RAN Evaluation of LTE-Femtocell Deployment and TV White Space Secondary Usage

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Abstract

Femtocells and secondary usage of TV white space are two non-mainstream technologies currently at the research edge of mobile industries and academia. However, femtocells have been exclusively assessed by the mobile operators’ point of view, while the TV white space secondary usage concept is being nurtured and has a long way to cover until it becomes technically mature. With incumbent and newly entering stakeholders challenged to find cost-effective ways of serving and exploiting the sharply increasing mobile traffic, evaluating the techno-economic and operational benefits of these solutions from a variant perspective becomes highly valued, but related methodologies are still missing.

This dissertation addressed this gap by proposing a method for the development and techno-economic evaluation of LTE-femtocells and secondary usage of TV white space considering four different types of operators: mobile network operators, wireless internet service providers, facility owners, and TV white space only operators. These actors were examined as LTE-femtocell network operators delivering indoor mobile broadband over the three distinct spectrum paths of licensed, unlicensed, and TV white space spectrum. The network modeling and assessment took into account the assets each actor can activate to deploy and operate the LTE-femto networks in order to generate actor-customized results.

The main findings were that the LTE-femtocell venture is in all cases economically feasible. The indoor LTE-femto networks can deliver 5 Mbps average capacity to 1000 users under stable costs, while when traffic becomes even greater, bandwidth becomes the prominent factor defining the femto network total cost of ownership. Under ideal assumptions, the TV white space secondary usage was found to bear substantial cost reduction benefits compared to licensed spectrum femto deployments, while unlicensed operation was shown to constitute the most cost-effective alternative. Licensed operation might not be the most resource-efficient solution according to the research’s findings, but is the only solution guaranteeing quality of service at the time.
Acknowledgements

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I feel very grateful towards the KTH Wireless department for providing a research-friendly environment and all the means necessary for working creatively.

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Last but not least, I would like to especially thank my colleague Chris for being my fellow traveller in this long and exciting journey.

Ilias Karonis
Stockholm, September 2012
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<th>Full Form</th>
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<tr>
<td>3GPP</td>
<td>3rd Generation Partnership Program</td>
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<tr>
<td>BS</td>
<td>Base Station</td>
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<td>CAPEX</td>
<td>Capital Expenditure</td>
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<td>CR</td>
<td>Cognitive Radio</td>
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<tr>
<td>DSL</td>
<td>Digital Subscriber Line</td>
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<tr>
<td>EDGE</td>
<td>Enhanced Data rates for GSM Evolution</td>
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<td>EPC</td>
<td>Evolved Packet Core</td>
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<td>EPS</td>
<td>Evolved Packet System</td>
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<td>E-UTRAN</td>
<td>Evolved Universal Terrestrial Radio Access Network</td>
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<tr>
<td>FAP</td>
<td>Femtocell Access Point</td>
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<tr>
<td>FDD</td>
<td>Frequency Division Duplex</td>
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<tr>
<td>GSM</td>
<td>Global System for Mobile Communications</td>
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<tr>
<td>GPRS</td>
<td>General Packet Radio Service</td>
</tr>
<tr>
<td>GTP</td>
<td>GPRS Tunneling Protocol</td>
</tr>
<tr>
<td>HeNB</td>
<td>Home Enhanced Node B</td>
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<td>HSPA</td>
<td>High Speed Packet Access</td>
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<tr>
<td>IP</td>
<td>Internet Protocol</td>
</tr>
<tr>
<td>IPsec</td>
<td>IP security</td>
</tr>
<tr>
<td>ISM</td>
<td>Industrial, Scientific, and Medical (radio bands)</td>
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<tr>
<td>ISP</td>
<td>Internet Service Provider</td>
</tr>
<tr>
<td>LAN</td>
<td>Local Area Network</td>
</tr>
<tr>
<td>LIPA</td>
<td>Local IP Access</td>
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<tr>
<td>LTE</td>
<td>(3GPP) Long Term Evolution</td>
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<tr>
<td>MIMO</td>
<td>Multiple Input Multiple Output</td>
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<tr>
<td>MME</td>
<td>Mobility Management Entity</td>
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<tr>
<td>MNO</td>
<td>Mobile Network Operator</td>
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<td>OFDMA</td>
<td>Orthogonal Frequency Division Multiple Access</td>
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<td>Abbreviation</td>
<td>Full Form</td>
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<tr>
<td>OPEX</td>
<td>Operational Expenditures</td>
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<td>O&amp;M</td>
<td>Operation &amp; Maintenance</td>
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<tr>
<td>QoE</td>
<td>Quality of Experience</td>
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<tr>
<td>QoS</td>
<td>Quality of Service</td>
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<tr>
<td>PoP</td>
<td>Point of Presence</td>
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<tr>
<td>RAN</td>
<td>Radio Access Network</td>
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<td>RAT</td>
<td>Radio Access Technology</td>
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<tr>
<td>RRM</td>
<td>Radio Resource Management</td>
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<tr>
<td>SCT</td>
<td>P Stream Control Transmission Protocol</td>
</tr>
<tr>
<td>SGW</td>
<td>Serving Gateway</td>
</tr>
<tr>
<td>SINR</td>
<td>Signal to Interference plus Noise Ratio</td>
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<tr>
<td>SIPTO</td>
<td>Selective IP Traffic Offload</td>
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<tr>
<td>SLA</td>
<td>Service Level Agreement</td>
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<tr>
<td>TCO</td>
<td>Total Cost of Ownership</td>
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<tr>
<td>TDD</td>
<td>Time Division Duplex</td>
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<tr>
<td>TDM</td>
<td>Time Division Multiplexing</td>
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<td>TVWS</td>
<td>TV White Space</td>
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<tr>
<td>TVWSO</td>
<td>TV White Space only Operator</td>
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<tr>
<td>UDP</td>
<td>User Datagram Protocol</td>
</tr>
<tr>
<td>UMTS</td>
<td>Universal Mobile Telephony System</td>
</tr>
<tr>
<td>WCDMA</td>
<td>Wideband Code Division Multiple Access</td>
</tr>
<tr>
<td>WiMAX</td>
<td>Worldwide Inter-operability for Microwave Access (IEEE 802.16)</td>
</tr>
<tr>
<td>WISP</td>
<td>Wireless Internet Service Provider</td>
</tr>
<tr>
<td>WLAN</td>
<td>Wireless Local Area Network</td>
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Chapter 1

