than the Earth’s population, with industry experts predicting 1000x growth in traffic volumes by the end of 2020.¹

Not surprisingly, the world’s mobile network infrastructures are quickly being maxed out. While the surging demand for connectivity certainly makes for opportunity, mobile operators also face unprecedented risk.

Subscriber expectations for quality and reliability continue to rise, and operators must consistently deliver compelling new services and pricing plans based on performance. Doing so means increasing network coverage and capacity exponentially — in record time and with limited resources.

The world’s leading mobile operators have already invested heavily in building bigger, faster 4G infrastructures, embarking on more than 350 deployments in 100+ countries. LTE is delivering quantum gains as expected, but that’s not enough to pace demand. To compete profitably into the future, operators must deviate from the traditional playbooks that have worked so well for so long, beginning with a fundamental shift in network access infrastructures.

Mobile networking is at a crossroads: traditional macrocell build-outs no longer scale profitably to accommodate growth. Operators must find new, more cost-effective ways to improve coverage, capacity, and quality while reducing cost.

One emerging strategy is to evolve toward more diversified or heterogeneous access networks –called “HetNets”—that help operators bridge the cost / capacity gap, meet landmark demand, and compete profitably into the future.

¹ Enhance Mobile Networks to Deliver 1000 Times More Capacity by 2020. ©2013 Nokia Solutions and Networks
The Growing Role of HetNets

Coverage and capacity requirements are literally going through the roof as applications grow more challenging and the “bring your own device” trend proliferates. The capacity crunch is felt most keenly in crowded metro areas and commercial buildings where usage is high and penetration from outdoor macrocells is often poor.

Heterogeneous networks push network access closer to the customer. Small cells (femtocells, picocells, metrocells) and Wi-Fi access points (APs) are used to offload traffic from traditional base stations, along with alternative topologies such as Distributed Antenna Systems (DAS). By bolstering quality within buildings, along highways, and on busy streets, HetNets improve satisfaction, enabling new business models to emerge.

Through improved coverage and quality, HetNets deliver diverse benefits to mobile operators and enterprises:

- Increased productivity and user satisfaction
- Dramatic savings of both capital and operating expenses
- Higher revenues
- Ongoing competitive advantages

A Market Poised for Growth

HetNets will play a vital role in accommodating data growth and improving the economics of service delivery:

- Small cells are expected to carry nearly half of all mobile network data traffic by 2016, and, in conjunction with Wi-Fi, to offload more than 200 exabytes of data per year by 2017.²
- By 2017, ARCchart forecasts annual shipments of more than 5 million small cells representing a $40 billion market.³
- By 2018, analysts say some 11 million small cells will be in use (roughly a 5x growth versus 2013), with massive growth occurring in non-residential sectors.
- By 2020, SNS Research predicts HetNets will account for more than $350 billion in mobile data service revenues.⁴

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³  HetNet Market Summary & Forecasts: Macro Cells, Small Cells & Wi-Fi Offload, ARCchart, 2012
⁴  Signals and Systems Market Intelligence and Consultancy Solutions, The HetNet Bible (Small Cells and Carrier WiFi) – Opportunities, Challenges, Strategies and Forecasts: 2013 – 2020 © 2013 SNS Research
Operators and enterprises alike are already ramping up deployments accordingly. The Small Cell Forum recently reported that more than 55 operators worldwide are already leveraging small cells. The trend will only continue, but it won’t be without challenge.

A New Approach is Needed

Dotting high-traffic coverage areas with smaller, lower-cost access nodes sounds simple in theory. In reality, HetNets represent a major evolution of the current model:

- The sheer number and proximity of devices creates new challenges for mobility management, interference management, and backhaul.
- Mobile networks using small cells require intelligence and self-organizing network (SON) capabilities that must be understood and optimized.
- Small cells increasingly integrate Wi-Fi, 3G, and LTE technologies, requiring greater coordination and expertise to deploy and manage.

But like any quantum shift in network architecture, adoption of full-blown HetNets won’t be without its challenges. While making the shift, operators must embrace the unknown, keeping their sights fixed on the end-goal of delivering higher quality of experience (QoE). They must carefully examine and validate decisions every step of the way, from site acquisition and planning to device selection and configuration.

However, the old approach to validating deployments—drive tests and detailed radio planning—doesn’t address the new complexities inherent in HetNets. To bridge the gap and accelerate the benefits, new validation strategies are emerging that reduce risk by adding realism, automation, and flexibility.
Benefits and Obstacles to Deploying HetNets

As we'll see in Chapters 1 and 2, HetNets deliver a powerful mix of practical and economic advantages:

- **Spectrum reuse**
- **Better coverage and capacity** in urban areas and within buildings
- **Fast-tracking compelling new services** while growing revenues from existing offerings
- **Extensive capex/opex savings** from reduced equipment, power, management, and backhaul costs
- **Increased retention** and better relationships with enterprise customers
- **Regulatory approvals accelerated**: Small cells radiate at a much lower temperature, often requiring no regulatory approval

We'll explore the inevitable technological questions in detail in Chapter 4—managing interference between devices, ensuring mobility, maintaining security, and the like. From a business perspective, the most formidable challenges are:

- **Embracing the unknown**: HetNets involve lots of moving pieces, often from multiple vendors, and major changes in deployment and management dynamics:
  - With so many more cells being deployed, manual planning and optimization must give way to SON, which is still new and unproven with much to be learned. Algorithms and settings need to be validated prior to deployment.
  - Intelligence and functionality shift from trusted operator facilities to street lamps, roadsides, and customer premises creating issues with management, control, and security.
  - New and diverse expertise will also be needed as cellular and Wi-Fi technology become increasingly integrated.
- **Urgency**: To meet near- and long-term demand, mobile operators and enterprises alike must fast-track planning, site acquisition, network design, and the inevitable learning curve.
Small Cells, Big Challenge

- **Taking control of performance validation.** HetNets represent a whole new world, with many competing and unproven approaches in play. The old approach to validating access network deployments – drive tests and detailed radio planning – won’t scale down from the macro to the micro world. Instead, operators must thoroughly model designs and devices in the lab by:
  - Evaluating new devices and services in the context of live networks
  - Replicating the complexities and variables of wireless networks
  - City-scale testing under simulated peak conditions
  - Evaluating SON, mobility handoffs, and interference management
  - Measuring QoE in the face of interference, mobility, outages, heavy traffic loads, and other variables
  - Modeling subscriber usage profiles – business, enterprise, etc.
  - QoS / service validation of policies and the end-to-end performance achievable across the network
  - Replication of field issues

With so much at stake, relying on vendor performance data, drive tests and other traditional approaches to validating large macro cell deployments is no longer an option. A new, more exhaustive and realistic approach to modeling real-world scenarios in the lab is essential.

The strategies and methodologies provided in this book go a long way toward demystifying and optimizing HetNet deployments. Let’s begin with a more in-depth overview of how diversifying network access improves the quality of services in high-profile areas, and the bottom line benefits of rolling out HetNets.
Chapter 1
HetNets Improve Performance and Profitability
Mobile operators face a daunting challenge: improving the scope and quality of their services in the face of explosive growth. With a 1000-fold spike in mobile traffic unfolding, operators must amp up coverage and capacity at warp speed in order to grab their fair share—and avoid losing core revenues to the competition.

Mobile access networks continue to feel the strain as more and more subscribers use more and more devices to run challenging applications such as video, messaging, and unified communications (UC). Nor can today’s boundless demand for connectivity be met by simply over-provisioning.

Spectrum remains limited, and traditional models for building out access networks won’t scale economically, or quickly enough to meet demand. Massive investments in faster, higher-capacity 4G infrastructures notwithstanding, the quest for more flexible, intelligent, and economical approaches to network access ranks high on providers’ priority lists.

Evolution to heterogeneous networks or “HetNets” has moved to the forefront, enabling a new, more cost-effective model for increasing coverage and capacity. Ideally suited to densely populated areas and buildings where usage and expectations for performance are highest, HetNets play a pivotal role in raising performance and profitability into the future.
1.1 What is a HetNet?

At a high level, HetNets represent a strategic evolution of the mobile access network in which operators augment macrocell capacity in step with demand. HetNets push the network closer to the customer, locating lower-cost, lower-power access nodes indoors and out, on lampposts, roadsides, and within corporate buildings.

**Small cells**, radio access nodes with a range of ten to several hundred meters, **Wi-Fi access points**, and other techniques are used to bolster coverage and capacity and in turn call quality. Femtocells, picocells, and microcells are all considered “small,” along with emerging “metrocells” used outdoors to expand capacity to users across relatively short distances. Emerging Cloud Radio Access Network (C-RAN) architectures also introduce cost-efficiencies by concentrating processing at regional data centers.

To facilitate HetNet deployments, infrastructure vendors are integrating 3G, LTE, and Wi-Fi interfaces within small cells. Industry and standards groups like the Small Cell Forum and 3rd Generation Partnership Project (3GPP) are also working to overcome deployment hurdles, and maximize the promise of HetNets.

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1 “Small Cells: What’s the Big Idea,” Small Cell Forum, Document 030.01.01
1.2 How HetNets Improve Performance

In Chapter 2, we’ll take a closer look at how HetNets improve the profitability of both mobile operators and enterprises customers. The diverse economic benefits stem in large part from improved service enabled by technological innovations and improved logistics.

1.2.1 Better Use of Spectrum

Small cells, placed within the area covered by macrocells, reuse the same spectrum over a smaller area. Each small cell can in theory offer the same bandwidth as the macrocell, multiplying the use of the available spectrum many times over.

Packing more devices into a given area and allowing spectrum to be reused expands network capacity exponentially. LTE is already allowing operators to use new and wider spectrum, but radio link improvement is fast approaching theoretical limit. HetNets promise another quantum leap in wireless spectrum efficiency.

Over time, HetNets will also promote increased use of higher spectrum traditionally considered unsuitable for cellular networks due to short range. RCR Wireless believes, “Ultimately, the almost 200 megahertz of spectrum at 2.6 GHz in the Americas and the 100 megahertz at 2.3 GHz in Asia will be much more valuable for small cells in HetNets than the sub-1 GHz spectrum.”2 An Infonetics Research survey indicates the use of the 2.3GHz - 2.7 GHz bands may reach nearly 20% by 2015, up from 8% in 2013.

![Figure 1-2 - Potential rise of LTE small cells deployed in newly allocated high frequency bands](image)

(A pure directional statistic of averages of percentages with no weighting to actual volume of usage in each band per respondent)

3 Infonetics Research, Small Cell Coverage Strategies: Global Service Provider Survey, October 1, 2013.
Chapter 1: HetNets Improve Performance and Profitability

Small Cells, Big Challenge

LTE Advanced (LTE-A), an enhancement of the LTE standard driven by the 3GPP, aims to maximize the spectrum efficiency gains possible with HetNets. LTE-A improves utilization in both licensed and unlicensed spectrum, adds carrier aggregation, and introduces enhanced inter-cell resource and interference coordination (eICIC) into the network.

1.2.2 Improving Capacity, Service Quality in Urban Areas

As smartphones and tablets abound, the growing capacity crunch is felt most in urban areas where nearly 60% of all mobile traffic is generated by just 30% of users. Building out macrocell networks proves particularly cost-prohibitive in large cities where many cells are needed and other costs—site acquisition, power, management—are much higher over time.

HetNets offer a compelling alternative for scaling network access in metro regions. Lower-powered devices do not entail the same permits and upfront deployment costs as macrocells, so they can be used effectively to shore up coverage and capacity where—and as—needed.

High numbers of small cells and access points can be strategically placed within high-traffic lobbies, malls, airports, sports complexes and the like to deliver powerful capacity gains:

- Offloading as much as 80% of data during peak usage times.\textsuperscript{4}
- Tripling network capacity using 3 multi-standard small cells combining 3G, LTE, and carrier Wi-Fi per macrocell.\textsuperscript{5}
- Increasing overall capacity 80 to 130%.\textsuperscript{6}

\textsuperscript{4} Wiki article http://en.wikipedia.org/wiki/Small_cell
\textsuperscript{5} http://www2.alcatel-lucent.com/techzine/why-carrier-wi-fi-and-metro-cells-are-better-together/

\textsuperscript{Public access small cells in busy urban areas are set to be one of the defining mobile network trends in the coming years. They are arguably [operators’] best tool for bringing massive extra capacity to mobile networks.}

– Dimitris Mavrakis, Principal Analyst, Informa Telecoms and Media
The use of small cells also helps overcome regulatory roadblocks. Many countries have rules in place to limit wireless radiation. Small cells emit much less, reducing or eliminating the need to wait for approvals that might otherwise take years to obtain.
1.2.3 Improving In-building Coverage / Coping with BYOD

Growing pains are also keenly felt indoors, where up to 80% of mobile traffic is now generated. A survey conducted by YouGov found 40-60% of offices suffered poor in-building coverage, with many businesses inclined to switch service providers if better in-building coverage was assured.

The task is far from simple. The increasing number of users participating in the “bring your own device” trend makes usage, and in turn in-building capacity requirements, harder to predict and manage. Security risks also mount as employees and guests introduce unauthorized devices.

The challenge may be compounded by poor indoor penetration by outdoor macrocells. Intensity may be further diminished by certain energy efficiency efforts used at lower frequencies in 2G/3G, and in LTE deployed at higher frequencies.

HetNets that bring cellular capabilities indoors provide a cost-efficient option for bolstering in-building coverage and capacity. Operators and business users both stand to benefit from delivering a better user experience, better voice quality, higher data rates, and differentiated services enabled by small cells—VoLTE, UC, managed PBX services, and the like.

![Figure 1-4 - Number of Buildings Potentially Equipped with Small Cells to 2020 (G7 countries)](image)

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8 DAS and Small Cell Solutions Deployment Trends That Impact Your Business, HetNet Forum and Bisci
9 YouGov international survey of IT decision makers in the US, Germany, Spain and Britain, February 2013 http://www.spidercloud.com/yougov
10 The Business Case for Enterprise Small Cells, Real Wireless, November 2013, Version 3.11
In an in-depth analysis of the business case for small cell adoption within the enterprise, Real Wireless estimates 9.7 million buildings in G7 countries could benefit from the deployment of small cells comprising an addressable market of 3.1 million commercial buildings by 2020. This number could include as many as 1.5 million enterprise premises in the US alone.

### 1.2.4 The Other “Growth” Factor: Rising Expectations for Quality

Subscribers continue to raise the bar for performance as mobile usage skyrockets, expecting a higher-quality experience everywhere, every time, and from every device. While dropped calls and poor voice quality remain a perennial cause of churn, slow downloads and choppy video will increasingly drive users to switch providers as well.

Though harder to quantify than traffic volumes, subscribers’ rising expectations for quality fuel the case for HetNets. Increased deployment of small cells and Wi-Fi hotspots arm operators and enterprises to guarantee a smooth mobile experience to employees, customers, and guests alike, mitigating the growing risk to retention, revenues, and reputation.

It’s here that economics come into play, so let’s look at the business case.

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11 Assumes an average of one enterprise building for every 60 people, and that 80% of enterprises are engaged in activities that are likely to benefit from small cell deployment.
Chapter 2
HetNet Market Drivers: Rising to the Challenge of 1000x Growth
CHAPTER 2
HetNet Market Drivers: Rising to the Challenge of 1000x Growth

At the heart of all the flux and change is growth the likes of which few industries have ever seen. This unprecedented surge in wireless broadband traffic will largely ensue from smartphones and video-based applications.

In a recent update of its Visual Networking Index (VNI),1 Cisco projects that by 2017:

- Smartphones will represent nearly 70% of total mobile data traffic compared to 44% in 2012
- Nearly 70% of all mobile data traffic will be video, up from 51% in 2012

According to SNS Research, the annual throughput of mobile data traffic will increase from 58 Exabytes in 2013 to nearly 335 Exabytes in 2020, a CAGR of 28% between 2013 and 2020.

Figure 2-1 - Annual Global Throughput of Mobile Network Data Traffic by Region: 2010 – 2020 (Exabytes)²

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2 SNS Research, The HetNet Bible (Small Cells and Carrier WiFi) – Opportunities, Challenges, Strategies and Forecasts: 2013 – 2020
HetNets stand to vastly improve the economic models in play at both mobile operators and enterprises. Many already rely on Wi-Fi to support business-critical services and offload traffic from overtaxed networks. Wi-Fi will continue to play a key role as HetNet strategies evolve, but it’s not enough.

Expanded use of microcell base stations and the increased integration of cellular, Wi-Fi, DAS, and other technologies is vital both in maintaining the status quo, and making new, more profitable business models a reality. With resources limited and time of the essence, HetNets address the diverse and rapidly changing business goals of both operators and enterprises.

### 2.1 HetNet Benefits to Mobile Operators

For operators, opportunity exists to increase revenues from existing services while rolling out differentiated multimedia offerings. Guaranteed coverage and mobility will continue to lure traffic off traditional networks, enabling premium pricing while reducing the perennial churn arising from poor quality. Massive savings and more strategic relationships with customers also come into play.

<table>
<thead>
<tr>
<th>Additional Revenues</th>
<th>Cost savings from offload</th>
<th>Churn</th>
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<tbody>
<tr>
<td>Voice Services: outgoing increased usage = more expensive bundle (see data)</td>
<td>RAN and Backhaul cost savings Appropriate costs On a per minute and per MG basis Subtract core transport costs</td>
<td>Lower Churn Take business churn rate Reduction in churn = increase in lifetime Calculate revenue impact</td>
</tr>
<tr>
<td>Voice Services: incoming Calling party pays: termination charges Receiving party pays: higher bundle charges</td>
<td></td>
<td>Lower retention costs Take difference between:</td>
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<tr>
<td>Data Services Increased usage = more expensive bundles</td>
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<td>- Average retention costs - Cost of small cells (the offer to retain customers)</td>
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<tr>
<td>Enhanced Services Hosted PBX Location, compliance or other VAS Uptake phased over 5 years</td>
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*Figure 2-2 - Sources of Operator Benefits from Enterprise Small Cells*

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2.1.1 Increased Revenues from Existing Services

Most HetNet discussions cite the growth of traffic from smartphones and bandwidth-intensive applications like video, unified communications (UC), and rich communications services (RCS) as major drivers. HetNets also prove vital to sustaining the quality—and increasing the value — of traditional services:

- **Voice traffic** continues to migrate from wired networks and traditional desktop handsets to mobile phones, making small cell infrastructures highly valuable within the enterprise. Where voice-over-Wi-Fi may lack the necessary quality assurances, adding cellular technology within buildings improves performance and flexibility while reducing service and equipment costs.