Introduction

Internet is nowadays shifting from a service available at certain locations to a ubiquitous anytime service. The increasing overlap of the internet and mobile domains in combination with the explosive growth of data traffic challenge the mobile market and create unprecedented requirements for the successful and profitable provisioning of mobile broadband.

After an intense upward trend, the mobile broadband market is entering the maturity phase. Following end-users, web-based applications and services migrate from wireline to wireless at high numbers. A plethora of newly developed mobile applications and handsets try to match the high demands of end-users developed through their fixed broadband experience. The number of fixed and mobile devices connected to the internet cloud is also growing at an accelerated pace, making the information technology experts picture the cloud in its future state as the ‘Internet of Things’. Taking into consideration more uprising trends, such as cloud computing and high definition (HD) content, the mobile market is preparing for the arrival of a vast data traffic growth with staggering capacity demands.

The mobile market is becoming an environment where new threats and opportunities emerge. As non-traditional actors such as internet service providers (ISPs) and wireless internet service providers (WISPs) enter the mobile business arena, and incumbent operators are in increasing need of low-cost capacity, innovating solutions in technology, infrastructure planning, marketing strategies and business models may prove crucial to the success, if not the survival, of even well-established mobile business entities [1].

1.1 Background

1.1.1 The ‘traffic tsunami’

The vast data traffic growth phenomenon, referred to as the ‘traffic tsunami’, ‘avalanche of data’, and ‘exabyte flow’, has become the center of an intensive debate with two main discussion points: a) whether the mobile infrastructure can handle the rising data volume and b) whether the flat rate pricing can bring sufficient revenues.

The dominant theory forecasts a continuous traffic growth which will cause a traffic-revenues decoupling, known as the revenue gap [2]. On the other hand,
Chapter 1. Introduction

a community part opposes the conclusion that revenues are not keeping up with the traffic growth, supporting that the mobile data traffic growth is attributed to the heavy-user profile of the early adopters and will slow down as mobile broadband reaches the top of the s-curve. Operator data show that the average data consumption per user tends to decline, and existing solutions, if viewed from a marginal cost perspective, can successfully cope with the traffic demand and the revenue requirements [3].

1.1.2 Increased demand for indoor capacity

The mobile data traffic growth along with the strict quality of experience (QoE) requirements of manifold new web applications and services for mobile handsets lead to a soaring demand for mobile capacity. According to recent researches, approximately 70-90% of this mobile data traffic is generated indoors [4], a fraction forecast to reach 95% by 2015 [5].

While mobile traffic is generated indoors at an increasing pace, indoor environments typically confront poor coverage and quality degradation due to the additional attenuation caused by the building penetration losses. Compensating this degradation through dedicating more radio resources is no longer adequate under the pressure buildup for improved capacity and coverage. Taking all above facts into account, cost-effective ways of delivering wireless indoor capacity are becoming valuable.

1.1.3 Traditional barriers no longer impenetrable

The mobile business has traditionally had two major entry barriers keeping would-be suitors at a distance: costly network infrastructure and spectrum licensing. However, things seem to be presently changing.

Wireless access shifts to Internet protocol (IP) architecture, indicative of which is the recent example of the market-driven migration of terrestrial trunked radio (TETRA) from time division multiplexing (TDM) to IP. Long term evolution (LTE) seems to be winning the fourth generation (4G) race against worldwide interoperability for microwave access (WiMAX), bringing an all-IP end-to-end mobile network architecture for the first time. Unlicensed IEEE technologies such as 802.11 Wi-Fi empower IP-centric operators to reach mobile users and new business models flourish (FON, The Cloud, Glocalzone) without the need for deployment and operation of costly macro layer mobile infrastructure or spectrum licenses.

The long term licensing of spectrum has been protecting its owners from new entrants, resulting in the formation of powerful oligarchies in most national mobile markets. Moreover, this policy has led to ineffective management of spectrum resources, and sharing alternatives are increasingly gaining attention to address this issue. Among these considered alternatives is the exploitation of frequencies unused or unoccupied at specific locations and times, initially allocated for broadcasting TV or radio services. These frequencies are referred to as white space.

In conclusion, future mobile networks might not strictly remain an infrastructure neither a long term spectrum licensing business as new technologies and policies make their appearance into the transforming mobile landscape.
1.2 Problem Formulation

In such an uncertain and intensely competitive environment, innovative network models can prove extremely valuable. TV white space (TVWS) secondary usage and femtocell deployment are two of the non-mainstream concepts promising to make an impact on the radio access network (RAN) segment.

From a technical point of view, both options have been evolving. Cognitive radio (CR) [6], geolocation databases, and opportunistic spectrum access mechanisms [7] [8] have made significant progress for addressing the two key technical challenges for the secondary usage of TVWS: spectrum scanning and interference management [9]. The adequacy of femtocells as a radio access solution has also been widely studied in all of its major technical aspects: interference management, quality of service (QoS) and security over a 3rd party backhaul, operation and maintenance (O&M), seamless handover and network interoperability. The technical specifications for LTE femtocells have been standardized by the 3rd generation partnership program (3GPP) providing the means for large scale production and deployment of femtocell devices.

While the way for the industrial femtocell roll-out has been paved, actual techno-economic deployment models have been considered almost exclusively from the mobile network operator’s (MNO) point of view. Regarding TVWS secondary usage systems, they might have entered trial phase but their techno-economic evaluation is still underdeveloped, even for MNOs. As a result, the LTE-femtocell and TVWS solutions’ potential at the RAN side remains largely unidentified.

This gap was addressed by the present work by examining four different actors as candidate femto operators providing mobile broadband: MNOs, WISPs, facility owners (FO), and TVWS-only operators (TVWSO). Examining the femtocell and TVWS approaches from a RAN perspective, the main research questions have as follows:

- What costs are involved for different actors to deploy and operate an indoor LTE-femtocell RAN over licensed, unlicensed, and TVWS spectrum?
- Which key network benefits\(^1\) and handicaps does each spectrum alternative offer?
- Is it feasible to deploy and operate LTE-femto RANs over TVWS?
- How does traffic increase impact on the size and cost of the actor-customized RANs?

1.3 Related work and contribution

Most femtocell and TVWS related work revolve around technical features and challenges and techno-economic studies have been more limited. In [10], the findings of the 2009 Signals Research Group report for the Femto Forum indicated strong femtocell business cases under a plethora of varying mobile operator situations on a global basis. However, the research adopts exclusively the mobile

\(^1\) In the Thesis context, the term network benefits is defined and used herein below as a) capital expenditure (CAPEX) and operational expenditure (OPEX) cost savings, b) network performance improvements in terms of capacity and complementary operational features.
network operator’s point of view and focuses on the residential use case, excluding installation and deployment costs. In [11], Markendahl and Mkitalo assessed the indoor mobile broadband access service provided by a local operator using TVWS secondary resources as a viable business case, carrying out a high-level analysis. Furthermore, the research concluded that the major cost driver for deploying macro TVWS infrastructure is site acquisition, motivating further investigation of the indoor deployment case. In [12], Lin et al. discussed the business mode in macro-femto heterogeneous networks, proposing three different frameworks based on the deployment type of femtocells. In [13], Johansson developed a methodology for evaluating the cost structure of macro layer and wireless local area network (WLAN) heterogeneous networks and proposed cost-effective deployment strategies for mobile operators. This methodology was not applied for femtocells or scenarios different than the MNO licensed case. In [14], Katsiyannis et al. developed a quantitative model for evaluating the costs and revenues of operating public local area access from the point of view of mobile operators and service application providers. However, this model did not take into consideration neither different spectrum types nor was femto-specific. In [15], Loizillon et al. performed a techno-economic analysis discussing strategies for large scale deployments.

The contribution of this Thesis was the introduction of a simplified method for the development and techno-economic assessment of RAN models customized for a set of four different actors: MNOs, WISPs, FOs, and TVWSOs, considering three spectrum types: licensed, unlicensed, and TVWS spectrum. In this way, LTE-femtocell deployment and TVWS secondary usage were seen from multiple perspectives in order to reveal their highly relative costs and benefits and have a more complete understanding of their potential in delivering indoor mobile broadband.

1.4 Thesis Outline

The Thesis backbone was the design, dimensioning and techno-economic evaluation of customized LTE-femto RAN models. Taking into account the assets each actor can activate in order to provide indoor LTE-femto coverage, a simplified method of estimating customized infrastructure costs was proposed. The method was applied for three spectrum paths: licensed, unlicensed, and TVWS spectrum. In order to discover how the cost structure is affected by the growing user traffic, each femto RAN was dimensioned to serve scaling number of users. Furthermore, a Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis and qualitative technical analysis of each RAN implementation was performed. For gathering primary input data and sanity check of employed parameters members of different origin within the mobile domain were interviewed. The Thesis methodology is more analytically discussed in Chapter 2.

In Chapter 3, the femtocell and LTE technologies are examined from a technical and economic perspective, mentioning use cases, proposed architecture variations, deployment strategies, requirements, and potential benefits.

Chapter 4 introduces the three different spectrum usage paths of licensed, unlicensed, and TVWS spectrum. In equivalence to the previous chapter, each solution is assessed by a techno-economic aspect at an initial high-level, examining use cases, impact of each path on infrastructure requirements, deployment
strategies, and potential benefits, including significant regulatory issues.