- **Targeted mobile data services** may also benefit as cell technology moves indoors. Next-generation 802.11ac-based Wi-Fi networks will deliver expanded capacity, but may not inherently guarantee the quality mandated by compliance and security policies in industries such as finance and healthcare.

- **Tablets.** Once Wi-Fi only, Cisco predicts 34% of all tablets will be cellular-connected by 2017, adding to the data burden but allowing operators to charge added fees for using multiple devices. Migration to cellular-enabled tablets also helps prompt customers to upgrade to data plans based on higher usage.

- **Large Public Venues (LPVs).** Increasing capacity and the ability to control usage within stadiums, conference centers, and other large public venues stands to generate new revenues for operators and facility managers. To this end, existing DAS techniques used to boost coverage inside LPVs will become increasingly integrated with small cells and Wi-Fi technology.

The BYOD trend will continue to fuel usage and more enterprises will adopt a “mobile first” philosophy, moving more voice and data calls off landlines onto mobile networks. All of this will give rise to higher-priced but more compelling bundled-service plans.

2.1.2 Fast-tracking Delivery of Compelling New Services

As voice and data continue migrating to wireless networks, enterprises and consumers alike will be more inclined to pay a premium for higher data usage, ubiquitous coverage, seamless mobility, and guaranteed quality. But long-term, the greatest benefit of HetNets may be increased support for differentiated services enabled by better coverage and QoS:

- **VoLTE**
- **Videoconferencing and unified communications (UC)**
- **Increased access to cloud-based services**
- **International roaming**
- **Hosted PBX services**
Small Cells, Big Challenge

- Value-added location services
- Compliance services and analytics
- High-capacity hot-zones suited to gaming and video streaming

2.1.2.1 Managed Services on the Rise

Along with more flexible and attractive service bundles, small cell deployments within the enterprise enable mutually rewarding managed services. SpiderCloud Wireless, provider of small cell Enterprise Radio Access Network (E-RAN) systems to mobile operators, recently engaged Exact Ventures to analyze the managed mobility services market.

Among enterprises of 100 to 4999 employees, findings indicate enterprise mobility services will grow to a $100 billion market by 2020 for operators while saving enterprises 35% a year.

Figure 2-3 - Enterprise Mobility Services Cumulative Revenue, Cost Savings

4 Exact Ventures, “Enterprise Mobility Services: Market Opportunity for Mobile Service Providers,” January 2013
2.1.2.2 Targeted Offerings to Vertical Industries

Small cells and the increased integration of cellular and Wi-Fi technology also facilitate targeted offerings meeting the needs of specific industry sectors:

- **Finance companies** required to record voice and data communications to maintain compliance

- **Retailers** leveraging location-aware services to track customers and push targeted promotions as they move through stores

- **Hospitals** seeking to expand real-time mobile patient care, improve entertainment, or track assets and employees

- **Warehouses** and other environments ill-suited to radio-based communications

2.1.2.3 Profitable Expansion to Rural Areas

While urban areas will be their major focus initially, operators can also leverage HetNets to profitably service rural areas that would not otherwise be viable to serve. Small cells can also be used instead of repeaters to cost-effectively extend coverage to select remote sites and hotspots, enabling higher use and premium pricing. At the same time, improving coverage in rural areas serves to protect traditional voice revenues from being lost to bundled offerings from satellite or cable providers.
2.1.3 Increased Revenue per Customer

The intensive modeling conducted by Real Wireless explored the business case for small cell deployments including the long-term impact on average revenue per user (ARPU) and customer lifetime value (CLV) realized by operators. Looking at small cell’s ability both to increase revenue from existing services and enable new ones, the study explored a half-dozen use cases among enterprises in different regions and industries.

In nearly all cases, the net benefits to operators were substantial with high ROI, dramatic increases in CLV, and payback realized within the first year. Assuming the cases related in the study are representative of typical customers in each segment, findings indicate massive opportunity to increase revenues:

- In large enterprises, projected CLV increased 230% for basic services and nearly 310% if enhanced services were offered. This constitutes a ROI of roughly 2300% to the operator and 135% to the user.

- In medium-sized companies, CLV stood to increase 200% for basic services and 330% for enhanced offerings, an ROI of 1000% for operators.

- In small businesses, the prospective CLV increased nearly 160% for basic services and 290% for enhanced for an ROI of 400% for operators.

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Real Wireless defines CLV as the, “net present value of the benefits minus the costs over the lifetime of the customer,” or the value of the current and future net benefits from the small cell system.
Overall, the study concludes mobile operators deploying HetNets can achieve payback quickly and continue to profit well into the future. Real Wireless expects a 10% increase in ARPU, calling the estimate, “a relatively conservative assumption in the face of a 40% increase in voice calls.”

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6 Real Wireless
2.1.4 Dual Capex and Opex Reductions

While launching new services, operators must find aggressive new ways to reduce the cost of delivering them. HetNets play a key role in bridging the cost/capacity gap, delivering dramatic savings throughout the deployment life-cycle.

Along with more controlled growth, HetNets:

- **Reduce equipment costs**: Where macrocells cost $30,000 on average depending on the configuration, small cells average $5,000 to $10,000.

- **Lower site acquisition costs** though more sites will need to be negotiated and surveyed.

- **Reduce opex**. Along with vastly reducing power consumption, Huawei Technologies estimates the SON capabilities inherent in micro base stations can reduce manpower cost by up to 30%.7

- **Consolidating cellular and Wi-Fi**. Alcatel-Lucent claims 3G and LTE metro cells can reduce cost per bit by half versus equivalent macro cell technology, while integrating Wi-Fi slashes another 75%.8

- **Backhaul**. Small cells, especially femtocells located in residences, can make use of existing Internet connectivity, reducing the need for dedicated backhaul lines.

- **“Offloading” costs to the enterprise**. Additional, ongoing savings may ensue from new service models in which enterprises assume a greater percentage of the costs associated with deploying and managing small cell networks. For example, enterprise cellular deployments may leverage the company’s own backhaul and power resources.

While the fine points of who controls which aspects of the network—access, security, regulatory compliance—would need to be negotiated and fine-tuned, a flexible win-win model may emerge.

- **Reduced retention cost**: Real Wireless estimates that churn may fall by as much as 15% as voice and data service quality improves through the use of small cells. The implication is that, instead of discounting services and equipment upgrades as they do now, operators may be able to improve retention by offering value-added services based on small cells (hosted PBX, location, compliance, analytics, and the like).

- **Emerging Small Cells as a Service (SCaaS) models** in which providers deploy a network of small cells and market usage to multiple operators stands to further improve the economics of supporting large numbers of sites.

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“Going forward, amidst skyrocketing data traffic, [operators] will invest a larger proportion of their RAN spend on LTE small cells, which will yield significant savings on capex in addition to increased capacity.”

—Ying Kang Tan, ABI Research
2.1.5  Last but Not Least: A More Strategic Role in the Enterprise

Mobile operators have long strived to raise their profile with enterprise IT and justify higher fees by adding value. Real Wireless believes achieving that goal can more than double ARPU for enterprise customers versus consumers while significantly lowering churn rates.

The changes enabled by HetNets can make it happen. Carrier technology and expertise stands to increase in value as the mobile network becomes more tightly integrated with traditional PBX-based infrastructures, and plays a greater role in critical business functions. Operators can evolve from “minutes” providers who deal with the telecom manager to impactful strategic partners of IT.

Enterprises may need to relinquish some control over the corporate network and assume a greater percentage of equipment and opex costs, but they’ll be working more closely with providers and have a greater say in deployment strategies and service level agreements (SLAs). In the end, HetNets can—and must—deliver a powerful “win-win” for operators and enterprises.

Let’s look briefly at the other side of the equation: the enterprise.

2.2  HetNet Benefits to the Enterprise: Higher Productivity at Reduced Cost

Within the enterprise, the main benefits of small cells and increased cellular / Wi-Fi integration stems from the ability to do more and do it better. With the reliable, enhanced services enabled by small cells, businesses can improve customer relations, operational efficiency, and their competitive edge.

Employees increasingly use smartphones for voice, video, messaging, and UC within corporate facilities, making improved coverage and QoE more valuable. Better voice coverage and quality will be primary drivers of small cell adoption early on, but the bottom line will benefit in other ways long term.
2.2.1 Capex and Opex Reduced

Early picocell deployments within corporate buildings did not deliver compelling savings, but today’s enterprise small cells dramatically improve the business case. For one thing, subscribing to new carrier offerings based on small cells allows decreased spending on PBX systems and desktop phone systems.

Exact Ventures believes managed offerings including mobility, UC, telephony, device management, and location-based services could save enterprises more than $160 billion in capital expenditure.\(^9\) This equates to $264 per user per year, or a 35% savings versus the corresponding capital investment.

Over time, the migration of traffic away from traditional infrastructures further decreases opex from landlines and services. Within five years of implementing small cell networks, enterprises may net savings as high as:

- $16 per month per user through reduced spending on PBX hardware and ongoing costs
- $8 per month per user from reduced spending on desktop phone hardware\(^10\)

2.2.2 Increased Bargaining Leverage

Larger enterprises also stand to benefit from an increased ability to negotiate more flexible deals with operators for multinational roaming and the like. Those assuming a larger share, or the entire cost of deployment, may even require operators to bid for management of the network. And in shared or multi-tenant environments, small cell networks may reduce costs by enabling those managing facilities to negotiate deals with operators for hosting.

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\(^10\) Ibid.

“The benefits from increased use of voice and data is enough to outweigh the small cell costs that fall to the enterprise – even if the local management costs are significant.”

—Real Wireless
2.2.3 Tighter Control / Security

With BYOD, IT departments may lose control of which networks employees are on, and in turn visibility into the costs they accrue. Small cell deployments allow greater control over voice costs and mobile usage.

A mobile indoor network controlled at least in part by IT enables businesses to tighten security and better analyze traffic and device usage in order to manage fees. Different classes of users can be granted varying access rights and the risks associated with virtualization reduced.

2.3 How Soon Will We Get There?

Enabling higher-quality, more flexibility, and reduced investment, HetNets may well unlock the future of mobile communications. It’s no surprise, therefore, that deployments are set to soar.
Chapter 3
HetNet Deployment Plans on the Rise
CHAPTER 3
HetNet Deployment Plans on the Rise

Informa Telecoms & Media reported that by early 2013 nearly 11 million small cells had already been deployed in residential, enterprise, and public facilities with the largest initiatives exceeding 1 million units. By 2017, ARCchart foresees annual unit shipments of:

- 1.4 million macrocells
- 5 million small cells
- 11.5 million Wi-Fi access points

Nine of the top ten mobile operators worldwide have begun deploying small cells. AT&T’s trial of public access small cells reportedly delivered nearly perfect coverage in challenging metropolitan areas, and plans to roll out some 40,000 units by the end of 2015 are ongoing.

Verizon and Vodafone UK have also announced near-term deployment plans with the latter including tri-mode 3G/4G/Wi-Fi units. Infonetics expects this trend to continue as the percentage of mobile data carried by 4G networks rises. The firm projects more than half (53%) of all outdoor small cell deployments will feature triple-mode 3G/LTE/Wi-Fi technology by 2017.

Figure 3-1 - Annual Global Throughput of Mobile Network Data Traffic by Access Network Type

![Figure 3-1](image)

3 Infonetics Research, Small Cell Coverage Strategies: Global Service Provider Survey, October 1, 2013
DS and traditional macrocells will continue to enjoy steady growth, but small cells and carrier Wi-Fi will grow much faster, accommodating more than 60% of mobile network traffic worldwide by 2020.\textsuperscript{5} Spending and deployment projections are set to soar across the board.

## 3.1 Total Units Deployed

Informa projects growth from 3.2 million units in 2012 to 62.4 million by 2016 — a 2000% or 20x increase — and that small cells will account for nearly 90% of all base stations worldwide.\textsuperscript{6} Between 2012 and 2016, the firm predicts:

- Femtocells will continue to dominate, growing 24X from 2.5 million in 2012 to 59 million in 2016
- Enterprise and public area picocells will grow 4x from 140K to 540K
- Microcells, metrocells, and other public access small cells deployed primarily outdoors will grow 5x from 595K to 2.9 million

## 3.2 4G Deployments

Carrier spending on small cells and Wi-Fi technology is expected to accelerate as 4G networks build out. According to Mobile Experts, more than two-thirds of all small cells deployed will target LTE-FDD or LTE-TDD by 2017.\textsuperscript{7}

## 3.3 Outdoor Deployments

The portion of traffic offloaded onto outdoor small cells is projected to grow the fastest as operators increasingly leverage HetNets to alleviate the capacity crunch in urban areas. The number could rise from 3% in 2013 to 11% in 2015 with the number of cells deployed outdoors quadrupling by 2017.\textsuperscript{8}

As a result, Infonetics projects the number of outdoor small cells deployed per macrocell to more than double by 2017. ABI Research concurs, forecasting 125% year-on-year growth of units shipped in roughly the same timeframe for a $3.6 billion market.\textsuperscript{9}

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\textsuperscript{5} Ibid.
\textsuperscript{6} http://www.smallcellforum.org/newsstory-small-cells-to-make-up-almost-90-percent-of-all-base-stations-by-2016
\textsuperscript{7} Informa Telecoms & Media, “Small Cell Market Status,” February 2013
\textsuperscript{8} CNET, “The carriers’ not-so-secret weapon to improve cell service,” Roger Cheng, June 9, 2013
\textsuperscript{9} http://www.rcrwireless.com/article/20130722/wireless/hetnet-news-abi-sees-small-cell-market-rebound/
3.4 Enterprise Deployments

Real Wireless speculates that if enterprise small cells were to be adopted at a similar rate, nearly 350,000 companies worldwide might employ them by the end of 2014, and as many as 4.3 million by 2020.

![Figure 3-2 - Number of Enterprises Potentially Adopting Small Cells 2014 to 2020](image)

The business case for HetNets is strong and the future bright. Before taking an in-depth look at the challenges operators face in delivering and profiting from initiatives, let’s take a more in-depth look at what HetNets are, and how they work.

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10 Real Wireless
Chapter 4
HetNet Technology
4.1 Overview

HetNets utilize a combination of devices and technologies that work together to enable wireless voice and broadband access. Voice communication is the key revenue generator, with digital data transmission as a high second factor.

Radio links have improved over the years, but several factors limit their expanded use. Among them are a scarcity of spectrum, poor in-building coverage, high site acquisition and construction costs, long regulatory approval cycles, and per-antenna power limitations. As consumption continues to grow operators are looking for new strategies to address the challenge of better quality of experience (QoE). Several types of devices are being deployed to satisfy both needs, including small cells. Small cells are independent antenna plus base station devices that service customers in a smaller geographic area that is smaller than that serviced by macrocells. Figure 4-1 demonstrates some of the types and uses of small cells.

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1. “Small Cells: What’s the Big Idea,” Small Cell Forum, Document 030.01.01
Small cells support a range of wireless technologies, including GSM, CDMA2000, UMTS/HSPA, LTE, LTE Advanced, and Wi-Fi standards. Although there is no specifications for these devices, the generally accepted definitions are:

- **Small cells**: a general term for low-powered radio access nodes using both licensed and unlicensed spectrum. They have a range that varies between 10 meters to several hundreds of meters, as opposed to the tens of kilometers served by macrocells. Devices included in this category are femtocells, picocells, microcells and metrocells.

- **Femtocells**: a low-power, self-contained antenna and base station. Femtocells were initially intended for home use, but are also used in businesses, and in rural and metropolitan areas. They use existing Internet connections for backhaul, self-optimization, and ease of installation.

- **Picocells**: a low-power, compact base station intended for businesses and public indoor areas, although they are sometimes used in outdoor settings as well. They often use the same self-optimizing techniques found in femtocells.

- **Microcells**: an outdoor, short-range base station used where macrocell coverage is insufficient. They are intended for increased coverage both indoors and outdoors and they are used occasionally as more powerful picocells.

- **Metrocells**: small cells used outdoors to enhance macrocell coverage in high density areas. Metrocells are commonly mounted on buildings, lampposts, and other utility poles.

- **Carrier Wi-Fi**: Wi-Fi networks operated by wireless carriers or their partners. They serve to offload data traffic from macrocells.

The characteristics of non-Wi-Fi small cells are described in Table 4-1.

<table>
<thead>
<tr>
<th>Power</th>
<th>Macro</th>
<th>Micro</th>
<th>Metro/Pico</th>
<th>Femto</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>40-60W</td>
<td>10-20W</td>
<td>1-10W</td>
<td>&lt; 1W</td>
</tr>
<tr>
<td>UEs</td>
<td>1000s</td>
<td>&gt;256</td>
<td>64-256</td>
<td>15-32</td>
</tr>
<tr>
<td>Deployed by</td>
<td>Operator</td>
<td>Operator</td>
<td>Operator</td>
<td>Consumer</td>
</tr>
<tr>
<td>Managed by</td>
<td>Operator</td>
<td>Operator</td>
<td>Consumer</td>
<td></td>
</tr>
</tbody>
</table>

*Table 4-1 - Small Cell Characteristics*

The overlap of usage of these devices is demonstrated in Figure 4-2.
Small Cells are usually operated by carriers, but fixed line ISPs are beginning to place small cells on their networks which they offer as a service to one or more carriers.

In addition to small cells that include base station functionality, there are two antenna-based techniques that are used to increase coverage in specific areas: distributed antenna systems (DASs) and remote radio heads (RRHs). Distributed antenna systems utilize macrocell-level base stations in conjunction with antennas distributed across a specific area. Each antenna services a smaller geographic area with better capacity and signal strength than would be possible with a single, larger antenna.

RRHs use the same distribution of antennas across an area, but forward signals to a cloud-based radio access network (Cloud RAN) so as to concentrate base station and other wireless processing at a central point.

There are a number of different uses for small cells:

- **Home**: the original intended use for femtocells. Femtocells provide a short range, self-configuring base station that is connected to the wireless core network through the home’s Internet connection. Dedicated systems-on-a-chip have been developed to lower the cost of these high-volume devices. Extensive software development, both in the femtocell and OA&M systems, have made them easy to deploy and configure.

- **Enterprise**: picocells and microcells, with more RF power and coverage, are generally used in enterprises. Multiple units can be deployed for more coverage. Backhaul to the core network may use existing Internet connections or dedicated connections.

- **High-rise building**: require multiple small cells to operate correctly, as walls and floors block signals, although on the positive side they also tend to reduce interference between offices and floors. Picocells and RRHs are frequently used, with or without concentration at local base stations located in the building.

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2 “Small Cells: What’s the Big Idea,” Small Cell Forum, Document 030.01.01
3 Operation, administration and management.
Small Cells, Big Challenge

- **Urban areas**: designed for high traffic areas. Microcells and macrocells used in this environment are designed to support a larger number of users than found in home or enterprise environments.

- **City streets**: including outdoor hotspots such as bus stops and indoor areas such as cafes. Depending on macrocell coverage, picocells and/or Wi-Fi hotspots can be used to satisfy demand.

- **Airports**: along with shopping malls and railway stations, demand can be very high, with a great deal of user mobility. DAS and RRH technologies are often used in these circumstances. Wi-Fi hot spots are used to augment this coverage in areas where passengers spend extended periods.

- **Rural areas**: designed to satisfy the needs of remote areas, where macrocells are too distant to provide good service or not economically justified. A small cell appropriate to the number of users is deployed.

A host of infrastructure elements support the small cell environment. Backhaul, the transport of data to and from base stations, is one critical element. In order to meet the objective of broadband service for everyone, it is essential that the network that connects small cells to the Internet be ready to handle the traffic. A variety of technologies, old and new, are being used for this purpose.

In addition, specialized gateways are required to connect small cells to the core network. These gateways are often shared across multiple small cells, especially femtocells. The core wireless must also be upgraded to handle additional traffic.
Chapter 5
Small Cell Technology
CHAPTER 5
Small Cell Technology

5.1 Radios and Base Stations

5.1.1 Femtocells, picocells and microcells

These small cells provide enhanced mobile broadband service in a number of ways:

- Small cells serve smaller areas closer to end-users. This provides better, higher quality connections with higher bandwidth and lower latency.

- Small cells allow the available spectrum to be reused many times over, albeit with concern over interference from macrocells and other small cells. The peak throughput of picocells and microcells is the same as that of the macrocells, since they both use the same radio bandwidth.

- Small cells can provide coverage in areas that are poorly serviced by macrocells due to building placement, distance, and interference. This is especially useful at the edge of a macrocell’s covered area, where service is degraded. Small cells can even extend the coverage area of a macrocell.

- Small cells, along with Wi-Fi networks, improve macrocell service by offloading traffic. Remaining end-user devices that are not serviced by the small cell get better macrocell service.

Small cells differ in their power, ability to handle geographic areas, and numbers of users, as shown in Table 5-1.

<table>
<thead>
<tr>
<th></th>
<th>Output Power</th>
<th>Cell Radius</th>
<th>Number of Users</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Femtocells</td>
<td>1mW – 250mW</td>
<td>10m – 100m</td>
<td>1 - 30</td>
<td>Indoor</td>
</tr>
<tr>
<td>Picocells</td>
<td>250mW – 1W</td>
<td>100m – 200m</td>
<td>30 - 100</td>
<td>Indoor</td>
</tr>
<tr>
<td>Microcells</td>
<td>1W – 10W</td>
<td>200m – 2km</td>
<td>100 - 2000</td>
<td>Indoor/outdoor</td>
</tr>
<tr>
<td>Macrocells</td>
<td>10W – 50+W</td>
<td>8km – 30km</td>
<td>2000+</td>
<td>Outdoor</td>
</tr>
</tbody>
</table>

Table 5-1 - Comparison of Cellular Coverage

The number of small cells deployed per macrocell is expected to increase dramatically in the next few years. According to Infonetics Research¹, the number of outdoor small cells per macrocell in dense urban areas is expected to increase from 24 in 2013, to 53 in 2015 and to 160 in 2017. As of 2013, most small cells used 3G and earlier technologies, with only a few operators deploying 4G/LTE.

Figure 5-1 shows how small cell, DAS, and RRH technologies serve to overlap with macrocell coverage.

---

Small Cells, Big Challenge

5.1.2 Femtocells

Femtocells typically cover a cell radius of 10 to 100 meters. Femtocells, when used in residences, are also known as home NodeBs or HNBs for 3G technology, and as home eNodeBs or HeNBs for LTE technologies. We will use the HNB or HeNB term to refer to both.

Millions of femtocells are deployed to homes each year. They are physically the same size as a home router, and may even be combined with one. Berg Insight\(^2\) estimates that more than 70 million femtocells will be in use by the end of 2014. Femtocells use their customers’ Internet connection for backhaul, consume low power, and are almost always installed by the end customer.

Initially designed to support a small number of simultaneous users, modern units can support up to 30 users. With this increased capacity, they have found usage in business and public locations. Once installed, the HNB owner is may be required to build a whitelist of handset phone numbers that the HNB will allow. This whitelist is called the Closed Subscriber Group (CSG).

Figure 5-2 shows the infrastructure associated with femtocells, macrocells, and picocells. On the left, the smartphone represents one of the possible pieces of user equipment, or UE. Other equipment in that category include tablets and some laptops. Smartphones, tablets and laptops also operate using Wi-Fi offload, which are discussed later in this chapter.

At the top, we have the radio access network, which includes macrocells and some metrocells and microcells. The eNodeB includes both the antenna and the radio controller that were separate entities in pre-LTE technologies. eNodeBs communicate to the evolved packet core, or EPC, with the mobility management entity, or MME, and the serving gateway, or SGW. The MME manages UE mobility between cells, while the SGW takes care of data transmission and reception.

In the center box is the home eNodeB system, or HeNB. The femtocell is a miniature eNodeB. The other components in this box are actually inside the operator’s core network, but they are critical to femtocell processing. A number of femtocells are backhauled to a security gateway, or SeGW, for encryption/decryption and other security measures. Data traffic

\(^2\) www.berginsite.com
is forwarded to the HeNB Gateway, or HeNB-GW, which uses standard cellular protocols to interface with the serving gateway in the EPC. The security gateway and the femtocell receive configuration information from the HeNB Management System, or HMS).

The lower box is quite interesting, representing the thoughts and recommendations of the Small Cell Forum, and are discussed in the next section.

**Figure 5-2 - HNBs and Related Infrastructure**

### 5.1.3 Picocells

Picocells typically support up to 100 users with a cell radius of 100 to 200 meters. Picocells have similar functionality to femtocells, but with higher power output, longer reach, and support for more users. They are generally used in enterprises and in public indoor areas. Multiple picocells can be used to cover larger enterprises, especially when used in multiple floors of a high-rise building, shopping malls, train stations, and airports.

Multiple picocells connect to picocell eNodeBs that are physically the size of a large book. Connections between the antennas and the base station use on premise Ethernet. The eNodeB performs radio resource management and handover functions, and aggregates data to be passed to the evolved packet core (EPC) and/or the gateway GPRS support node (GGSN).
Small Cells, Big Challenge

Some vendors package a picocell antenna with an eNodeB and partial EPC functionality to behave as an “enterprise femtocell.”

Two new management devices have been recommended by the Small Call Forum in order to aggregate multiple picocells in an enterprise and to provide direct access to PBXs, intranets, and Internet. The elements are the enterprise small cell concentrator (ESCC) and enterprise small cell gateway (ESCG). The enterprise small cell network (E-SCN) encompasses one or more copies of these devices plus the picocell access points distributed in an enterprise.

![Figure 5-3: Enterprise Small Cell Framework](image3)

The ESCC aggregates the signaling associated with multiple access points and provides one stream to the mobile network core. Mobility events between the enterprise’s access points are locally handled. In order to provide this function, the ESCC uses a single IPsec session to the mobile core, as shown in Figure 5-4. A virtual access point (VAP) is established, which can be maintained by management systems. The ESCC may provide IPsec tunneling.

![Figure 5-4 - Enterprise Small Cell Concentrator](image4)

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3 “Enterprise small cell network architectures,” Small Cell Forum document number 067.02.01.
4 Ibid.
The ESCG may provide direct access to the enterprise’s intranet for a range of IP addresses (LIPA – Local IP Access) and to the Intranet by an alternate connection to the small cell’s backhaul. The ESCG may also provide access to the enterprise’s land lines via its PBX.

Access to the public Internet via the enterprise’s Internet connection offloads the mobile core network.

5.1.4 Microcells

Microcells typically support up to 2000 users with a cell radius of 200 meters to 2 kilometers. Microcells are used in small outdoor areas to improve coverage where macrocell coverage is insufficient. They employ short-range transmitters with integral low-power cellular base stations. They can also be found indoors where picocells lack sufficient coverage.

Microcells cover a limited area, such as a shopping mall, hotel, or transportation hub. A microcell is usually larger than a picocell, though the distinction is not always clear. A microcell uses power control to limit the radius of its coverage area.

5.1.5 Distributed Antenna System (DAS)

A distributed antenna system, or DAS, is a set of separated antenna nodes connected to a common base station via a transport medium, usually fiber connections. DASs provide wireless service within a geographic area or structure. The concept behind a DAS is shown in Figure 5-5. Multiple, lower power antennas (B) are used to replace a single high power antenna (A), covering the same area with less power and greater quality. Less power is used to penetrate buildings and cover shadow areas because line-of-sight between the UE and antenna is more frequently available.

Figure 5-5 - DAS Concept

5 Wikipedia article on Distributed Antenna Systems.
DAS is used to provide wireless coverage and capacity to high concentrations of users. For example, DAS can often be found in office buildings, convention centers, airports, train stations, stadiums, campuses, and plazas. They can also be found along streets to provide city and rural coverage. Extensive planning is needed to correctly place DAS antennas so as to maximize coverage and minimize interference. DAS can also be combined with carrier Wi-Fi to provide additional data bandwidth.

DAS antennas may be connected to their base stations using passive RF connections, active connections augmented by repeaters, or digitized over fiber optic cables.

The downside to DAS deployments is that a thick RF cable is needed to connect all of the antennas. Other approaches, wherein RF signaling is processed by the small cell, only require attachment to existing Ethernet infrastructures.

### 5.1.6 Cloud RAN and Remote Radio Heads

Cloud RAN (C-RAN) centralizes the processing of RAN segments of a mobile network in one or more cloud-based data centers. Multiple remote radio heads (RRHs) can be placed much as in DAS, but without the need to connect to a local base station. Instead, RRHs connect to RAN servers in the cloud. Connections from the RRHs to the cloud can occur over existing lines or use dedicated high capacity fiber links. With current technology, 15 cell sites seem to be an optimal number per C-RAN processing element.

The C-RAN architecture is described in Figure 5-6. Sector remote radio heads are placed throughout a contiguous geographic area. The common public radio interface (CPRI) protocol is used over fiber optic links to a cloud facility where a load balancer connects the RRHs to elements of a pool of baseband unit (BBU) processors. These use the S1 and X2 protocols to forward traffic to the EPC and coordinate handoffs to other cells, respectively.

![Figure 5-6 - C-RAN Architecture](image-url)
A cloud RAN can do a better job of coordinating handoffs with local processing obviating the need for X2 signaling. The same concentration of BBU processing allows significantly better cooperative multipoint processing (CoMP) wherein multiple cells are used to send and receive data to and from a UE to ensure the optimum performance is achieved even at cell edges.

Separating baseband processing from the antenna can also result in a more compact macrocell that is easier and cheaper to install. With some extension to the C-RAN concept, processing for small cells may be incorporated — ensuring better interference, handoff and SON handling.

A cloud RAN can be used to provision greater data capacity, since the radio units can be densely populated. A significant downside to C-RAN is the need for high capacity links to the data center. One sector of a 20MHz LTE 2x2 cell connecting over a fiber optic link requires 2.5Gbps. Both China and Korea have had successful deployments of cloud RANs.

5.1.7 Carrier Wi-Fi

Carrier Wi-Fi consists of Wi-Fi services owned or leased by wireless carriers. Carriers offer this service to their customers in order to offload packet data from their wireless network, as shown in Figure 5-7. Carrier Wi-Fi is often found in conjunction with small cell deployments, sometimes in the same device.

An important distinction between RANs and Wi-Fi is that RANs utilize licensed spectrum, which may only be used by the licensee in a geographic area. Licensed spectrum makes it possible for carriers to guarantee levels of service. Wi-Fi, on the other hand, operates in an unlicensed band. As we all know, there can be significant interference between Wi-Fi access points located near to each other that share Wi-Fi channels.

![Figure 5-7- Carrier Wi-Fi Offload](image-url)

Carrier Wi-Fi deployments are most often found in indoor locations where people congregate for a reasonable length of time. Such deployments must integrate with the carrier’s
networks. That function and others is performed by the Wi-Fi Offload Gateway. It performs several important functions:

- **Authentication**: clients are authenticated locally with the access point, or remotely with different carriers’ services. There are several basic authentication options:
  - **Open access**: users manually configure their devices to work with the carrier’s Wi-Fi network.
  - **SIM-based authentication**: the Wi-Fi access point interacts with the carrier’s network to deliver SIM-based authentication that transparently connects the UE to the network.
  - **Fully integrated**: Wi-Fi is a fully integrated part of the carrier’s RAN, transparently offloading data to Wi-Fi when it is available.
- **Charging**: where appropriate, usage is charged against the client’s account. Quality of service (QoS) tags may also be applied to client traffic to match their service level.
- **IP persistence**: an advanced feature that allows the user to retain the same IP address during transitions from the cellular to Wi-Fi network and back again.

Several technologies and standards are being developed to aid in transparent Wi-Fi offload:

- **Hotspot 2.0**: enables seamless and secure authentication to Wi-Fi hotspots. Any of a number of security standards, including IEEE 802.11u, WPA2-Enterprise, and EAP can be used.
- **IEEE 802.11u**: this protocol allows Wi-Fi access points to broadcast additional information to prospective UEs. This includes available authentication mechanisms, terms of use, and any carrier or roaming partner affiliation. 802.11u-enabled UEs can use this information to automatically choose the particular network that they wish to connect to.
- **WPA2-Enterprise**: a standard for encryption and mutual authentication of the UE and the carrier’s security gateway. This ensures that all communication is private and that the UE is connected to the desired network.
- **OMA DM 1.2**: a device management feature that allows Wi-Fi policy to be downloaded to UEs, along with wireless carrier policies. This causes the UE to favor carrier-supported Wi-Fi networks.
- **ANDSF**: a 3GPP technology standard that allows mobile users to discover non-3GPP networks such as Wi-Fi and to seamlessly switch between them.
- **NextGen Hotspot (NGH) Program**: a program established by the Wireless Broadband Alliance that focuses on transparent interoperability between Wi-Fi networks. NGH works in conjunction with Hotspot 2.0, extending the local authentication between the UE and access point into the carrier’s backend where it can be treated in the same manner as a regular cellular mobile connection.
Carrier Wi-Fi handover may occur at the same time as cellular handover, or asynchronously. Carriers maintain or lease Wi-Fi networks for their smartphone and tablet subscribers in order to offload macrocell data traffic much as in the same manner as small cells. Carrier Wi-Fi customers may encounter issues that leave them without adequate Wi-Fi service:

- **Reaching:** Wi-Fi devices generally switch over to a Wi-Fi access point when it is in range. This might be premature, before the access point offers them superior performance. It can also unnecessarily overload the access point. Figure 5-8 shows how this might happen. As the smartphone travels farther and farther away from the macrocell, it receives deceasing data rates. At the point where it sees the Wi-Fi at acceptable levels it switches to Wi-Fi despite the fact that the 3GPP antenna is providing better service.

- **Unhealthy choice:** the Wi-Fi device will switch over to an access point even though a macro or small cell is less loaded and can provide better service.

- **Dribbling:** although a Wi-Fi access point provides a better connection than cellular connections, its backhaul connection may limit it more than the cellular network can provide.

- **Ping pong:** a Wi-Fi device may experience a ping pong effect with respect to Wi-Fi hotspots, quickly moving between hot spots and macrocell coverage.

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Integration is required to ensure that Wi-Fi access points and cells exchange key performance indicators (KPIs), so that they can avoid these problems. Where a small cell is packaged with a Wi-Fi access point, this information is readily available.

Otherwise, alternative solutions need to be explored. The iWLAN specification, which includes the access network discovery and selection function (ANDSF), and the Hotspot 2.0 policy specification specifically address some of these issues. Both of these will be discussed in the next section on device management with self-organizing networks (SON).

5.2 Self-Organizing Networks

Historically, macrocell placement, configuration, and maintenance have been difficult, technical tasks that demand trained wireless engineers and required significant amount of time and planning. As the number of macrocells, small cells, and carrier Wi-Fi access points grows, the sheer number of devices makes manual operation impossible. A carrier may need to support 100,000 small cells and thousands of macrocells operating a combination of at least three mobile network technologies (2G, 3G, and LTE). What’s more, femtocells are customer-installed and may appear without notice.

Self-organizing network techniques are still very much theoretical, with only a few basic implementations to date. Major network equipment manufacturers are developing their own approaches, making it difficult for operators to choose which to deploy.

Release 8 of the 3GPP specification detailed the types of SON activities and a number of use cases. Broadly, they are organized into four categories:

- **Planning**: covering the planning of new eNB locations, hardware configuration, initial radio and transport parameters, network integration, and eNB procurement.
- **Deployment**: covering hardware installation, eNB network authentication, software installation, radio and transport setup, and testing.
- **Optimization**: a closed loop process of configuration, performance measurement, optimization, and reconfiguration. Optimization can be motivated by prioritized considerations for capacity, coverage, and performance.
- **Maintenance**: covering hardware upgrade, repair, and replacement, software upgrade, network monitoring, and failure recovery.

Concentrating on activities that can be programmed or automated, SON activities can be divided into three areas, which will be discussed in the following sections.

- **Self-configuration**: aiming toward plug-n-play eNBs.
- **Self-optimization**: automatically providing the best capacity, coverage, and/or performance.
- **Self-healing**: dealing with device and network failure and recovery.
SON algorithms may be implemented in three ways:

- **Centralized**: all decisions are made in a central office system, with configuration parameters distributed to all devices.

- **Distributed**: configuration and optimization decisions are made by the eNBs, access points, and other network devices. High-level policies may still be created at the central office and distributed to the devices.

- **Hybrid**: a combination of both techniques, with many devices – especially femtocells – making their own configuration decisions, and the central office dictating overall operational parameters.

### 5.2.1 Self-configuration

With the large number of devices expected to be deployed, it is important that all network devices be self-configuring to some extent. Residential femtocells are a prime example; they are being installed and self-configured by the millions every year.

New eNBs must quickly and automatically connect to their domain management system. Five steps are involved:

- **Basic connectivity**: the base station needs an initial IP configuration, such as that supplied by DHCP, in order to connect to its domain management system.

- **Initial secure connection**: a temporary, secure connection, such as that available with IPsec or TLS, must be established. An encryption key may be built into the base station. Once a secure connection is established, further data may be downloaded.

- **Site identification**: the site must identify itself.