In Chapter 5, the RAN design, dimensioning, and cost structure models are described including parameter values and assumptions.

The Preliminary Analysis of Chapter 6 introduces the examined actors and their assets, presents the scenarios that were investigated, and discusses key considerations that differentiate the RAN design, dimensioning, and cost structure over the different spectrum paths.

In Chapter 7, the qualitative and quantitative results are presented.

Chapter 8 attempts to filter the results in order to highlight the most important findings, answer the research questions, and state what is the essence someone should keep from this work, pointing towards future directions that could extend the dissertation’s context and utility.
Chapter 2

Methodology

2.1 Outline

The femtocell and TVWS concepts have been widely discussed in the telecommunications sector and their potential has been mentioned in many academic and industrial studies. However, a methodology of estimating the cost structure of actor-customized deployment arrangements has not been developed yet.

In this Chapter we proposed a simplified method to construct and quantify the cost structure of LTE-femtocell deployments for a set of four different actors: MNOs, WISPs, FOs and TVWSOs, considering the alternatives of licensed, unlicensed, and TVWS spectrum. Among all the possible scenarios represented by the different formed actor-spectrum pairs, a preliminary analysis was performed to focus on those scenarios that combined motivation and feasibility, as thoroughly described in section 6.2 of the ‘Preliminary Analysis’ Chapter.

As traffic growth in future mobile networks is extremely hard to forecast, it is substantial to have an estimation of how the actor-customized RAN deployment and operational costs adapt to traffic demands. This estimation was modeled...
as a one-way sensitivity analysis conducted for the RAN cost structure models, where the number of users and the average capacity demand per user were modeled as independent variables, and CAPEX and OPEX as dependent variables.

In order to give a more complete answer to the research questions expressed in the ‘Problem Formulation’ section, besides the cost structure model design, dimensioning and sensitivity analysis, SWOT and qualitative technical analysis were used as a means to assess important operational features and business aspects.

The methodology breakdown leads to the following distinct tasks:

1. **Literature study** and **interviewing** of mobile community members to identify business actors with a strong business case, gain insight on the core their activities, assets, challenges, and place in the mobile market, collect primary data for the component costs of the RAN cost structure model, as well as to perform sanity check of assumptions and parameter values.

2. Implementation of **network design and dimensioning** for the scenarios stated in section 5.2, producing scenario-customized RAN models.

3. **Cost structure** drafting of the RAN models.

4. **One-way sensitivity analysis** of the cost structure models as a function of input number of users and average capacity per user input variables.

5. **SWOT analysis** discussing substantial actor-specific internal and external factors influencing the LTE-femto RAN deployment and operation venture.

6. **Qualitative interpretation** of the RAN models’ synthesis and their cost structure results as a means to reveal the actor-specific benefits of each model.

The individual models for the tasks of network design and dimensioning, cost structure, and one-way sensitivity analysis are thoroughly described in Chapter 5 ‘RAN Design, Dimensioning, and Cost Model’.

2.2 Assumptions

The main objective of the research was to develop and techno-economically evaluate tailor-made RAN deployment models. Towards this end, bold assumptions were employed over some key issues:

- High mobile broadband service demand and paying users were assumed.

- Since adequate TVWS availability is a vital parameter for the enablement of TVWS secondary usage, we assume that there are sufficient TVWS resources available for secondary use at all times.

- LTE operation is extended over TVWS and unlicensed spectrum.
Full utilization of available unlicensed and TVWS band spectrum resources was assumed.

Working CR technology was assumed. In reality, the roll-out of CR capable base stations (BS) is still in trial phase, while database-assisted secondary systems are a feasible alternative favored by many regulators.

The TVWSO is a hypothetical entity inserted to examine the potential of TVWS operation more thoroughly. We assumed that the TVWSO had already made a successful market entry.

These assumptions followed an optimistic approach that examined a best-case scenario for the TVWS secondary usage and unlicensed band operation. If the deployment and operation of a TVWS-based or unlicensed-based femto RAN turn up to be unattainable or bear no substantial benefits under these ideal conditions, then there would be no real motivation for the venture.

In contrast, a promising techno-economic RAN model case proven under ideal assumptions would not eradicate underlying problems. As most of the aforementioned issues were crucial for the overall network evaluation, the above assumptions were removed during the SWOT and qualitative analysis procedures.

2.3 Data Collection

The empirical input data was collected through two methods: literature study and interviews. The literature study content included published papers from standardization bodies and academic institutions, textbooks, data sheets, and white papers from mobile actors such as operators, manufacturers, and telecommunications organizations.

When planning the interview methodology, it was taken care of that respondents held different positions in different business actors in order to acquire a varied sample of perspectives.

The interview respondents were:

- Tord Sjölund, President, Mic Nordic (Vendor)
- Anders Norberg, Director of Node B product line, COMMSCOPE (Vendor)
- Örjan Fall, Vice-president, 3GNS Telecom Group (IT R&D, Services, and Consultancy)
- Panayotis Chiras, Network Administrator, Technical Institute of Cyprus, (Facility owner)

2.4 SWOT and Qualitative Analysis

The generated RAN models were assessed in a qualitative manner to point out technical, economical, and business points of importance. The main issues considered in the qualitative analysis are listed as follows:
• What is the initial capital requirement for building the femto network?
• What is the cost to keep the femto network up and running?
• Is end-to-end QoS provisioning possible?
• Does the actor have independence in operating and managing the network or does running the femto network rely on 3rd party entities (e.g. backhaul provider)?
• Can access be protected and QoS guaranteed?
• Is the RAN network capable of core network offloading?
• Is there a modified or dual mode handset requirement?
• What are the pros and cons of each examined backhaul solution?
Chapter 3

LTE-femtocells

3.1 Femtocells

3.1.1 Introduction

Femtocells are low-power, small area coverage BSs, typically designed for operation in residential or small business environments, that route mobile traffic to the operator’s core network (CN) through an existing fixed broadband connection [16]. The femtocell access points (FAP) are designed to be plug-and-play, self-configurable, network managed, and to require zero end-user intervention and on-site tuning.

The introduction of the femtocell concept brings forward a diverse set of use cases: indoor standalone femtos for homes, indoor networked femtos for enterprises, public hotspots networked femtos with open access, outdoor femtos used as mobile relays for transport media, outdoor femtos used as fixed relays.

3.1.2 Benefits

The key technical benefits of using femtocells over macro BSs are signal quality enhancement and coverage improvement, as well as load sharing [17]. The same structural wall attenuation limiting the indoor coverage and capacity of macrocell BSs has a positive effect on femtocell networks’ performance, since the walls provide an isolation barrier for cross-layer and inter-terminal interference. Providing superior indoor coverage and capacity translates to better QoE, fixed and mobile convergence, advantageous price plans, and new personalized services for the end-user [18].

Femtocells can deliver operational cost reduction by backhauling the RAN traffic through existing IP connections. The cost-effective, IP-based femtocell architecture is attractive towards all different kinds of mobile actors. MNOs find a candidate to offload their macrocell networks ever-increasing traffic, lowering service delivery costs and avoiding costly investments in further macro network upgrades; ISPs obtain a pathway to reach mobile customers leveraging their IP infrastructure; FOs come across a way to offer value added services in order to support their core businesses or gain competitive advantages.
3.1.3 Operational Requirements

The modern cooperative concept of using small cells for mobile coverage and capacity provisioning shows increased complexity, posing unprecedented challenges and requirements that demand developments beyond trivial solutions.

Legacy infrastructure deployed to serve nodes of the order of thousands is unable to support the sheer number of small indoor cells expected in the imminent future. At a large scale, optimization becomes an arduous task and costs of management based on human intervention are unsustainable, while the femto form-factor augments on-site operation complexity. All above reasons call for as simple as possible deployment models and novel management systems performing consolidated mass-management. The so far promoted solution is pushing intelligence to the femto edge to incorporate self-organization, self-configuration, and self-optimization capabilities that can decentralize and minimize costs of planning, deployment, optimization, and maintenance.

What is more, delivering end-to-end QoS requires the adaptation of backhaul links to monitor QoS metrics such as packet delay, jitter, and loss rate over the backhaul segment. This task’s difficulty is intensified if the backhaul is non-dedicated, owned or operated by a 3rd party ISP. The untrusted 3rd party backhaul must also be secured through IP security (IPsec), requiring the establishment of a bidirectional transport relationship.

Last but not least, the multitude of use cases itself suggests that a femto operator needs to have a wide variety of solutions adapted to meet the plethora of case-specific requirements.

3.1.4 Deployment Strategies

There are two main femto deployment strategies: a) Femtocells are deployed as ‘islands’ without centralized management or frequency planning, in an ad-hoc fashion identical to the one used in Wi-Fi. b) Femtocells are integrated into the existing macro network’s planning and management. Naturally, the second is an option only in the presence of a co-channel macro layer and it is currently MNO-specific.

The adequacy of each strategy depends on the use case and its scalability. In the residential scenario for instance, FAPs can be deployed in an ad-hoc manner by the users themselves, cutting CAPEX and OPEX from the operator. In contrast, deployments of femtocells in facilities like enterprises or shopping malls would require more careful planning to achieve optimization of operation and management without degrading the macro network performance.

3.2 LTE

The LTE is a wireless communication standard was developed by 3GPP, specified for the first time in release 8. As a part of the evolved packet system (EPS), the LTE RAN is called evolved universal terrestrial radio access network (E-UTRAN), while the CN of the EPS is named evolved packet core (EPC). The EPS constitutes the first mobile network architecture shifting all traditional circuit-switched operations to the IP domain. The all-IP EPS implements a flattened architecture with fewer network elements targeting at providing high data rates, low latency and packet-optimization.
Expanding the global system for mobile communications (GSM)/enhanced data rates for GSM evolution (EDGE) and universal mobile telephony system (UMTS)/high speed packet access (HSPA) technologies, LTE employs new digital signal processing, modulation, coding schemes, and scalable bandwidth usage, delivering improved spectral efficiency (2 to 4 times more than 3GPP release 6).