- **Configuration download**: the domain management system can then download initial radio and transport configuration data.

- **Permanent secure connection**: the temporary secure connection is replaced with a permanent one using IPsec or TLS.

Although some radio transmission parameters may be pre-configured in the device or in a central location, the timeliest information should be gathered automatically onsite. A technique known as dynamic radio configuration (DRC) is used to adapt base stations to the current radio network topology. DRC can be used to configure such items as cell ID, initial power, and antenna tilt settings among other things.

Base stations and UEs must maintain a list of neighbor cell relationships in order to accomplish handover. In the past, this was maintained centrally and pushed to base stations. This approach could be error prone, out of date, and may not reflect outages quickly. In a process called automatic neighbor relation (ANR) management, every base station dynamically maintains a list of neighbors, along with their supported radio access technologies (RAT). UEs help to build this data by sending ENBs information for visible cells.
The SON automation and optimization of this process will result in fewer unsuccessful handovers, and reduce the network load from additional set-ups required by poor handovers. Finally, the eNB must conduct a self-test and self-inventory. The latter operation allows it to discover its own capabilities.

5.2.2 Self-optimization

Even though base stations are self-configuring, it is essential that they continuously reconfigure themselves to account for changes in the network. Such changes include:

- **Propagation**: changes in signal coverage due to new buildings being constructed or destroyed. Even temporary conditions, such as leaves in autumn, can have an effect.
- **Traffic patterns**: in addition to daily patterns, the usage community can change due to school and national holidays, vacations, new apartments, or viral videos.
- **Deployments**: the surrounding macrocell may change, or new eNBs may be installed or optimized.

Mobility robustness optimization is an important component of self-optimization. It ensures that there are a minimum of dropped calls during handover, the single most important component of user satisfaction. It also minimizes unnecessary handovers, such as ping-pongs, that may be due to improper handling of users at cell borders. Mobility management also deals with radio link failures, ensuring that there is adequate coverage and then quickly reestablishing the connection.

SON self-optimization can optimize cell boundaries by adjusting power and antenna tilt to limit ping-pong effects. Cell boundaries can be adjusted often to account for new cells and propagation changes. With increased measurements and statistical analysis, SON can better self-optimize handover. Handover is an excellent example of the value of distributed SON processing; decisions can be more quickly and more accurately than waiting for a central decision process.

Load balancing is related to mobility management discussed below. SON algorithms, coordinated across all overlapping cells, seek to move traffic from highly loaded cells to less loaded cells within the limits permitted by coverage and interference. Load balancing also attempts to move macrocell traffic to smaller cells, such as picocells and Wi-Fi, to make better use of macrocells. To minimize unnecessary handovers, moving UEs should not be handed off to small cells, since they would need to be handed over again very quickly.

Capacity and coverage optimization (CCO) is an aspect of SON that addresses optimization of capacity while maximizing coverage and ensuring that inter-cell interference is kept at a minimum. One of the parameters that can be adjusted is antenna tilt, as shown in Figure 5-9. By either mechanical or electrical means, the antenna can be tilted down or up to reduce interference or increase range. Transmitted power can also be adjusted, but it is important to not increase it by much. UEs will be able to receive data, but may not have enough power to reach the antenna to respond.
Random Access Channels (RACHs) are used to allow new connections between UEs and cells. An optimal RACH configuration can strongly impact system performance. One point of optimization is the number of allocated RACH slots. If this number is too small, the probability of a successful access is reduced by collisions. On the other hand, allocating too many RACH slots can be a waste of physical resources, as these slots cannot be used by other traffic. Therefore, selecting the optimal number of access slots is of strong importance to the system. The optimal number depends on the number of users and on the network configuration.

The UE starts its RACH transmission with a preamble. If there is no response, the UE again sends a preamble, this time with an increased power. The purpose of this procedure is to minimize interference by accessing the system with the minimum power. However, if the preamble rejection is not caused by a too-weak power, but is due to congestion, another preamble with a further increased power is transmitted.

Self-optimizing networks can reduce energy requirements in a number of ways:

- **Reduce active carriers**: where multiple carriers are used for high data throughput, some of them may be turned off during periods of inactivity.

- **Sleep mode**: some base stations are capable of going into sleep mode. For example, picocells in business locations might handle no traffic during non-business hours.

- **Local energy generation**: outdoor cells may be partially powered by solar cells during their peak day usage periods.
5.2.3 Self-healing

The self-healing aspects of SON deal with detecting and compensating for cell degradation or loss, as well as restoring normal operation when a cell has recovered. Base stations can self-monitor and repair certain faults. For example, they can restore an earlier version of software should a new download fail to operate properly. Hardware failures can sometimes be rectified when redundant hardware is available.

The key to self-healing is degradation detection. Key performance indicators (KPIs) such as power output and interference must be maintained by base stations for themselves and for nearby cells. KPIs for the entire network, including backhaul traffic, must likewise be available at the OA&M center for automatic or manual action triggering based on threshold parameters.

Once an outage is detected, the overall network should respond by assessing the degree of the degradation and compensating for the loss. Where a base station cannot self-repair, compensation must come from nearby cells. Nearby cells can use their self-optimization algorithms to establish new cell boundaries. COO antenna tilting can also be used to increase the range of a nearby cell.
5.3 Interference Compensation

In an ideal world, macrocells would be placed in an evenly spaced arrangement, as shown in Figure 5-10. The cells would fit together, providing complete coverage and necessary overlap for handoff.

The world isn’t so neat, however. Figure 5-11 shows a recent deployment of a 4G network in an urban environment. Macrocells are placed opportunistically on building roofs, along highways, and on cell towers which are available and allowed. Transmission sectors are tuned to minimize overlap between cells.

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Things become significantly more complex when we add small cells to the picture, as shown in Figure 5-12.

Figure 5-12 - Real-World Macro and Small Cell Placement (Courtesy Bennis/Saad)

It’s easy to see how many opportunities there are for cells to overlap and interfere with each other. A few specific cases will help to illustrate the problem. In these illustrations, the term Aggressor is used to indicate the cell that is interfering and Defender is used to indicate the cell that is being interfered with.

Figure 5-13 illustrates a case in which a UE receives a download (DL) from a macro base station (Defender). A nearby small cell (Aggressor), downloading to a nearby UE interferes with the communication.

Figure 5-13 - Small Cell / Macrocell Interference
Figure 5-14 shows the opposite case, wherein an upload (UL) from a UE to the small cell (Defender) is interfered with by the macrocell UE (Aggressor), which is transmitting to the far away macro base station with a strong signal.

Interference also occurs when the small cell is very close to the macrocell. In Figure 5-15 the small cell (Defender) is trying to download from its local small cell. This faces interference from the macrocell (Aggressor), which is trying to download to a faraway UE.

Similarly, an upload from multiple UEs (Aggressors) to their local small cell can interfere with a UE talking to its macrocell (Defender).
Small Cells, Big Challenge

Small cells can interfere with each other as well. Under the assumption that the macro base station is not uploading or downloading to its faraway UE, Figure 5-17 and Figure 5-18 show download and upload interference between small cells.

Figure 5-16 - Small Cell near Base Station – Upload

Figure 5-17 - Small Cell to Small Interference – Downlink

**Aggressor/Defender:** small cell/macrocell

**Aggressor/Defender:** small cell/small cell
Small cells and UEs can independently control their own operation through several techniques:

- **Adaptive pilot power control**: the small cell detects signals from nearby macrocells and small cells, dynamically adjusting its own transmit power while attempting to maintain its service area.

- **Dynamic receiver gain management**: phones dynamically limit their transmitted power to the minimum needed so as to conserve power and not interfere with nearby cells.

- **UE uplink power capping**: limiting UE power output ensures that the UE will hand off to the macro network before its transmitting power rises to the point where it interferes with the macro network.

Other techniques are used by carriers, some of which are unique to those carriers. The 3GPP release 8 standard for LTE defines techniques for inter-cell interference coordination (ICIC). ICIC is designed to address interference issues at the cell edge, dealing with user traffic channels only. It uses both power and frequency controls to mitigate cell-edge interference. ICIC information between cells is exchanged through X2 protocol messages through the backhaul channel. Three schemes were defined:

1. Resource blocks are LTE’s allocation units, defined by a combination of frequency and time. In the first scheme, resource blocks are allocated among neighboring cells so that no two cells use the blocks at the same time. This works well, but diminishes cell throughput for all involved cells.

2. The second scheme exhibits different behavior for UEs that are near to the cell antenna versus those near the edge. Centrally located UEs use all resource blocks, while those near the edge use scheme 1.
3. The third scheme adds power management to the equation. All neighbor cells use different power schemes for their UEs. Low power is used for near UEs and power boost is used for edge UEs, while sharing resource blocks.

3GPP release 10 for LTE Advanced addresses more HetNet issues with eICIC, mitigating both traffic and control traffic. Power, frequency, and time domain are all used to mitigate ICI. These include:

1. **Almost blank subframes**: Release 10 introduces the concept of the almost blank subframe (ABS), which can be configured by a macrocell to carry control channel frames with very low power. Small cells can then use the ABS to transmit data that will not interfere with macrocells’ transmissions. This is illustrated in Figure 5-19. The allocation of ABSs can be static or dynamic.

   ![Figure 5-19 - Use of Almost Blank Subframes](image)

2. **Cell range expansion (CRE)**: although a macrocell may be closer to a UE, it may make more sense for a UE to associate with a small cell because it is lightly loaded.

3. **Component carriers**: 3GPP release 10 also defines the use of up to five component carriers, which may be used individually or in combination. Assignment of particular component carriers to interfering cells can avoid interference.

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8  4g-lte-world.blogspot.com/2012/06/icic-and-eicic.html
5.4 Mobility

UEs are inherently mobile and can move between macro and small cells multiple times in a day. Handover is the technique by which UEs are passed between cells. Handover between macrocells is fairly well understand and managed, even when different 2G/3G/4G technologies are involved.

When small cells and Wi-Fi networks are added, things get more complex, since small cells and Wi-Fi networks are within macrocell coverage. A number of cases must be considered:

- **Inbound**: where the handover takes place from the macrocell to a small cell.
- **Outbound**: where the handover takes place from a small cell to a macrocell.
- **Small cell to small cell**: where the handover takes place between small cells.

Inbound and outbound handovers can suffer from several problems. In order for a handover to go smoothly the cell base stations must communicate well, but they may be located on different backhaul networks. Where small cells use different backhaul paths, small cell to small cell handovers may incur delays.

Small cells increase the number of handovers that must be performed. Since cellular performance is worst at cell edges, there is more opportunity for poor quality. Handoffs must be done at the correct time in order to maintain QoE, especially when users are highly mobile.

UEs and cell sites both participate in the decision to hand off the UE. When their policies do not match or when control signaling is delayed by disparate backhaul channels, UEs may drop off too late or too early or associate with the wrong cell. All of these occurrences will leave the UE without coverage or with conflicting coverage.

An interesting problem exists when a cellular user is moving in a vehicle between macro and small cells, as shown in Figure 5-20. Handovers are rapidly executed to accommodate the UE, resulting in excessive signaling that can create pauses that affect QoE.
Load balancing between macro and small cells is a very challenging issue. In order to achieve the best QoE for users, it may make more sense to associate a UE with its macrocell rather than a small cell that may be busy with other clients. The issue is not only related to wireless bandwidth, but also backhaul congestion. A small cell with lower available bandwidth may perform better than a macrocell by virtue of the higher bandwidth of its backhaul connection.

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5.5 Backhaul

Backhaul is the process of transmitting data from RANs to the wireless core network. This includes small cells, DAS, cloud RAN, and Wi-Fi connections.

Where multiple picocells are aggregated to a common base station, as in floors of a building, then backhaul requirements may stretch into multiple gigabits per second. Aggregation of outdoor small cells may occur along city streets, at one of the small cells, or at street mounted cabinets, and may require significant backhaul bandwidth.

The common rule of thumb today is for 1 Gbps backhaul from large macrocells and 100 Mbps from small cells for LTE readiness. Looking into the future, carriers will likely need 10 Gbps on rooftops and 1 Gbps on lampposts.10

The peak and loaded backhaul requirements for several different types of cellular technologies is shown in Table 5-2.

<table>
<thead>
<tr>
<th>Air Interface</th>
<th>Peak Rate (Mbps)</th>
<th>Average Rate (Mbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Downlink</td>
<td>Uplink</td>
</tr>
<tr>
<td>HSPA+ (64QAM)</td>
<td>16</td>
<td>6</td>
</tr>
<tr>
<td>HSPA+ (MIMO)</td>
<td>21.6</td>
<td>6</td>
</tr>
<tr>
<td>HSPA+ (DC, 64QAM)</td>
<td>32</td>
<td>6</td>
</tr>
<tr>
<td>2x5 MHz LTE</td>
<td>36.7</td>
<td>12.6</td>
</tr>
<tr>
<td>2x10 MHz LTE</td>
<td>73.4</td>
<td>25.5</td>
</tr>
<tr>
<td>2x20 MHz LTE</td>
<td>149.8</td>
<td>51</td>
</tr>
</tbody>
</table>

Table 5-2: Peak and Average Data Rates for HSPA and LTE Technologies

A number of transmission techniques are used in backhaul. In dense urban environments, existing copper and fiber connections can be used or expanded. Overall, microwave transmission accounts for 50% of all backhaul transmission11. Table 5-3 is an overview of the advantages and disadvantages of the wireless options. The following acronyms are used in the table and the ensuing discussion:

- LOS – line of sight
- NLOS – non-line of sight
- P2P – point to point
- PMP – point to multipoint
- TVWS – TV white space

10 “Backhaul Technologies for Small Cells,” Small Cell Forum, Document 049.01.01
11 Ericsson presentation at TIA 2012 conference.
<table>
<thead>
<tr>
<th>Backhaul Type</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>NLOS Licensed Band (&lt; 6 GHz)</td>
<td>• Simple to plan</td>
<td>• Lower reliability than LOS systems</td>
</tr>
<tr>
<td></td>
<td>• Easy to install</td>
<td>• Smaller channel bandwidth than LOS systems</td>
</tr>
<tr>
<td>NLOS Unlicensed Band (&lt; 6 GHz)</td>
<td>• Low equipment cost</td>
<td>• Unpredictable levels of interference</td>
</tr>
<tr>
<td></td>
<td>• No licensing cost</td>
<td>• Varying reliability and performance</td>
</tr>
<tr>
<td></td>
<td>• Immune from interference</td>
<td>• Limited range</td>
</tr>
<tr>
<td>PTP Microwave</td>
<td>• High capacity</td>
<td>• Limited LOS reach</td>
</tr>
<tr>
<td></td>
<td>• Low latency</td>
<td>• Longer planning cycle</td>
</tr>
<tr>
<td></td>
<td>• High availability</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Immune from interference</td>
<td></td>
</tr>
<tr>
<td>PMP Microwave</td>
<td>• Very low cost licensing</td>
<td>• Limited LOS reach</td>
</tr>
<tr>
<td></td>
<td>• Low configuration cost</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Low latency</td>
<td></td>
</tr>
<tr>
<td>60 GHz</td>
<td>• Gbps speeds</td>
<td>• Limited LOS reach</td>
</tr>
<tr>
<td></td>
<td>• Lightly licensed</td>
<td>• Longer planning cycle</td>
</tr>
<tr>
<td></td>
<td>• Immune from interference</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Low latency</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Small, inexpensive equipment</td>
<td></td>
</tr>
<tr>
<td>E-band (70/80 GHz)</td>
<td>• Gbps speeds</td>
<td>• Limited LOS reach</td>
</tr>
<tr>
<td></td>
<td>• Lightly licensed</td>
<td>• Longer planning cycle</td>
</tr>
<tr>
<td>Satellite</td>
<td>• Remote locations</td>
<td>• Cost</td>
</tr>
<tr>
<td></td>
<td>• Variable bandwidth per location</td>
<td>• Long planning cycle</td>
</tr>
<tr>
<td></td>
<td>• Variable bandwidth per location</td>
<td>• Higher jitter and latency</td>
</tr>
<tr>
<td>TVWS</td>
<td>• Non- or lightly licensed</td>
<td>• Susceptible to interference</td>
</tr>
<tr>
<td></td>
<td>• Good for rural backhaul</td>
<td>• New applications may interfere</td>
</tr>
<tr>
<td></td>
<td>• Excellent penetration and range</td>
<td></td>
</tr>
</tbody>
</table>

Table 5-3 - Advantages and Disadvantages of Wireless Backhaul Solutions
Small Cells, Big Challenge

Total bandwidth generally increases with frequency. Figure 5-21 illustrates the allocated bandwidth in the UK for the range of frequencies used for wireless backhaul.

![Figure 5-21 - Total Bandwidth Available for Wireless Backhaul Frequencies](image)

Wavelength plays an important part in whether NLOS connections can be used. As shown in Figure 5-22, the wavelength decreases as the frequency of transmission increases.

![Figure 5-22 - Wavelength as a Function of Frequency, Log-log Scale](image)

At lower frequencies wavelengths are longer than obstructions, allowing NLOS transmission that penetrates obstructions or diffracts around them. Carriers that operate below 6 GHz are generally useful for NLOS operation. Above 6 GHz, interference losses tend to be too high and only LOS connections are useful. Bandwidth requirements are increasing, while the distance between base stations is decreasing. In dense urban areas, the distance between macrocells can be 500m and small cells can be as close as 50m apart.

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5.5.1 Millimeter wave: 60, 70-80 GHz

Millimeter wave transmission is ideal for mobile backhaul, offering high throughput over short LOS reaches. Using a single channel for data transmission, these technologies are less complex and costly to deploy.

Under adverse atmospheric conditions, 60GHz microwaves can reach 1km and E-band can reach 3km. Relays can be used to overcome obstructions and to extend reach. Due to their narrow beamwidth antennas, they are not subject to interference. They are subject to only light licensing, or in some cases, no licensing restrictions. Globally, at least 5GHz is available in the 60GHz band without licensing costs.

The short wavelength translates into a smaller package. 60 GHz systems can be used for street to street connections, while E-band systems are perfect for rooftop installations. LOS installation, in general, requires careful planning to find applicable locations and ensure continued direct line-of-sight.

5.5.2 Microwave: 6-60 GHz

Microwave, from 6 to 60 GHz, is a mature technology that today accounts for 55% of backhaul traffic. As shown in Figure 5-21, a significant amount of bandwidth is allocated to microwave. Both point to point and point to multipoint usage are licensed, with the licensing authority allocating channels to avoid interference from other, nearby towers.

Microwave channels are usually multiples of 7 MHz in width; modern equipment can transmit using up to 56 MHz of adjacent channels and 112 MHz in some regions. Higher order modulation techniques\(^\text{13}\) are used to get higher efficiency. A variety of other techniques can be applied to boost throughput to multiple Gbps. Microwave systems are susceptible to rain fading, but they automatically reduce data rates to increase robustness.

Point to multipoint antennas broadcast to a wider sector, targeting multiple small cells. The bandwidth available to the microwave system is shared among the small cells. This arrangement takes advantage of the bursty nature of communications, wherein the bursts do not frequently coincide in time.

Depending on the frequency range used and the desired throughput, the reach of microwave backhaul is from 2 to 30 km for PTP connections. PMP connections are only slightly reduced, but the 30-42 GHz band is used for small cell support with a 2-4km reach. Being LOS technologies, careful planning is necessary for antenna placement. PMP deployments, in particular, can get tricky when having to “see” multiple small cells antennas.

Since the speed of microwaves through air is faster than fiber optics, latency is very low — on the order of 1ms round trip.

\(^\text{13}\) 256, 512 and 1024 QAM (Quadrature Amplitude Modulation)
5.5.3 Sub-6 GHz licensed bands

Despite the cost and government overhead, carriers prefer to use licensed spectrum because it allows them to guarantee class of service (CoS) and quality of service (QoS) and it avoids external interference. Due to the longer wavelengths below 6 GHz, signals can propagate in harsh NLOS environments, making these bands perfect for backhaul connectivity.

A great deal of technological development has gone into improving spectral efficiency in this band, borrowing techniques from Wi-Fi and 3G/4G. These include beam-forming, beam switching, network-wide synchronization, high order modulation techniques, MIMO\textsuperscript{14}, and highly directional antennas. Typical net TCP/IP bandwidth over a 20 MHz TDD channel today is 170 Mbps, with an expectation of 425 Mbps with additional improvements.

Both PTP and PMP connections are used, although most of the backhaul connections are PMP. Network-wide synchronization is necessary to maintain efficiency when using PMP connections. This results in an average latency of 5 – 12ms. Real-time scheduling is needed to maintain QoS for latency and delay sensitive services. Typical distances between points of presence (POP) vary from 1.5km in urban settings to 10km in rural settings.

5.5.4 Sub-6 GHz unlicensed bands

The same usage applies to unlicensed and licensed use of the sub-6 GHz bands. The difference is that carriers are able to work within certain bands that are designated to not require a license or are lightly licensed. This saves both time and money for the operator.

Although radiated power is normally controlled, wider bands of 40 MHz and up can be used. There is additional freedom in the technology of choice for use of the band. In fact, Wi-Fi MAC and PHY devices have been used. They typically have a range of about 250m.

The challenge is to minimize interference from adjacent channels and co-channels. This can be achieved by tuning equipment to avoid other sources. Because the use is unmanaged, this is an ongoing concern.

5.5.5 Satellite

Satellite backhaul can be universally used and rapidly deployed. The costs for satellite bandwidth, however, limit their economic viability. It is particularly useful in remote locations, where quick deployment is needed, for mobile applications such as on airplanes, ships, and “cells-on-wheels.”

Any reasonable capacity can be provided, from a few kbps to 350 Mbps. The operational cost is proportional to the capacity desired. Typical capacities for rural voice-only services in developing countries are 1 Mbps outbound and 512 Kbps inbound. Voice and data services in developed countries might be 10 Mbps outbound and 2 Mbps inbound.

\textsuperscript{14} Multiple-in, multiple-out use of multiple antennas to multiply bandwidth.
Small Cells, Big Challenge

Jitter is higher than in terrestrial backhaul: 5-25ms on an outbound link and 10-50ms on an inbound link. Latency is high as well, due mostly to the speed of light component between the ground and satellite: 275-310ms.

5.5.6 Television white space

This unlicensed frequency band is in the sub-1 GHz space and includes bands that were vacated when television went digital. They are especially good for small cell backhaul in rural locations. Channel width varies between 6 and 8 MHz, depending on the country. Although unlicensed, governments have prepared geolocation databases to indicate where TVWS is available, while regulations restrict power emission.

TVWS channels offer better propagation in terms of range and through and around obstacles than Wi-Fi and cellular bands. A customized version of Wi-Fi 802.11n technology can be used for backhaul with multiple small cells. TVWS backhaul can operate over distances of up to 5000m with throughput of up to 10 Mbps for a single channel or 40 Mbps for four channel aggregation.

Latency is on the order of 10ms, typical for 802.11-based networks.

5.5.7 Timing Considerations

An important component of HetNets maintains timing synchronization between UEs, eNodeBs and other cellular elements. It is critical that all these devices remain synchronized to support basic call connection, handover, and interference compensation. Depending on the technology and the environment, one, two, or all three synchronizations may be necessary:

- Frequency
- Phase alignment
- Time of day

The required synchronization accuracy also varies. In general, FDD (frequency duplex divisioning) requires frequency accuracy of 50 to 250 ppb (parts per billion). TDD (time division duplexing) requires similar frequency accuracy and also requires phase alignment of less than 3 microseconds. Some features of LTE-Advanced need phase alignment on the order of 1-5 microseconds.

FDD operates using frequency multiplexing, with two-way communications over different frequencies. Data for each frequency is transported over multiple subcarriers. Excessive frequency offsets between eNodeBs and UEs can mean interference between subcarriers that results in an inability to connect, dropped calls during handover, and lack of support for interference compensation protocols.
TDD operates using time division multiplexing with each party using well defined time slots. Phase synchronization is important to avoid interference between opposing traffic directions. Lack of synchronization can likewise result in the problems cited for FDD. LTE-TDD has a protection mechanism that uses guard periods; timing errors may only affect throughput.

LTE-Advanced utilizes advanced features, including CoMP and eICIC, that compensate for interference between adjacent cells. These technologies require frequency and phase synchronization to operate properly.

Five techniques are principally used for timing synchronization in HetNets. Their capabilities are summarized in Table 5-4.

<table>
<thead>
<tr>
<th>Technique</th>
<th>Frequency sync capable</th>
<th>Phase sync capable</th>
<th>Time sync capable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Synchronization distributed over backhaul network</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Precision Time Protocol (PTP)</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Network Time Protocol (NTP)</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Synchronous Ethernet (SyncE)</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Synchronization not using backhaul</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GNSS (Global Navigation Satellite Systems) – GPS</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Cellular Network Listening</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

Table 5-4: Synchronization Techniques

The technologies associated with these techniques are:

- **PTP.** Time, phase, and frequency information is transported over packet networks. PTP utilizes high-accuracy master clocks and boundary clocks to provide servers with timing information in a client/server interchange with eNodeBs and other components. PTP is supported over Ethernet and over IPv4/v6 in both unicast and multicast modes.

- **NTP.** NTP operates in a similar manner as PTP, providing time, phase, and frequency information. NTP is widely used by Internet-connected computers to maintain system time.

- **SyncE.** Synchronous Ethernet is a physical level technique that uses the PHY transmit clock in each device in a chain to maintain frequency synchronization. It requires every node in a chain to be SyncE-capable.

- **GNSS/GPS.** This technique uses the timing associated with global positioning satellites to maintain frequency, phase, and time information. GNSS-based devices can maintain better than 100ns accuracy. Four satellites must be visible unless the GNSS system’s position is accurately known, in which case only one satellite is required.

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15 “Synchronization for LTE small cells.” Small Cell Forum document 075.02.01. Produced in cooperation with the Metro Ethernet Forum (MEF)
Small Cells, Big Challenge

- **Cellular network listening.** Small cells obtain frequency and phase information by listening to their larger neighbors. Listening uses a subset of UE technology to monitor several cellular technologies at the same time.

In many cases a combination of techniques is used to fill in the gaps left by individual technologies. The more popular combinations are:

- PTP and NTP used with GNSS
- Cellular network listing with GNSS
- PTP used with SyncE

5.5.8 The Role of Carrier Ethernet in Mobile Backhaul

The discussion thus far in this section has concentrated on transport layer techniques, but it is important to consider the manner in which mobile data is transported. Wireless backhaul was initially accomplished through the use of TDM circuits leased from land-line carriers. These circuits came in fixed bandwidth amounts and were seldom shared. As shared Carrier Ethernet took hold the relative expense of TDM circuits made them a secondary choice for backhaul. Despite that, TDM circuits continue to be used for backhaul for two use cases:

- TDM circuits continue to be used for voice, timing and some high-priority services. Carrier Ethernet connections are used for low-priority, high-bandwidth data.
- TDM circuits are left in place for timing only, although this option is not ideal due to the additional opex costs.

Where TDM circuits are no longer used, timing can be provided using PTP and/or SyncE and/or GPS.

Carrier Ethernet supports both point to point and point to multipoint connections to connect multiple RANs to core networks. Carrier Ethernet offers several services that are used for mobile backhaul connections:

- **Ethernet Private Line Service (EPL).** Each RAN base station to core network is connected by a private connection.

- **Ethernet Virtual Private Line Service (EVPL).** A single network connection in the core network is shared among several RAN base stations, using VLANs.

- **Ethernet Private LAN Service (EP-LAN).** A LAN is established that includes multiple RAN base stations and the core network. This not only allows multiple base stations to be serviced by a base station, but also allows direct base station to base station access for X2 or R8 interfaces.

- **Ethernet Virtual Private LAN Service (EVP-LAN).** As in EP-LAN, but with the ability to support multiple cellular technologies at the same time using VLANs.
A representative traffic profile associated with a 50 Mbps mobile backhaul circuit is shown in Table 5-5.

<table>
<thead>
<tr>
<th>Traffic Type</th>
<th>Required Bandwidth (Mbps)</th>
<th>One-way Frame Delay (ms)</th>
<th>One-way Jitter (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Synchronization</td>
<td>0.5</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>Voice/conversational &amp; control</td>
<td>3.5</td>
<td>15</td>
<td>5</td>
</tr>
<tr>
<td>Streaming media</td>
<td>6</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>Interactive and Background</td>
<td>40</td>
<td>37</td>
<td>N/A</td>
</tr>
</tbody>
</table>

*Table 5-4 - Representative Traffic Profile Example*

Only a small amount of the traffic, synchronization and voice/conversation/control, has stringent latency and bandwidth requirements. Transport mechanisms that only offer one class of service (CoS) for backhaul must meet the most restrictive latency and jitter requirements and maximum bandwidth for the traffic.

Carrier Ethernet also offers multiple classes of service for Ethernet virtual circuits (EVCs). Each CoS has its own requirements for bandwidth, delay, and jitter. Using just two levels of service, operators can provide a low-latency path for synchronization and voice/conversation/control, and a lower cost path for all other data services. Aggregating traffic from multiple UEs and RAN base stations means lower bandwidth requirements overall.

5.6 Subscriber Quality of Experience

Cellular systems by nature have finite resources. Radio spectrum and transport backhaul resources are limited, expensive, and shared between many users and services. Mobile broadband networks must support many different voice, video, and data applications on a single IP-based infrastructure. These converged services each have unique traffic-handling and QoE requirements. While LTE and small cells provide more capacity, the issues cannot be economically solved by over-provisioning the network. A positive user experience must be obtained through efficient use of the available wireless network resources. Emerging rich media services, such as, voice over LTE (VoLTE) and conversational video based on rich communication services (RCS) are driving the wireless industry to tackle these challenges.

The 3rd Generation Partnership Project (3GPP) – the Universal Mobile Telecommunications System (UMTS) and Long-term Evolution (LTE) standards body – has developed a comprehensive QoS, charging, and policy control framework to address this problem. The policy and charging control (PCC) is the heart of the Evolved Packet Core (EPC), and ensures user QoE for a particular subscription and service type. Granular control of service quality is critical for operators to establish new business models and monetize services. It enables operators to employ fair-use policies that limit subscriber service abuse (for example, bandwidth hogs such as file sharing), and maintains network performance during peak traffic times.

Today’s mobile broadband networks carry many services that share radio access and core network resources. In addition to best-effort services, wireless networks must support delay-sensitive, real-time services. Each service has different QoS requirements in terms of packet delay tolerance, acceptable packet loss rates, and required minimum bit rates.

As mobile networks evolve to high-speed, IP-based infrastructure, the wireless industry is ensuring high-quality services by developing QoS and policy-management techniques in addition to adding network capacity. These techniques are designed to ensure application quality, allow operators to offer differentiated services to users, manage network congestion, and recoup the substantial sums that have been invested in building out new networks.

Policy management plays a fundamental role in the implementation of QoS in mobile broadband. Policy management is the process of applying operator-defined rules for resource allocation and network use. Dynamic policy management sets rules for allocating network resources, and includes policy enforcement processes. Policy enforcement involves service data flow detection and applies QoS rules to individual service data flows. The following section discusses policy enforcement details.
5.6.1 Using QoS and Policy Management to Limit Congestion and Enhance Service Quality

Additional transmission lines, fatter pipes, and improved efficiency are common responses to network congestion. However, this strategy works better for wired networks than for wireless networks. Increasing capacity with additional spectrum and improving spectrum efficiency are important steps in handling the substantial growth of mobile data. However, capacity improvements alone will not solve this complex challenge.

Mobile operators do not have unlimited resources and capital. The radio spectrum is finite, and gains from improved spectral efficiency can only go so far. Even if operators significantly increase capacity, bandwidth-hungry applications such as peer-to-peer (P2P) services and video will eventually consume any excess capacity. Providing high service quality by over-provisioning network capacity will eventually leave an operator at a competitive disadvantage to providers that offer the same or better QoS, at a lower cost. A solid policy strategy maintains network performance during peak traffic times and spikes in user demand, saving the operator from having to carry excess capacity.

With proactive management policies, combined with other strategies such as network offloading and demand calibration, mobile broadband networks with finite resources can better satisfy consumers’ demand for multiplay services. Policy management differentiates services and subscriber types, and then controls the QoE of each type.

Table 5-6 demonstrates how subscriber QoE expectation varies by service type. It also highlights how different services have different performance attributes that impact the user’s
perception of quality. There is a significant distinction between real-time services such as conversational video and voice and best-effort services such as Internet browsing. Real-time services must reserve a minimum amount of guaranteed bandwidth, and are more sensitive to packet loss and latency/jitter.

<table>
<thead>
<tr>
<th>Services</th>
<th>QoE Expectations</th>
<th>Performance Attributes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internet</td>
<td>Low – best effort</td>
<td>• Variable bandwidth consumption</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Latency and loss tolerant</td>
</tr>
<tr>
<td>Enterprise/Business Services</td>
<td>High – critical data</td>
<td>• High bandwidth consumption</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Highly sensitive to latency</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• High security</td>
</tr>
<tr>
<td>Peer-To-Peer</td>
<td>Low – best effort</td>
<td>• Very-high bandwidth consumption</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Latency and loss tolerant</td>
</tr>
<tr>
<td>Voice</td>
<td>High – Low latency and jitter</td>
<td>• Low bandwidth – 21-320 Kbps per call</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• One-way latency &lt; 150ms</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• One-way jitter &lt; 30ms</td>
</tr>
<tr>
<td>Video</td>
<td>High – low jitter and extremely-low packet loss</td>
<td>• Very-high bandwidth consumption</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Very sensitive to packet loss</td>
</tr>
<tr>
<td>Gaming and Interactive Services</td>
<td>High – low packet loss</td>
<td>• Variable bandwidth consumption</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• One-way latency &lt; 150ms</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• One-way jitter &lt; 30ms</td>
</tr>
</tbody>
</table>

Table 5-6 - Comparison of QoE Expectations and Performance Requirements by Service Type

Policy management allows operators to granularly control the availability and QoE of different services. First, policies are used to dynamically allocate network resources – for example, a particular bandwidth can be reserved in the radio base station and core network to support a live video conversation. Next, policy rules control the priority, packet delay, and acceptable loss of video packets in order for the network to treat the video call in a particular manner.

In other cases, policy rules might be used to limit traffic rates on the network in order to curb network abusers and provide fair use – preventing one user from negatively impacting the quality of another service. P2P file sharing is one example of a very bandwidth-intensive, non-real-time service. P2P services, if left unmanaged, can consume a disproportional amount of network resources and negatively impact the network’s ability to establish and maintain real-time service quality.
5.6.2 3GPP’s Vision for QoS/Policy Management in LTE

Latency for user plane services depends on the latency for the end-to-end connection between the UE and the Internet-based application server, as shown in Figure 5-24 for a typical LTE/EPC-based set of the components and connections.

The figure shows the many possible delay components. UE-to-UE connections such as a VoLTE voice or video call would require a trip from the UE to the Internet and another back out to another UE.

The 3GPP’s goal is to define an access-agnostic policy control framework, with the objective of standardizing QoS and policy mechanisms for multi-vendor deployments that enable operators to provide service and subscriber differentiation. 3GPP standards explain how to build transmission paths between the UE and the external packet data network (PDN) with well-defined QoS. To this end, the 3GPP has defined an extensive “bearer model” to implement QoS.

**Bearer Model**

A “bearer” is the traffic separation element that enables differential treatment for traffic with differing QoS requirements. Bearers provide a logical, edge-to-edge transmission path with defined QoS between the user equipment (UE) and packet data network gateway (PDN-GW).

Each bearer is associated with a set of QoS parameters that describe the properties of the transport channel, including bit rates, packet delay, packet loss, bit error rate, and scheduling policy in the radio base station. A bearer has two or four QoS parameters, depending on whether it is a real-time or best-effort service:

- QoS Class Indicator (QCI)
- Allocation and Retention Priority (ARP)

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17 “Backhaul Technologies for Small Cells,” Small Cell Forum, Document 049.01.01
**Small Cells, Big Challenge**

- Guaranteed Bit Rate (GBR) – real-time services only
- Maximum Bit Rate (MBR) – real-time services only

**QoS Class Indicator (QCI)**

The QCI specifies the treatment of IP packets received on a specific bearer. Packet forwarding of traffic traversing a bearer is handled by each functional node (for example, a PDN-GW or eNodeB). QCI values impact several node-specific parameters, such as link layer configuration, scheduling weights, and queue management.

The 3GPP has defined a series of standardized QCI types, which are summarized in Table 5-7. For first deployments, a majority of operators will likely start with three basic service classes: voice, control signaling, and best-effort data. In the future, dedicated bearers offering premium services such as high-quality conversational video can be introduced into the network.