The worldwide-first LTE-based service was launched in Oslo and Stockholm on 14 December 2009 by TeliaSonera. Although LTE is marketed as a 4G technology, the release 8 and 9 LTE specifications do not satisfy the international mobile telecommunications (IMT) advanced requirements set by the radiocommunication sector of international telecommunication union (ITU-R), a goal to be fulfilled by LTE-Advanced. Release 12 procedures have already started and candidate features such as integration of machine-to-machine communication integration, direct terminal-to-terminal communication, advanced small cell technologies, and more energy-saving carrier types are examined.

3.2.1 Technical Features - Requirements

LTE accommodates scalable bandwidths and supports both paired spectrum for frequency-division duplexing (FDD) and unpaired spectrum for time-division duplexing (TDD). In the uplink, single carrier frequency division multiple access (SC-FDMA) is used, while orthogonal frequency division multiple access (OFDMA) is used in the downlink. By dividing the time and frequency dimensions to multiple users, OFDMA can achieve higher granularity and more effective utilization of radio resources.

LTE uses adaptive modulation, including three modulation schemes: QPSK, 16QAM, and 64QAM which is the highest modulation scheme. Among the main features of LTE is the sub-5 ms latency requirement for the RAN and the sub-10 ms end-to-end round-trip time.

3.2.2 Evolved Packet Core (EPC)

The EPC implements a much flatter IP architecture as opposed to the tiered 3G architecture which employs radio network controllers, S/G-GSN hierarchy and asynchronous transfer mode (ATM) transport. The cascade of Iu interfaces in 3G UMTS has been replaced by the S1 interface. What is more, LTE introduces the X2 interface for interconnecting eNBs, enabling a portion of the control traffic to be routed via the aggregation node without traversing the CN.

The key advantage of the EPC is the scalability of its core elements to handle the rising volume of connections, bandwidth and mobility requirements.

3.2.3 LTE-enabled femtocells

LTE-enabled FAPs are referred to as Home evolved Node Bs (HeNB) in the 3GPP terminology. In this work, we will interchangeably use the terms FAP and HeNB to refer to femtocell BSs.

LTE is a diversity-based technology and multiple-input multiple-output (MIMO) benefits can be enhanced in indoor environments, which represent rich sources of multi-path signals. As a result, LTE can perform at highest modulation rates and achieve greatest spectral efficiency in indoor environments.
On the other hand, satisfying the strict end-to-end latency and delay requirements of LTE over a possibly non-dedicated backhaul is going to be extremely challenging.

Besides the improved performance Examining LTE-femtocell deployments is also motivated by the dominant opinion that the migration to LTE should be done in an ‘inside-out’ manner, covering indoor locations with concentrated traffic demands first and then moving to the integration of LTE in wide area networks.

3.2.4 LTE and TVWS

When it comes to LTE operation over TVWS, the main problem identified is spectrum availability. As Petri Mähönen, Head of RWTH Institute for Networked Systems of Aachen, wonders ¹, “Are operators eager to deploy TVWS-based infrastructure when TVWS resources are not guaranteed”?

In indoor environments however, the situation is more promising since sufficient TVWS resource availability, more thoroughly described in section 3.2.3 dedicated in TVWS, can be assumed due to the wall “shielding” effect. Thus, it is well-founded to explore the potential of operating LTE-femtocells in TVWS.

3.3 LTE HeNB architecture

The femtocell integration into the EPS can be implemented in three variations defined by the role and location of the HeNB gateway (HeNB-GW). The HeNB-GW can act as a concentrator combining traffic from multiple HeNB sources, thus reducing the number of S1 connections towards the CN in either or both user plane and control plane. The mobility management entity (MME) lies in the control plane and the serving gateway (SGW) is the EPC element that handles user plane traffic.

3.3.1 Variation 1 HeNB-GW as both c-plane and u-plane gateway

In the first variation, the HeNB-GW terminates all stream control transmission protocol (SCTP) connections and the general packet radio service (GPRS) tunneling protocol (GTP) tunnels and opens new ones towards the MME and the SGW.

This architecture provides security as the addresses of the MME and SGW core elements are not exposed, and denial of service (DoS) can be prevented. The HeNB-GW aggregates the SCTP connections from the HeNBs to the MME, maintaining only one active connection towards the MME regardless of the number of operating HeNBs, protecting the MME from user-originated on and off switching that would result in a high number of connection releases and reestablishments. Similarly, the SGW sees only one GTP/user datagram protocol (UDP) tunnel, which is easier to handle.

On the other hand, increasing numbers of connected HeNBs put stress at the HeNB-GW side due to the tunnel and SCTP switching. For this reason,

¹Crowncom 2012 7th International Conference on Cognitive Radio Oriented Wireless Systems, Stockholm
the HENB-GW has the highest scalability requirements among the EPC core elements. The HeNB-GW is a single point of failure, while load sharing cannot be achieved as femtocells connect to a single gateway.

Moreover, this scheme allows HeNB-GW to perform paging optimization and offload traffic off the mobile packet core through selective IP traffic offload (SIPTO). HeNBs do not need to support S1-flex, leading to fewer S1 connections and simplifying the HeNB equipment implementation.

This architectural variation is most adequate when there are high scalability requirements, for instance in the residential deployment scenario where large HeNB numbers are involved. Under this scenario, it would be most beneficial for operators to minimize the traffic and processing load in their CN.