<table>
<thead>
<tr>
<th>QCI</th>
<th>Resource Type</th>
<th>Priority</th>
<th>Packet Delay Budget</th>
<th>Packet Error Loss Rate</th>
<th>Example Services</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>GBR</td>
<td>2</td>
<td>100ms</td>
<td>$10^{-2}$</td>
<td>Conversational voice</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>4</td>
<td>150ms</td>
<td>$10^{-3}$</td>
<td>Conversational video (live streaming)</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>3</td>
<td>50ms</td>
<td>$10^{-3}$</td>
<td>Real-time gaming</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>5</td>
<td>300ms</td>
<td>$10^{-5}$</td>
<td>Non-conversation video (buffered streaming)</td>
</tr>
<tr>
<td>5</td>
<td>Non-GBR</td>
<td>1</td>
<td>100ms</td>
<td>$10^{-3}$</td>
<td>IMS signaling</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>6</td>
<td>300ms</td>
<td>$10^{-5}$</td>
<td>Video (buffered streaming) TCP-based (e.g., www, email, chat, FTP P2P file sharing, progressive video, etc.)</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>7</td>
<td>100ms</td>
<td>$10^{-5}$</td>
<td>Voice, video (live streaming), interactive gaming</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>8</td>
<td>300ms</td>
<td>$10^{-3}$</td>
<td>Video (buffered streaming) TCP-based (e.g., www, email, chat, FTP P2P file sharing, progressive video, etc.)</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>9</td>
<td>300ms</td>
<td>$10^{-5}$</td>
<td></td>
</tr>
</tbody>
</table>

*Table 5-7 - 3GPP Standardized QCI Attributes*
These delay budgets can be mapped against the typical round trip delays found in end-to-end wireless communications, as detailed in Table 5-8.

<table>
<thead>
<tr>
<th>Segment in Delay Budget</th>
<th>Typical Round Trip Delay, in milliseconds</th>
</tr>
</thead>
<tbody>
<tr>
<td>UE processing</td>
<td>4</td>
</tr>
<tr>
<td>Radio Interface (scheduling, retransmission, etc.)</td>
<td>11</td>
</tr>
<tr>
<td>eNodeB (small cell) processing</td>
<td>4</td>
</tr>
<tr>
<td>Small cell backhaul (S1 interface)</td>
<td>10</td>
</tr>
<tr>
<td>RAN backhaul</td>
<td>4</td>
</tr>
<tr>
<td>Aggregation and IPsec encryption (SeGW)</td>
<td>2</td>
</tr>
<tr>
<td>Core transport (S1 interface, likely in VPN)</td>
<td>2</td>
</tr>
<tr>
<td>EPC (SGW + PGW) processing</td>
<td>1</td>
</tr>
<tr>
<td>Service LAN (Gi or SGi interface)</td>
<td>3</td>
</tr>
<tr>
<td>ISP: router, firewall, etc.</td>
<td>1</td>
</tr>
<tr>
<td>External networks, Internet, local peering, etc.</td>
<td>8</td>
</tr>
<tr>
<td><strong>Total round trip delay</strong></td>
<td><strong>50</strong></td>
</tr>
</tbody>
</table>

*Table 5-8 - Typical End-to-End Delay Budget for an LTE Small Cell*

**Allocation and Retention Priority**

The 3GPP standards provide mechanisms to drop or downgrade lower-priority bearers in situations where the network become congested. Each bearer has an associated allocation and retention priority (ARP). ARP is used in bearer establishment, and can become a particularly important parameter in handover situations where a mobile subscriber roams to a cell that is heavily congested. The network looks at the ARP when determining if new dedicated bearers can be established through the radio base station.

**Guaranteed Bit Rate and Non-GBR Bearers**

There are two major types of bearers: guaranteed bit rate and non-guaranteed bit rate. GBR bearers are used for real-time services, such as conversational voice and video. A GBR bearer has a minimum amount of bandwidth that is reserved by the network, and always consumes resources in a radio base station regardless of whether it is used or not. If implemented properly, GBR bearers should not experience packet loss on the radio link or the IP network due to congestion. GBR bearers will also be defined with the lower latency and jitter tolerances that are typically required by real-time services.

Non-GBR bearers, however, do not have specific network bandwidth allocation. Non-GBR bearers are for best-effort services, such as file downloads, email, and Internet browsing. These bearers will experience packet loss when a network is congested. A maximum bit rate for non-GBR bearers is not specified on a per-bearer basis. However, an aggregate maximum bit rate (AMBR) will be specified on a per-subscriber basis for all non-GBR bearers.

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18 "Backhaul Technologies for Small Cells," Small Cell Forum, Document 049.01.01
5.6.3 Service Data Flows

Service data flows (SDF) are another fundamental concept in the 3GPP’s definition of QoS and policy management. SDFs represent the IP packets related to a user service, web browsing, email, etc. SDFs are bound to specific bearers based on policies defined by the network operator. This binding occurs at the PDN-GW and UE using traffic flow templates (TFT). TFTs contain packet filtering information to identify and map packets to specific bearers. The filters are configurable by the network operator, but at a minimum will contain five parameters, commonly referred to as a 5-tuple. The parameters include:

- The source IP address
- The destination IP address
- The source port number
- The destination port number
- The protocol identification (i.e., TCP or UDP)

The policy and charging enforcement function (PCEF) in the PDN-GW filters packets coming from external networks (i.e., the Internet or corporate VPNs) using TFTs.

5.7 Security

The security associated with small cells and Wi-Fi access points is a significant concern for several reasons:

- **Internet connectivity:** virtually all femtocells and some percentage of picocells and microcells are backhauled through the Internet. Internet connectivity opens small cells to security threats normally associated with Internet access: snooping, denial of service, hacking, and man-in-the-middle attacks.
- **Physical tampering:** whereas macrocells are locked and/or inaccessible, small cells and access points are normally easily accessible in homes or in enterprise wiring closets.
- **Wireless access:** unauthorized users may gain access to small cells for fraudulent activities.

Several mechanisms are used by small cells to ensure security:

- **Cryptography:** IPsec and IKEv2 protocols are used to encrypt traffic from small cells and access points to the core network. These protocols also allow mutual authentication of the small cell/access point and the femtocell gateway or other MSC component, defeating man-in-the-middle attacks. Femtocells identify themselves via an embedded SIM card or x.509 certificate.
- **Service area:** small cells can limit fraudulent usage by limiting the size of their area, as discussed in the section on Interference. Femtocells often require their owners to manually configure the phone numbers of allowed users.
Chapter 6
Small Cell Deployment Challenges
In this chapter we’ll discuss the major deployment issues associated with small cells. Femtocell, and in most cases, picocell deployment is controlled largely by the customer. After initial installation, device operation is largely self-controlled or dictated by SON algorithms. These devices are designed to broadcast in a restricted area and do so by managing their power. This chapter will address the deployment considerations for microcells.

### 6.1 Design Considerations

The placement of microcells must be carefully considered so as to maximize coverage and capacity, while minimizing interference with macrocells and other microcells. Simulation tools are available to test various scenarios so as to create the greatest amount of spectral reuse.

Backhaul is a particularly important part of cellular network design. Bandwidth requirements dictate whether existing network infrastructures can be used or new backhaul connections are required. Where wireless backhaul connections must be used the location of backhaul radio towers will indicate when line of sight (LOS) or non-LOS connections will be used. Available backhaul bandwidth will also dictate whether point to point (PTP) or point to multipoint (PMP) connections can be used.

Regulatory restrictions and local zoning will affect the physical placement of small cells and also restrict wireless backhaul options.

The mean and peak traffic through a RAN depends on its type, coverage, and capacity. Peak traffic rates occurs during quiet times for an excellent RAN-UE connection and when there is no service contention. During busy times, the cell’s spectral resource is shared among multiple users, not all of whom can be located at the optimal location within the cell. Although user plane traffic constitutes the largest part of backhaul traffic, there are other contributors shown in Table 6-1.

<table>
<thead>
<tr>
<th>Component</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPsec overhead</td>
<td>14%</td>
</tr>
<tr>
<td>Transport protocol overhead</td>
<td>10%</td>
</tr>
<tr>
<td>X2 U and C-plane</td>
<td>4%</td>
</tr>
<tr>
<td>Control plane</td>
<td>Negligible</td>
</tr>
<tr>
<td>OA&amp;M, time synchronization, etc.</td>
<td>Negligible</td>
</tr>
</tbody>
</table>

*Table 6-1 - Traffic Contribution by Type*
Backhaul connections should be provisioned to match the type of service and user expectations. For example, a Wi-Fi access point offering 802.11n service has a theoretical limit of 150 Mbps for single antenna UEs that form the largest class of smartphone and tablet usage. Backhaul for such a connection should be on the order of 100 Mbps. As another example, consider an LTE-enabled macrocell, where expect 20 Mbps and more from their quiet time connections.

An interesting observation by Intel\(^1\) is that backhaul requirements can be reduced 30-40% by a combination of proactive and predictive caching in access points and base stations.

The selection of backhaul technology also affects how base station timing will be accomplished. Some technologies, such as TDM circuits, provide inherent timing. Other technologies provide one, two, or all three of frequency, phase, and time of day requirements. Other timing requirements may require supplemental technology, such as GPS-based receivers.

### 6.2 Physical Placement

The physical placement of small cell antennas and base stations is an important consideration that can feed back to the design process. These can be mounted indoors in large venues such as train stations or outdoors to service pedestrians and vehicles. Outdoor placement locations can include exterior walls or rooftops or existing street-level structures such as utility poles, lampposts, and traffic lights. Each placement option has its own RF characteristics that may restrict coverage and capacity.

Physical placement is also dictated by the availability of power, access to backhaul technology, environmental concerns, and physical security.

### 6.3 Installation

In addition to physical attachment and cabling for power and backhaul connectivity, small cells must be commissioned and acceptance tested. A number of elements are configured, either manually or automatically from a central management system center:

- Small cell configuration, including:
  - Cell ID
  - Frequency and bandwidth
  - Interference parameters
- Backhaul configuration
- IP configuration

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\(^1\) [http://www.etsi.org/](http://www.etsi.org/)
Small Cells, Big Challenge

- Connectivity to core network, and in some cases local networks and Internet
- Interference parameters, including power management

Likewise, the management system must be configured with details about the small cell and its related components.

Finally acceptance tests must be run to ensure functionality, including:

- Basic functionality
- Frequency and output power
- Coverage
- End to end delay
- Throughput
- Quality
- Packet loss
- Peak user throughput
- Mobility in and out of macro cells
- Interference

6.4 Operations

In addition to troubleshooting network problems, cellular network operations centers must monitor the health of their networks. The overall objective is to keep customers happy by minimizing dropped and poor quality calls, satisfying enterprise SLAs, and by maintaining consumer QoE. Essential performance indicators include:

- Ratio of dropped voice calls
- Voice call quality (MOS)
- Handover success ratio
- Transmission rates
- Throughput and latency for different types of data, busy hour rates over time
- Control plane KPIs: location updates, paging and responses, etc.

SON techniques, in particular, will be a challenge for network operators supporting small cells. Competing approaches to SON have been developed by equipment manufacturers and academia. SON techniques remain largely unproven, and may create problems of their own. Careful monitoring of network health will be necessary to provide the data for tuning or overriding of SON techniques. SON techniques and features have recently been standardized by the 3GPP. Competing approaches will probably fade away in favor of the standard.
6.5 Interoperability

Prior to the deployment of small cells, cellular operators were largely concerned with interoperability between their RANs and core network. With the addition of small cells, now operators must be concerned with the interoperability between macro and small cell RANs in addition to each of them interoperating with their core.

Small cells have changed all that. Small cells of every type are found under the macrocell umbrella, from multiple vendors. In addition, infrastructure elements such as the HeNB gateway and HMS may need to service small cells from different vendors.

The ETSI\(^2\), the European Telecommunications Standards Institute, and the Small Cell Forum\(^3\) have been the principle organizations testing interoperability among small cell and LTE components. As of January 2014 they organized four interoperability plugfests that have focused on the following RAN and MSC components:

- Small cells (femtocells, picocells, microcells)
- LTE Enhanced Packet Cores (EPCs)
- Security gateways (SeGWs)
- Macrocell eNodeBs (eNBs)
- Home eNodeBs (HeNBs)

Using devices from multiple vendors, they have demonstrated interoperability in the following operations:

- Zero-touch small cell installation and configuration
- First small cell call
- Mobility between small cells
- Hand-outs from small cells to macro cells
- Voice over LTE (VoLTE)

\(^2\) http://www.etsi.org/
\(^3\) http://www.smallcellforum.org/
Several protocols are essential to interoperability testing:

- **Iuh**: this protocol is used between the femtocell gateway and the 3G core network. It performs the necessary translations to ensure the femtocells appear as a radio network controller to existing mobile switching centers (MSCs).

- **X2**: this protocol is used between cells to handle handovers.

- **TR-069**: defined by the Broadband Forum⁴, it defines the interface used by small cell management systems.

- **IKEv2/IPsec**: these two protocols define the means by which secure endpoints authenticate each other, establish private keys, and encrypt/decrypt communications.

These plugfests are the first step in achieving true interoperability across a mixed macrocell/small cell environment. More extensive interoperability must be established, followed by performance measurements. Performance measurements ensure that components are ready to handle real-world conditions for the connections that they support.

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Chapter 7
Validating HetNets
CHAPTER 7
Validating HetNets

HetNets represent a fundamental shift in the access network architecture, and their success hinges on many moving parts coming together in harmony. Each provider will need to sort through many competing and unproven approaches to find the ones that will benefit them most—and fastest—validating both decisions and results each step of the way.

Just as performance issues can no longer be solved economically by overprovisioning networks, design decisions can no longer be made by relying upon vendor performance metrics and drive tests. New designs, equipment, and configurations must be fully evaluated before rolling out sites and services, not with the traditional focus on protocol testing, but with the goal of ensuring the end-user experience firmly in sight.

This chapter will take a closer look at risks, challenges, and emerging strategies for validating HetNets for quality, scale, and manageability. We’ll start with the risks, which, though somewhat obvious, become greater as HetNets proliferate.

7.1 Risks of Insufficient Validation

As HetNets grow, predicting user load, surges, and mobility becomes more challenging and complex, mandating thorough testing in both the lab and field. Failure to perform adequate testing and proper validation of technology and designs can lead to problems that impact users, such as:

- Inability to complete calls or dropped calls
- Limited mobility due to failed hand-offs to local small cells
- Poor quality in voice, video, and data-driven applications
- Missed SLAs

All of these can frustrate users, especially if problems persist. With voice, HD video, and unified communications all going mobile, customers will have diminishing patience for operators ironing out kinks in new services.

QoE must be assured beforehand to prevent churn and a costly hit to operators’ reputations. But the old approach won’t work.

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1 Testing of eNodeBs and all EPC components is critical, and is covered in other Ixia publications including Authoritative Guide to Advanced LTE Testing and Validating VoLTE: Definitive Guide to Successful Deployments.
7.2 Challenges to Validating HetNets

To date, service providers have relied upon equipment manufacturers to assess the performance of their own devices and overall network designs. During deployments, operators conduct drive tests to assess locations and macrocell performance and efficiency. The many variables introduced by HetNets mandate a more proactive and comprehensive approach:

- **HetNets involve new equipment and technologies, often from multiple vendors.** Most notably, more and smarter devices will interact in more intelligent and complex ways. Multiple radios are tightly integrated within newer small cells requiring more extensive validation and tri-fold expertise with 3G, 4G, and Wi-Fi technologies.

And instead of being centrally managed by one regional “band leader,” small cells are more self-directed and aware of each other. Microcell base stations detecting changes in the surrounding radio environment can act to optimize load balancing, interference, transmission power, mobility handovers, and more.

“Opportunistic small cells” are also emerging that dynamically turn themselves off and on in response to changing traffic conditions to reduce interference and power consumption.

- **Networks move closer to customers** making it harder for operators to maintain fully control and visibility into small cell utilization and security.

- **SON capabilities and increased automation** are employed to impose order over so many more nodes, but they add a level of complexity to configuration. Several competing approaches to SON have emerged and remain largely unproven.

- **Hotspot 2.0** and other enhancements aim to ensure seamless data hand-offs between Wi-Fi and cellular, and increase operators’ control over Wi-Fi, but the impact of these techniques on performance, mobility, and security must be fully validated.

- **Techniques defined by LTE Advanced** and other standards continue to evolve. Their ability to improve spectral efficiency and interference management must be put to the test under real-world conditions.

- **Sharing of small cells and frequencies** increases among multiple operators.

All of these variables factor into decisions about which technologies, equipment, and techniques to employ at various sites and stages—and they dictate new validation strategies. As thousands of new locations come online, including many within buildings, operators must be able to model the countless variables in play and replicate issues encountered in the field—all from one flexible test lab.

Fortunately, evolving best practices for validating HetNet strategies provide the scope and scale needed to make the best decisions.
7.3 Critical Test Capabilities

To meet the scope of the challenge, HetNet validation should include several critical components and capabilities:

7.3.1 Emulation

Test systems must support the process known as emulation, wherein external conditions are brought to bear in order to assess functionality, determine interoperability, and measure performance and QoE. In the case of HetNet testing, test equipment is used to emulate UEs and eNodeBs that are not part of the HetNet/EPC being tested. In order to properly test large scale HetNets, test equipment must emulate many users – often tens of thousands of UEs and dozens of eNodeBs.

7.3.2 Realism

Since it's common for equipment manufacturers to state performance metrics in terms of specific or “best case” configurations and use models, HetNet assessments should be based on actual or intended networks. The performance of prospective devices, handoffs, interference management techniques, and the overall scalability of intended deployments should all be benchmarked under simulated peak conditions, user mobility, power outages, and security threats.

Building complete replicas of the live network in the lab is cost-prohibitive and impractical. However, purpose-built test systems can be used to simulate the key components of the live network quite cost-effectively.

Test capabilities should include traffic generation, emulation of user services, automation, and real-time performance assessment at high-scale. The system must be able to simulate:

- Realistic numbers of UEs, macrocells, access points, and small cells in tandem
- User services, including voice, video, web surfing
- Subscriber mobility
- Interference
- Impairments
- Security threats
7.3.2.1 Subscriber Modeling

Mobile subscriber modeling is a pillar of any service quality validation strategy. The term refers to the process of defining subscriber types—for example, corporate vs. casual user—and associating applications to a subscriber such as Internet browsing, email, voice, video, and P2P. Modeling subscribers’ usage of applications and their mobility on the network allows testers to replicate real traffic types and usage patterns, and provides the information needed to fully understand capacity limits, how services interact, and the network’s ability to differentiate between services and subscriber types.

Subscriber modeling requires very granular control of service/subscriber emulation. Figure 7-1 shows an example of how a casual subscriber might use the network.