3.3.2 Variation 2 HeNB-GW as c-plane gateway only

In this variation, the HeNB-GW acts a control plane-only concentrator, maintaining a unique SCTP connection towards the MME. Opposingly, user plane traffic heads directly towards the SGW.

This architectural scheme protects the MME from flooding and massive connection maintenance, release and reestablishment, but poses high scalability requirements for the SGW which directly handles all GTP/UDP tunnels. Offloading the SGW off the user plane traffic through SIPTO can now be performed in a decentralized way since the SIPTO gateway is not necessarily based on the HeNB-GW. As the GTP tunnels terminate directly at the SGW, lower latency and reduced system level processing are achieved in the U-plane. Under this
variation there is no single point of failure for the user plane, as well as no S1-flex support is required at the HeNB side.

At the downside, when high numbers of HeNBs are deployed, the SGW might face overload issues that will pose the need for additional or dedicated SGWs. The SGW resource consumption originates mostly from the GTP-echo mechanism processing and secondarily from the GTP/UDP impact.

3.3.3 Variation 3 No HeNB-GW

This is the simplest architecture where no HeNB-GW is present. All SCTP connections and GTP tunnels terminate directly at the MME and SGW equivalently.

![Figure 3.3: HeNB architecture without HeNB-GW presence](image)

The main advantages of this variation are its architectural simplicity and flatness; the absence of HeNB-GWs leads to cheaper arrangements with fewer network elements to deploy and manage. Moreover, the incorporation of S1-flex support on the HeNBs can provide for compatibility with the macro architecture.

Nevertheless, this scheme exposes the MME and SGW IP addresses and leaves the MME vulnerable to flooding and uncontrolled on-and-off switching. As there is no control or user plane concentrator, large scale deployments might lead to overloading of the MME and SGW from SCTP heartbeats and GTP-echo messaging respectively.

There is no single point of failure, represented by the HeNB-GW in the two previous variations. Moreover, SIPTO gateways do not need to be collocated in the absence of HeNB-GW.

This variation is most suited when there are small numbers of managed HeNBs or when the HeNBs’ locations are geographically scattered.

3.3.4 HeNB architecture comments and conclusions

- The breakpoint after which the HeNB-GW is required is mostly defined by the capacity of the MME, which is the most sensitive core element to raising scalability.

- There is no standardized scheme for cooperation neither among femtocells nor between the femto and macro BSs. In the macro layer BSs are connected via X2 interfaces enabling decentralized mobility management, and the same method is assumed for HeNB interconnection.
3.3. LTE HeNB Architecture

- In all variations, if the backhaul is not dedicated the HeNB system mandates the presence of a security gateway (SeGW) logical entity to secure the untrusted IP backhaul using IPsec. The SeGW can be collocated with another physical entity or constitute a separate physical entity.
Chapter 4

Spectrum

4.1 Introduction

Accommodations of new startups and capacity extensions for incumbent operators are driving the demand for additional spectrum, which has become one of the most valuable commodities traded by governments. It is one of EUs ongoing tasks to identify 1200 MHz more, suitable for mobile broadband access.

Has spectrum indeed become scarce or does the long term license-based management policy result in its improvident usage? As Catarina Wretman, deputy director-general at the Swedish regulator National Post and Telecom Agency (PTS), points out regarding fixed radio spectrum allocation 1, “The spectrum problem is a problem we have created by giving exclusive usage rights. Sharing is the solution”. At the same wavelength, the director of Wireless@KTH Jens Zander says2: “There is no real shortage of frequency space. It is really a management problem on how to distribute resources in the best and most efficient manner”. It is a common secret that the long term licensing regulation of the market exacerbates the problem and impedes the introduction of more efficient cooperative access schemes [19].

As adding spectrum can no longer be a panacea for the capacity problem, technical or regulatory solutions able to enhance the efficiency of overall spectrum usage and prevent the exclusive spectrum usage from creating a bottleneck for wireless communications are nowadays highly valued.

4.2 Spectrum alternatives for femto deployment

4.2.1 Licensed spectrum

Licensing spectrum is the traditional way to achieve interference and congestion protection, whereby licensed wireless systems get exclusive access to a block of spectrum reserved for their services. Typically, deployed LTE systems utilize licensed blocks of 10 or 20 MHz.

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2Interview to Jannecke Schulman, available at the KTH Wireless Department website: http://www.wireless.kth.se/about/researchers/research-leaders/25-jens-zander-common-right-of-access-on-the-airwaves.
Regarding licensed spectrum, operators can follow two distinct deployment paths:

(a) Co-channel deployment. In the co-channel model, femto and macro networks operate over common spectrum. This option is more cost-effective as the channel remains idle for less time, thus achieving better utilization of the licensed spectrum resources. Nevertheless, since femto and macro cells share the same carrier, femto-macro interference needs to be well managed on both uplink and downlink directions, requiring precise engineering planning for interference mitigation in the desired coverage areas.

The access mode is also important; when it comes to access, femtocells can be deployed as closed, open, or hybrid cells. Under the closed access scheme, the uplink interference caused by the femto network to non-permitted handsets must be limited in order to avoid causing coverage holes in the macro network.