![Figure 7-1 - Example Usage Flow](image)

The subscriber may use the web browser on their smartphone to browse to a web site using a URL. The user pauses to read the web site, and after a certain amount of time clicks on a link to an interesting blog article. While reading the article, the causal user downloads an embedded YouTube video and watches a video clip for 1 minute. Once the video is finished, she might call a friend to discuss the blog and video they just watched.

This is a common multiplay scenario carried out by millions of mobile data subscribers every day. Testers need the ability to quickly define specific traffic models in a matter of minutes instead of hours or days.

An intelligent application-level test interface is required, along with the ability to emulate associated mobility protocols for network attachment, security authentication, and bearer establishment. To be effective and emulate a wide and varying degree of application services, the test system must not require users to be experts at the underlying protocol procedures.

After modeling the behavior of a specific mobile subscriber, the next step is to place them in a group of like subscribers and model usage over time. This emulates the behavior patterns of different categories of subscribers, such as business users, casual users, and telecommuters.

Traffic usage changes significantly by the time of day (see Figure 7-2). User behavior patterns should also be mapped to specific times of the day, allowing the emulation of peak usage times. For example, morning service usage is much different than evening traffic mixes.
Subscribers’ application use is rapidly evolving, and the distribution varies greatly by user type. The key point is flexibility. No one can predict exact usage out into the distant future as new applications emerge and become popular. A test framework must be highly adaptive to future trends.

7.3.2.1 Specific Deployments

Operators must be able to validate performance and profitability against the nuances of unique deployments:

- **Environmental factors** such as building construction, power costs, and the viability of using higher-frequency spectrum all dramatically impact requirements.

- **Usage patterns and performance goals** impact the type and number of devices needed to deliver the desired coverage and quality. The number of voice calls to be supported, video streaming, SLA compliance, the ability to access the cloud, and compliance with unique regulatory and security requirements all must be explored against varying traffic and environmental conditions.
7.3.3 Flexibility

HetNet validation requires the ability to isolate and evaluate individual devices and subsystems, and the flexibility to perform system-level end-to-end assessments of new configurations and services. Mobile operators need to be able to assess the impact of each device on the network and on other devices, and of the network on each device.

7.3.4 Scalability

The wireless core network is the aggregation point for wireless access network traffic. A core network is called on to terminate the traffic originating from millions of mobile subscribers across thousands of radio base stations. Today, the baseline for testing the wireless core is over 100 Gbps of stateful traffic, and this will evolve to terabits per second of data as mobile broadband takes off.

Since most issues occur at high scale, operators cannot qualify performance, scalability, and resilience just by using a handful of actual devices as has been done in the past. Realistic traffic must be generated at realistic scale to simulate high-load or stress conditions where network and application performance might suffer.

Along with performance, designs must be assessed for scalability and cost-performance over time, including the efficiency and accuracy of backhaul and billing. This means modeling peak usage and varying times throughout the day, simultaneously generating data, voice, and video to emulate the respective multimedia traffic loads.

7.3.5 QoS / Service Validation

Policy management and QoS will play an integral role in promoting new services and business models. In rolling out HetNets, operators must implement policies on multiple devices simultaneously, assessing the policy and QoS capabilities of each along with the end-to-end performance achievable across the overall network. Policy management strategies are particularly important in 4G networks, where the 3GPP has defined a framework to standardize QoS and policy mechanisms in multi-vendor deployments.

Policy/QoS mechanisms must be validated using high volumes of emulated subscriber traffic, when a network or node is at or near capacity. This again means generating millions of concurrent web transactions and transactions per second.
7.3.6 Actionable Metrics

The end-goals of HetNet and new service validation are subscriber QoE and the ability to profitably deliver high-quality services. QoE measures the overall level of customer satisfaction with a service, where expectations may vary by service type.

Similarly, different services have different performance attributes that impact the user’s perception of quality. For example, a significant distinction exists between real-time services such as conversational video and voice and best-effort services such as Internet browsing. Real-time services must reserve a minimum amount of guaranteed bandwidth, and are more sensitive to packet loss and latency/jitter.

Quantitatively measuring QoE requires an understanding of the key performance indicators (KPIs) that impact users’ perception of quality. KPIs are unique by service type, and each service type—conversational video, voice, Internet browsing—has unique performance indicators that must be independently measured:

- **Data applications** are typically best-effort services, characterized by variable bit rates, and are tolerant to some loss and latency before the user perceives poor quality. Some of the KPIs for data services include:
  - Transaction latency (including time-to-first-byte and time-to-last-byte of data)
  - Transactions per second
  - Concurrent transactions
  - Page hits and object hits
  - Uplink and downlink throughput
  - Re-transmissions
  - Failed-transactions

- **Voice applications** are real-time services requiring a constant bit rate. Voice services are sensitive to latency and jitter, but tolerant of some packet loss.

  The main KPI for voice is the mean opinion score (MOS). MOS_V is a perceptual quality score that considers the effects of CODEC/quantization level, the impact of IP impairments, and the effectiveness of loss concealment methods. Other important voice KPIs include packet inter-arrival delay (jitter), one-way latency, and the overall connection setup time for a voice call.
• **Video services** have characteristics similar to voice applications and mobile broadband networks typically support many different forms of video. Three important categories are live streaming (conversational video), progressive (buffered) download, and adaptive streaming.

Live streaming has the highest performance demands. It is a real-time service that is very sensitive to latency, jitter, and packet loss. Perceptual video quality analysis is the most important KPI for video services.

To fully understand QoE, KPIs must be evaluated over time, at varying load rates and application mixes. Policy and QoS mechanisms must be judged when a network is fully loaded, and there are competing demands for network resources. Only under these conditions can the effectiveness of rate limiting/policing, packet shaping, resource scheduling, and packet delay budgets be thoroughly analyzed and tuned.

### 7.3.7 Replication of Field Issues

Even the most thorough pre-deployment testing can’t anticipate everything that can go wrong in the real world. As issues arise, operators need a way to replicate the initial issues encountered in the field in their test labs before going live with new services or rolling out HetNet rollouts in additional areas.

### 7.3.8 Experience

Along with proven test methodologies, expertise with both cellular and Wi-Fi technologies proves invaluable in maximizing the value achieved using HetNets. Experience with next-generation services such as VoLTE will play a greater role as a higher percentage of deployments leverage 4G infrastructures.

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**Figure 7-3 - Mean opinion score (MOS)**

<table>
<thead>
<tr>
<th>MOS_v</th>
<th>What does it mean?</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Excellent</td>
</tr>
<tr>
<td>4.5</td>
<td>Very good</td>
</tr>
<tr>
<td>4</td>
<td>Good</td>
</tr>
<tr>
<td>3.5</td>
<td>Poor</td>
</tr>
<tr>
<td>3</td>
<td>Not acceptable</td>
</tr>
<tr>
<td>2</td>
<td>Severe</td>
</tr>
<tr>
<td>1</td>
<td>Useless</td>
</tr>
</tbody>
</table>
7.4 Scope of Testing

Along with pre-deployment testing, ongoing validation will be needed to maximize value throughout the HetNet life-cycle as new techniques, devices, and applications enter the fray. The comprehensive benchmarking needed to optimize HetNet deployments includes:

- Functional / feature testing
- Interoperability testing
- Capacity planning
- QoS and policy control assessment
- QoE measurement

At the end of the day, operators’ test systems and strategies must be as flexible and innovative as HetNets themselves.

In the next chapter, we’ll look at a number of test cases that utilize purpose-built equipment to ensure functionality, interoperability, and performance.
CHAPTER 8
Validating Heterogeneous Networks – Test Cases

This chapter will cover evaluation of HetNet topologies, technologies, and EPC components such as SON servers and subsystems, home eNodeB gateways, and Wi-Fi offload gateways that are specifically designed to support HetNets. These tests can be accomplished in the lab using cabled arrangements, where replicas of HetNets can be designed and modeled before actual deployments.

The tests discussed here can be used to validate a number of functions:

- Evaluate and compare different SON algorithms
- Validate for standards compliance
- Prove interoperability across different vendors
- Measure device and network performance
- Understand how user QoE is affected by different factors

Small cell deployments exist in both 3G and 4G/LTE environments. For simplicity, we will illustrate testing strategies with 4G/LTE in this section. The principals and test techniques, however, remain the same for 3G environments.

The testing procedures described in this chapter are organized with the following subsections:

- **Device under Test (DUT)** – the components being tested
- **Test Objective** – the desired result of the test
- **Test Environment** – how the DUT interfaces with the test equipment
- **Test Procedure** – the steps executed by the test equipment. This is generally broken down into three phases:
  - Setup up test conditions
  - Create connections and generate data traffic
  - Measure key performance indicators (KPIs) during test execution
- **Test Results** – evaluate functionality, performance, and optimization
- **Test Refinements** – additional modifications or test that could be performed
8.1 Testing SON Features

8.1.1 Interference: eICIC features

Device under Test

HetNet with mix of macro and small cells and associated EPC. In a centralized or hybrid SON deployment, this would also include SON server.

Test Objective

Test a HetNet eNodeBs ability to react to neighbor cell interference dynamically. Specifically, eICIC algorithms are tested and results may be compared across different vendors and across different releases from the same vendor. Evaluate and understand the impact of eICIC algorithms in maintaining high QoE.

Test Environment
Test Procedure

Test is configured, defining UEs and the interference load

UEs attach to DUT and generate maximum load

UE simulation evaluates and reports on compensation factor. Understand impact on QoE. Understand how eNodeB handles near, mid, and far cell UEs while it compensating for interference

eNodeB scheduler / SON server compensates for interference

Test Results

The simulated UEs report throughput and QoE for simulated users. The test measures:

- eICIC compensation factor, based on the interference load. That is, based on neighbor eNodeB interference data, how does the DUT change resource block (RB) allocation for its UEs and how does it vary based on the UE location (i.e. near, mid distance, Factors such as change in RNTP (relative narrow band transmit power), ABS pattern, UL and DL RB allocation would contribute to evaluating eICIC compensation factor.

- eICIC compensation latency. That is, how long does it take for the DUT to adjust after the neighboring eNodeBs report simulated interference?

- QoE. How does perceived QoE vary after interference compensation?
8.1.2 Automatic Neighbor Relations (ANR)

Device under Test

HetNet with mix of macro and small cells and associated EPC. In a centralized or hybrid SON deployment, this would also include SON server.

Test Objective

Test a HetNet’s eNodeBs ability to:

- Determine a new neighbor relation,
- Initiate and/or terminate X2 neighbor relation,
- Maintain a neighbor relation,
- Reject neighbor relations, when neighbor table is full
- Impact on eNodeB performance with a full populated neighbor table

Test Environment
Small Cells, Big Challenge

Test Procedure

<table>
<thead>
<tr>
<th>UE Sim</th>
<th>eNodeB Sim</th>
<th>Device under Test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>ANR operation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Test is configured, defining UEs and eNodeBs</td>
</tr>
<tr>
<td></td>
<td></td>
<td>UEs send RRC reports with new cells' identities (1)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>eNodeB processes PCls and initiates X2 with new cells</td>
</tr>
<tr>
<td></td>
<td></td>
<td>eNodeBs respond with new load values</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Validating UE QoE with full neighbor table</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Test is configured, defining UEs and eNodeBs</td>
</tr>
<tr>
<td></td>
<td></td>
<td>UEs attach and start measuring QoE</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Simulated eNodeBs initiate X2 connection to target eNodeBs (OUT)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fully loaded neighbor table. (Repeat until eNodeB is fully loaded)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>eNodeB accepts X2 connection</td>
</tr>
</tbody>
</table>

Notes

(1) Physical cell IDs (PCls) and cell global IDs (CGIDs).

Test Results

- Validate UE ANR functionality
- Determine the latency associated with ANR connection setup
Small Cells, Big Challenge

- Determine the maximum number of neighbor cells a eNodeB can handle
- Evaluate the impact of large number of neighboring cells

The simulated eNodeBs report whether the DUT’s eNodeBs have recognized it. The latency in ANR establishment can be determined from the time between UE Uu messages and DUT X2 message and TNL address discovery over S1 messages. Interoperability can be determined where different types of equipment is present in the DUT.

Test Refinements

1. The UEs can continue to report additional new eNodeBs in order to determine the maximum number of entries that the DUT’s eNodeBs can hold in their neighbor relation table (NRT).

2. UE data traffic can be used at the same time to determine the relationship between X2 connections and DUT performance.

3. The reverse can also be tested. The eNodeB simulation can request the TNL address from the DUT and then initiate the establishment of the X2 interface.
8.1.3 Mobility Load Balancing – Initiated by DUT

**Device under Test**

HetNet with mix of macro and small cells and associated EPC. In a centralized SON deployment, this would also include SON server.

**Test Objective**

Test a HetNet’s eNodeBs and SON server’s ability to load balance by handing over UEs to neighboring eNodeBs.

**Test Environment**
Small Cells, Big Challenge

Test Procedure

UE Sim  eNodeB Sim  Device under Test

Test is configured, defining UEs and eNodeBs

Overload DUT eNodeB with active UEs (1)

Uu

Load balancing algorithm kicks in. eNodeB initiates X2 negotiation with neighbors (2)

X2 negotiation to adjust mobility threshold

Accepts handover request (3)

X2

Rejects handover request (4)

Notes

(1) Load could be of different types.

(2) This is a load based handover request. Hardware, CPU, RRC, and TNL load are some of the load factors that are exchanged, and each eNodeB determines if it wants to renegotiate a handover threshold.

(3) Validate renegotiation of handover threshold.

(4) Some simulated eNodeBs could indicate that they are also under load. The DUT should try to handover to other eNodeBs.
Test Results

The simulated UEs report which eNB they are associated with. The test validates that the DUT is able to effect handovers that are triggered by load conditions instead of radio conditions. The specific reason that the DUT requests a handover should be validated.

This test can be used to understand how eNodeBs pick which neighbors receive UEs through handover. It also shows how an eNB reacts to other scenarios, including:

- Neighbor cells are also loaded.
- Neighbor cells are not loaded, but have not been reported by select UEs. That is, the UEs may not be covered by the neighbor cells.

Test Refinements

1. Utilize different types of load as per note (1) above: throughput load or RRC load.

2. An additional test can be configured in which the simulated neighbor eNodeBs are also overloaded, as indicated by their CPU, transport network, RRC, and TNL loads. This will evaluate if the DUT still attempts the handover knowing that client QoE would be negatively affected.

3. Measure UE QoE during the process.
8.1.4 Mobility Load Balancing – Initiated by Simulated eNodeBs

Device under Test

HetNet with mix of macro and small cells and associated EPC. In a centralized SON deployment, this would also include SON server.

Test Objective

Test a HetNet’s eNodeBs and SON server’s ability to load balance by receiving load from neighboring eNodeBs.

Test Environment
**Test Procedure**

1. This is a load based handover request. Hardware, CPU, RRC, and TNL load are some of the load factors that are exchanged, and each eNodeB determines if it wants to renegotiate a handover threshold. It would be a good idea to include it here.

**Test Results**

The simulated eNodeBs report whether the DUT accepted the handovers. The simulated UEs report which eNB they are associated with. The test validates that the DUT is accept the effect handovers.

**Test Refinements**

Another test would involve a heavily loaded DUT that would initiate a mobility load balancing procedure and handover from the simulated eNodeBs.
8.1.5 Robustness Optimization

Device under Test

HetNet with mix of macro and small cells and associated EPC. In a centralized or hybrid SON deployment, this would also include SON server.

Test Objective

Test a HetNet’s eNodeBs and SON server’s ability to handle cases in which handover failed. There are at least three handover failure scenarios possible: handover too late, handover too early, and handover to a different cell. This test case explores testing handover too early scenario. Similar method could be used for the remaining two scenarios as well.

Test Environment
Test Procedure

The simulated UE reports on the time to perform a handover. The simulated eNodeB report on correct handover failure handling, ending in RLF messages.

Test Refinements

1. Following an adjustment of handover parameters, additional UEs may handed over to the DUT to determine if the new parameters work correctly.

2. While failed handovers are processed in volume, traffic through other UEs connected to the DUT can be used to check that QoE is not affected.

3. Test interoperability for SON controller and eNodeBs where different vendors’ equipment is used. X2 messaging is critical to this testing.

4. Adapt procedure for handover too early and handover to a different cell.
8.1.6 RACH Optimization – UE report based optimizations

Device under Test

HetNet with mix of macro and small cells and associated EPC. In a centralized or hybrid SON deployment, this would also include SON server.

Test Objective

Test an eNodeB’s capability to adapt to conditions that require and trigger RACH optimization actions.

Test Environment
Small Cells, Big Challenge

Test Procedure

Test Results

The UE will verify that the expected RACH optimizations that were performed as a result
8.1.8 PCI selection

Device under Test

Small cell eNodeB.

Test Objective

Test a small cell’s ability to assign its own PCI in a variety of conditions.

Test Environment
Test Procedure

Verify the self-allocated PCI of the DUT.

Test Results

Setup X2 interfaces with various neighbor cells

Test Refinements

Use a variety of combinations of values between the O&M, neighboring cells on X2, and reports from UEs on Uu.
8.2 Testing Network Performance

A heterogeneous network by definition involves different types of device and networks coming together to deliver a high-quality customer experience. This, combined with the move to an all-IP flat architecture and well defined open interfaces with LTE, means that operators can practically build multi-vendor networks. They might do this to obtain better performance, develop a long-term roadmap, or benefit from vendor innovation. The trend to multi-vendor networks is clear if we consider the increase in the number of 4G LTE vendors versus 3G vendors.

One challenge to a multi-vendor network is validating network performance from end-to-end. Each has their own capacities and performance statistics, which must be matched to produce a high-performance end-to-end network. Component performance must be measured and matched using real-world traffic and environments in order to produce a seamless, efficient network.
8.2.1 Home eNodeB (HeNB) Gateway Performance

Device under Test

The femtocell gateway, also known as the home eNodeB gateway, which is used to connect a potentially large number of home eNodeBs to the EPC. Depending on the deployment model, an HeNB gateway could act as MME proxy or MME and SGW proxy. In some cases the home eNodeB GW might also have a built-in security gateway functionality.

Test Objective

- Determine the performance of an HeNB GW with respect to establishing connections with home eNodeBs, data throughput, and QoE.
- Determine device performance statistics under realistic user and control plane traffic.
- Validate network performance under stress for both the user and control planes.
- Prove that fallback schemes function as expected, and measure QoS during failure scenarios.
- Test for negative scenarios, such as paging storm and observe effects of network and device performance.

Test Environment
The initial part of the test validates the number of connections that the HeNB will accept and the maximum rate at which it will accept new connections. This latter number is very important, as it expresses the device’s ability to recover from power or other failures. The remainder of the test may be conducted with the maximum number of connections or with fewer connections. Data may be exchanged using only one UE, or with multiple UEs. Maximum data rates are often obtained with fewer UEs, due to the overhead associated with signaling.

Data tests should simultaneously use voice connections and Internet voice, video and data services. Throughput and QoE for each of the services should be measured overall and for individual users.

Specific measurements that should be made include:

- QoE of VoLTE calls.
- Data sessions should have lower priority than voice and video traffic.
- Control plane latencies should be within expected values, especially attach latency, bearer creation latency, handover latency, and paging latency.

Test Refinements

Throughput and QoE may vary with the number of femtocells. These tests may be performed with increasing numbers of femtocell emulations.
8.2.2  Home eNodeB (HeNB) Gateway as MME Proxy Performance

Device under Test

The home eNodeB gateway used as an MME proxy.

Test Objective

Determine the performance of an HeNB/MME proxy with respect to establishing connections with femtocells, data throughput, and QoE.

Test Environment
Test Procedure

Notes
(1) Perform actions that result in a large number of control plane signaling: attach, detach, handover, paging with IDLE to/from connected transitions, and tracking updates.

Test Results
The initial part of the test validates the number of connections that the HeNB will accept and the maximum rate at which it will accept new connections. This latter number is very important, as it expresses the device’s ability to recover from power or other failures. The remainder of the test may be conducted with the maximum number of connections or with fewer connections. Data may be exchanged using only one UE, or with multiple UEs. Maximum data rates are often obtained with fewer UEs, due to the overhead associated with signaling.

Data tests should simultaneously use voice connections and Internet voice, video and data services. Throughput and QoE for each of the services should be measured overall and for individual users.

Test Refinements
Additional test cases could involve SGW and MME relocation. Throughput and QoE may vary with the handover and paging activities. Throughput and QoE tests can be conducted under an emulation of handover and paging.
8.2.3 Security Gateway Performance

Device under Test

Security gateway (SeGW), often existing as part of an HeNB or other EPC component.

Test Objective

Measure the performance of the SeGW while establishing new and closed connections in addition to supporting the required number of connections. Measure throughput and QoE for users. Performance while handling traffic encryption and other security services is a major consideration.

Test Environment
Test Procedure

Notes

(1) Maximum number of connections: establish UE connections several at a time, waiting for success or failure of each until no more connections are accepted. This test is designed to measure capacity rather than rate.

Maximum connection rate: establish an increasing number of new UE to SeGW connections several at a time. As each connection succeeds or fails, new requests should be attempted.

Test Results

The maximum connection rate is visible from a graph of connections per second over time. There should be no connections that timed out, nor more than a small percentage that failed.

Test Refinement

In both cases, test traffic could be sent over established connections to determine the effect that new connections have on QoE.
8.2.4 HeNB Security under Attack

Device under Test

HeNB and associated security gateway (SeGW).

Test Objective

Measure the susceptibility of the HENB/SeGW to security attacks and measure the performance while under attack.

Test Environment
Chapter 8: Validating Heterogeneous Networks – Test Cases

Small Cells, Big Challenge

Test Procedure

Notes

(1) Establish a level of voice and data traffic from the UEs consistent with peak use, but with excellent call and data QoE.

(2) Determine HeNB’s susceptibility to denial of service attacks from the Internet.
   a. Attempt an increasing number of low level denial of service attacks against the UEs.
   b. Flood the UEs with volumes of data traffic.
   c. Continue to measure call and data QoE.

Test Results

Measurement of UE throughput and QoE while under attack will determine any susceptibility of the HeNB:

1. If throughput goes to 0, then the HeNB has successfully been attacked. Further testing of attacks one at a time, or with increasing volume will determine which the specific vulnerability.

2. If QoE drops below acceptable levels for an unacceptable length of time, then the HeNB may not have the needed capacity to handle the number of UEs.
8.3 Testing Wi-Fi Performance

8.3.1 Wi-Fi Offload Gateway Performance

Device under Test

Wi-Fi offload gateway.

Test Objective

Measure the ability of the Wi-Fi offload gateway to establish connections, to forward traffic, and deliver high QoE.

Test Environment
Test Procedure

![Diagram of test setup](image_url)

**Notes**

1. Connections use a combination of supported authentications: EAP-SIM, EAP-AKA, and open.

   Maximum number of connections: establish UE connections to SeGW several at a time, waiting for success or failure of each until no more connections are accepted. This test is designed to measure capacity rather than rate.

   Maximum connection rate: establish an increasing number of new UE to SeGW connections. As each connection succeeds or fails, new requests should be attempted.

**Test Results**

The maximum connection rate is visible from a graph of connections per second over time. There should be no connections that timed out, nor more than a small percentage that failed. Throughput for each Internet protocol is measured, along with QoE values for video and data services. Voice services should not fall below acceptable levels.

**Test Refinements**

Trusted versus non-trusted access, each requiring a different tunnel type. Trusted connections use GRE tunnels and QinQ. Untrusted connections will use IPsec.
8.3.2 Wi-Fi ANDSF Server Performance

Device under Test

Wi-Fi ANDSF Server.

Test Objective

Measure the effect of ANDSF policies on overall and individual QoE.

Test Environment
Test Procedure

Test is configured, defining UEs and access points

- Network configures UEs with ANDSF policies (OMA)
- UEs use policies to select LTE/Wi-Fi networks, including during offload and handover scenarios
- UEs request data from IP services using voice, video and data services

Test is configured, defining UEs and access points

- LTE/Wi-Fi
- Connections are authenticated and established.
- Forwards traffic to and from Internet

Notes

(1) The ANDSF servers should be configured to distribute policies to the emulated UEs that will case different percentages of UEs to be associated with different LTE and Wi-Fi networks. In addition core networks should be configured to complete authentications, and to provide IP/Internet services.

Test Results

Throughput for each Internet protocol is measured, along with QoE values for video and data services. Policies can be fine-tuned. Voice services should not fall below acceptable levels. Average throughput and QoE values across all UEs and for groups of UEs associated with different data networks should be measured.
8.3.3 Wi-Fi Hotspot 2.0 Performance

Device under Test

Small cells with integrated Wi-Fi access points and independent access points that support Hotspot 2.0.

Test Objective

Measure the ability to authenticate UEs based on Hotspot 2.0 policies.

Test Environment
Test Procedure

![Diagram showing test procedure]

Test Results

Authentication failures should be highlighted.

Test Refinements

Voice, video and data could be sent and received while establishing new connections to determine the effect of authentication on user QoE.
8.3.4 Wi-Fi Maximum Client Capacity

Device under Test

Small cells with integrated Wi-Fi access points.

Test Objective

Measure the maximum number of wireless clients that can be supported by the AP and core networks, with each client transferring a pre-set minimum amount of data per second.

Test Environment
Test Procedure

Client Sim

Device under Test

1. Configure full range of security modes, including open, WEP, WPA and WPA2 with different authentication mechanisms.
2. Configure DHCP server to assign a range of addresses.
3. Configure basic data rates for 802.11a/b/g/n standards.
4. Configure operation on appropriate 2.4GHz or 5GHz band channel.

Configure clients for no authentication/encryption.

Configure clients for range of 802.11 modes.

Configure traffic for UDP 512-byte frames at 10 frames per second.

Connect increasing number of clients to 150% of expected value. Each client should begin transmitting data as soon as it connects.

Repeat with additional types of authentication/encryption.

Test Results

The maximum number of clients supported with traffic using alternative authentication/encryption techniques. A carrier grade system should support at least 100 clients per AP and be capable of transferring data to every connected client at a sustained rate of at least 40Kbps.
8.3.5 Wi-Fi Mixed Mode Throughput

Device under Test

Small cells with integrated Wi-Fi access points.

Test Objective

Measure the bi-directional throughput for wireless clients.

Test Environment
Chapter 8: Validating Heterogeneous Networks – Test Cases

Small Cells, Big Challenge

Test Procedure

![Diagram showing test procedure]

Client Sim

- Configure clients for no authentication/encryption.
- Configure traffic for UDP frame sizes from 88 to 1518 bytes.
- Run several iterations of the test with 10, 20 and 50 clients.

Device under Test

- Configure open authentication.
- Configure DHCP server to assign a range of addresses.
- Configure basic data rates for 802.11n.
- Configure operation on appropriate 2.4GHz or 5GHz band channel.
- Set channel bandwidth to 40MHz.

Test Results

The maximum throughput for each of the iterations. A carrier grade AP and system should achieve the following upstream throughput for 40MHz bandwidth:

<table>
<thead>
<tr>
<th>1518 bytes</th>
<th>1024 bytes</th>
<th>512 bytes</th>
<th>256 bytes</th>
<th>128 bytes</th>
<th>88 bytes</th>
</tr>
</thead>
<tbody>
<tr>
<td>206.35 Mbps</td>
<td>208.51 Mbps</td>
<td>174.47 Mbps</td>
<td>129.82 Mbps</td>
<td>85.62 Mbps</td>
<td>65.66 Mbps</td>
</tr>
</tbody>
</table>

Test Refinements

Repeat the tests with fewer or more AP antennas. Also repeat with 20MHz bandwidth.
8.3.6 Wi-Fi Triple-Play Throughput

Device under Test

Small cells with integrated Wi-Fi access points.

Test Objective

Measure the throughput for wireless clients using voice, video and data services.

Test Environment
**Test Procedure**

![Diagram of test procedure]

**Test Results**

A carrier grade AP and systems should be able to support the different client and traffic loads without loss of stability or progressive degradation in system capacity (e.g. due to memory leaks or CPU overload). Further, all of the voice/video clients and traffic flows should have satisfied their required QoS levels. The latency levels for the data clients should remain under 50 msec.

A carrier grade system should be able to support the different client and traffic loads in a triple-play situation without loss of stability or progressive degradation in system capacity (e.g., due to memory leaks or CPU overload). Further, all of the voice/video clients and traffic flows should have satisfied their required QoS levels. The latency levels for the data clients should remain under 50 msec.

**Test Refinements**

Repeat the tests with alternative QoS settings. Repeat the test with alternate triple-play mixes:

- 40% HTTP data clients, 10% FTP data clients, 30% voice clients, and 20% video clients.
- 30% HTTP data clients, 4% FTP data clients, 33% voice clients, and 33% video clients.
8.4 Validating Backhaul Performance

Device under Test

Backhaul link to EPC.

Test Objective

Validate that the backhaul bandwidth is sufficient to support a specific number of UEs.

Test Environment
Test Procedure

![Diagram](image)

**Notes**

(1) Impairment is applied to backhaul using specific test equipment designed for that purpose.

**Test Results**

For each backhaul capacity, the throughput, and min/max/avg QoE is measured for each service. Note that the highest throughput is obtained with the smallest number of UEs, since signaling detracts from data transmission time.
Acronyms
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANDSF</td>
<td>Access network discovery and selection function</td>
</tr>
<tr>
<td>AP</td>
<td>Access point</td>
</tr>
<tr>
<td>ARPU</td>
<td>Average revenue per user</td>
</tr>
<tr>
<td>BBU</td>
<td>Baseband unit</td>
</tr>
<tr>
<td>BSC</td>
<td>Base station controller</td>
</tr>
<tr>
<td>BYOD</td>
<td>Bring your own device</td>
</tr>
<tr>
<td>CCO</td>
<td>Capacity and coverage optimization</td>
</tr>
<tr>
<td>CSG</td>
<td>Closed subscriber group</td>
</tr>
<tr>
<td>CLV</td>
<td>Customer lifetime value</td>
</tr>
<tr>
<td>CoMP</td>
<td>Cooperative multipoint processing</td>
</tr>
<tr>
<td>CoS</td>
<td>Class of service</td>
</tr>
<tr>
<td>CPRI</td>
<td>Common public radio interface</td>
</tr>
<tr>
<td>C-RAN</td>
<td>Cloud RAN</td>
</tr>
<tr>
<td>DAS</td>
<td>Distributed antenna system</td>
</tr>
<tr>
<td>DL</td>
<td>Downlink</td>
</tr>
<tr>
<td>DoS</td>
<td>Denial of service</td>
</tr>
<tr>
<td>DRC</td>
<td>Dynamic radio configuration</td>
</tr>
<tr>
<td>eICIC</td>
<td>Enhanced ICIC</td>
</tr>
<tr>
<td>eNB</td>
<td>eNodeB</td>
</tr>
<tr>
<td>eNodeB</td>
<td>Evolved node B</td>
</tr>
<tr>
<td>E-RAN</td>
<td>Enterprise radio access network</td>
</tr>
<tr>
<td>E-SCN</td>
<td>Enterprise small cell network</td>
</tr>
<tr>
<td>EPC</td>
<td>Evolved packet core</td>
</tr>
<tr>
<td>EPL</td>
<td>Ethernet private line</td>
</tr>
<tr>
<td>EP-LAN</td>
<td>Ethernet private LAN</td>
</tr>
<tr>
<td>ESC</td>
<td>Enterprise small cell</td>
</tr>
<tr>
<td>ESCC</td>
<td>E-SCN concentrator</td>
</tr>
<tr>
<td>ESCG</td>
<td>E-SCN gateway</td>
</tr>
<tr>
<td>ETSI</td>
<td>European Telecommunications Standards Institute</td>
</tr>
<tr>
<td>EVPL</td>
<td>Ethernet virtual private line</td>
</tr>
<tr>
<td>EVP-LAN</td>
<td>Ethernet virtual private LAN</td>
</tr>
<tr>
<td>FDD</td>
<td>Frequency-duplex divisioning</td>
</tr>
<tr>
<td>FNG</td>
<td>Femtocell network gateway</td>
</tr>
<tr>
<td>GBR</td>
<td>Guaranteed bit rate</td>
</tr>
<tr>
<td>GGNS</td>
<td>Gateway GPRS support node</td>
</tr>
<tr>
<td>GPRS</td>
<td>General packet radio service</td>
</tr>
<tr>
<td>GW</td>
<td>Gateway</td>
</tr>
<tr>
<td>HeNB</td>
<td>Home eNodeB</td>
</tr>
<tr>
<td>Acronyms</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>--------------------------------------------------</td>
</tr>
<tr>
<td>HetNet</td>
<td>Heterogeneous network</td>
</tr>
<tr>
<td>HMS</td>
<td>HeNB management system</td>
</tr>
<tr>
<td>HNB</td>
<td>Home NodeB</td>
</tr>
<tr>
<td>HNB-GW</td>
<td>Home NodeB gateway</td>
</tr>
<tr>
<td>ICI</td>
<td>Inter-channel interference</td>
</tr>
<tr>
<td>ICIC</td>
<td>Inter-cell interference coordination</td>
</tr>
<tr>
<td>IMS</td>
<td>IP multimedia subsystem</td>
</tr>
<tr>
<td>IPsec</td>
<td>IP security</td>
</tr>
<tr>
<td>ISP</td>
<td>Internet service provider</td>
</tr>
<tr>
<td>iWLAN</td>
<td>Interworking wireless LAN</td>
</tr>
<tr>
<td>KPI</td>
<td>Key performance indicators</td>
</tr>
<tr>
<td>LIPA</td>
<td>Local IP access</td>
</tr>
<tr>
<td>LOS</td>
<td>Line of sight</td>
</tr>
<tr>
<td>LPV</td>
<td>Large public venues</td>
</tr>
<tr>
<td>LTE</td>
<td>Long-term evolution</td>
</tr>
<tr>
<td>LTE-A</td>
<td>LTE Advanced</td>
</tr>
<tr>
<td>MIMO</td>
<td>Multiple-in multiple-out</td>
</tr>
<tr>
<td>MSC</td>
<td>Mobile switching center</td>
</tr>
<tr>
<td>NLOS</td>
<td>Non-line of sight</td>
</tr>
<tr>
<td>NGH</td>
<td>NextGen Hotspot</td>
</tr>
<tr>
<td>P2P</td>
<td>Point to point</td>
</tr>
<tr>
<td>PCC</td>
<td>Policy and charging control</td>
</tr>
<tr>
<td>PDN</td>
<td>Public data network</td>
</tr>
<tr>
<td>PDSN</td>
<td>Packet data serving node</td>
</tr>
<tr>
<td>PGW</td>
<td>PDN gateway</td>
</tr>
<tr>
<td>PMP</td>
<td>Point to multipoint</td>
</tr>
<tr>
<td>PPB</td>
<td>Parts per billion</td>
</tr>
<tr>
<td>QAM</td>
<td>Quadrature amplitude modulation</td>
</tr>
<tr>
<td>QCI</td>
<td>QoS class indicator</td>
</tr>
<tr>
<td>QoE</td>
<td>Quality of experience</td>
</tr>
<tr>
<td>QoS</td>
<td>Quality of service</td>
</tr>
<tr>
<td>RAN</td>
<td>Radio access network</td>
</tr>
<tr>
<td>RAT</td>
<td>Radio access technology</td>
</tr>
<tr>
<td>RB</td>
<td>Radio block</td>
</tr>
<tr>
<td>RIO</td>
<td>Return on investment</td>
</tr>
<tr>
<td>RNC</td>
<td>Radio network cell</td>
</tr>
<tr>
<td>RNS</td>
<td>Radio network subsystem</td>
</tr>
<tr>
<td>RRC</td>
<td>Radio resource control</td>
</tr>
</tbody>
</table>
**Small Cells, Big Challenge**

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>RRH</td>
<td>Remote radio heads</td>
</tr>
<tr>
<td>SCaaS</td>
<td>Small cells as a service</td>
</tr>
<tr>
<td>SeGW</td>
<td>Security gateway</td>
</tr>
<tr>
<td>SGW</td>
<td>Security gateway</td>
</tr>
<tr>
<td>SIP</td>
<td>Session initiation protocol</td>
</tr>
<tr>
<td>SLA</td>
<td>Service level agreement</td>
</tr>
<tr>
<td>SON</td>
<td>Self-optimizing networks</td>
</tr>
<tr>
<td>TDD</td>
<td>Time division duplexing</td>
</tr>
<tr>
<td>TDM</td>
<td>Time division multiplexing</td>
</tr>
<tr>
<td>TNL</td>
<td>Transport network local</td>
</tr>
<tr>
<td>TVWS</td>
<td>TV white space</td>
</tr>
<tr>
<td>UE</td>
<td>User equipment (cell phone)</td>
</tr>
<tr>
<td>UL</td>
<td>Uplink</td>
</tr>
<tr>
<td>VAP</td>
<td>Virtual access point</td>
</tr>
<tr>
<td>VoLTE</td>
<td>Voice over LTE</td>
</tr>
</tbody>
</table>