(b) Dedicated channel. In the dedicated channel model, femto networks have a separate chunk of spectrum for exclusive usage. The direct advantages over the co-channel arrangement are isolation of cross layer interference effects and guaranty of no degradation in the macro network performance [20]. On the downside, the need for additional licensed spectrum makes this solution less cost-effective. The access scheme does not affect the macro layer performance in this case.

4.2.2 Unlicensed spectrum

Facilitated by the open and approval-free unlicensed regime, systems and business schemes in industrial, scientific, and military (ISM) bands have been impressively evolving in the recent past.

On one hand, higher spectral efficiency is achieved compared to the exclusive access scheme where licensed devices can remain idle for a significant amount of time. On the other hand, there is the inherent risk of increased interference as a result of the uncoordinated spectrum usage and the ad-hoc deployment fashion. As there is no limit to the number of unlicensed devices in a location, coexistence is based on constraining interference levels and unlicensed devices are usually low-power as a means to achieve that.

For the above reasons, unlicensed bands are commonly used for services not requiring QoS, such as best-effort WLANs. Nevertheless, where the ISM bands congestion is prevented spectrum utilization can become significantly high. Recent 802.11n and 802.11ac TDD MIMO implementations have been able to utilize 40 MHz and 160 MHz bandwidths in the 2.4 GHz and 5 GHz ISM bands respectively.

4.2.3 TVWS

4.2.3.1 Introduction

The TV broadcasting analogue-to-digital switchover freed significant portions of the analogue TV broadcasting spectrum, known as digital dividend. Even though significant spectrum portions will be dedicated to digital video broadcasting terrestrial (DVB-T) used for digital terrestrial television (DTT) and
wireless microphone transmissions, the spectrum allocation of these primary services depends on the geographic region, i.e. not the whole spectrum will be used for DTT at a particular place, resulting in unoccupied bands which are geographically interleaved.

The viability of using TVWS for secondary services such as mobile broadband access is being closely examined by the wireless community, largely due to the excellent propagation characteristics of these frequencies. Naturally, the main prerequisite is that no harmful interference is caused to the primary users which should be protected at all times.

Governments and regulators are also moving towards the direction of exploiting TVWS: the recent rulings of the US Federal Communications Commission (FCC) [21,22,23] and the UK Office of Communications (Ofcom) [24,25] made significant portions of TVWS available for unlicensed use. The adoption of similar measures is expected in Europe in order to support the mobile data traffic growth in the increasingly complex and over-crowded urban spectrum environments.

4.2.3.2 Enabler technologies and uncertainties

The key technical challenges for the TVWS secondary usage regard spectrum resource sensing and interference avoidance mechanisms. Spectrum sharing, CR, and geolocation databases are major enabler concepts for the TVWS secondary usage, currently at the wireless research frontier.

From a technical implementation point of view, the radio access technology (RAT) standard evaluation is still ongoing as none of the available standards can meet the CR requirements without modification. TVWS BSs are most likely to employ TDD systems since the use of FDD systems would require frequency separation at the transmitter and receiver sides, limiting the number of available TVWS channels [26].

While it could be interpreted as a barrier to the deployment of TVWS systems, the fact that the exploitation of TVWS is still ongoing leaves a window for advanced network planning and radio resource management (RRM) techniques that can improve spectrum utilization and enable QoS provisioning.

What is more, the availability of TVWS resources is subject to time and location and cannot be guaranteed. Despite of recent efforts for quantitative evaluation, TVWS availability remains largely uncharted in Europe [27].

The TVWS usage is hence gaining ground as a concept, but its realization faces not only technical and regulatory, but economic challenges too; the technoeconomic viability of the cognitive radio technology, which is the enabler for spectrum sharing between the primary and secondary users, as well as whether feasible business cases could be based on it remain major questions [26].
Chapter 5

Network Design, Dimensioning, and Cost Models

5.1 Deployment scenario

Calculating the cost structure of a RAN can become an extremely complex task as it depends on a multitude of factors: use case, deployment strategy, existing assets, business relationships and large-volume orders giving access to privileged prices, deployment scale, region (advanced countries have more expensive labor fees), and many more. For this reason a common scenario of femtocell deployment in a shopping mall environment was defined.

The scenario parameters had as follows:

<table>
<thead>
<tr>
<th>RAT</th>
<th>LTE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environment</td>
<td>Shopping mall</td>
</tr>
<tr>
<td>Area</td>
<td>20,000 m²</td>
</tr>
<tr>
<td>HeNBs required for full coverage</td>
<td>25</td>
</tr>
<tr>
<td>Number of users</td>
<td>High</td>
</tr>
<tr>
<td>Access mode</td>
<td>Open/hybrid</td>
</tr>
<tr>
<td>Backhaul type</td>
<td>Built fiber/leased fiber / E-band Point-to-Point (PTP)</td>
</tr>
<tr>
<td>Femtocell interconnectivity</td>
<td>Yes</td>
</tr>
<tr>
<td>Manegement system</td>
<td>Local</td>
</tr>
<tr>
<td>Backhaul link distance</td>
<td>1.5 km</td>
</tr>
</tbody>
</table>

Table 5.1: Facility scenario details

- Full coverage was desired. Each HeNB was assumed to cover an average area of 800 m². Therefore, 25 HeNBs were needed to fully cover the facility premises.
- The number of HeNBs scaled to fit the fed number of users satisfying different values of capacity demand per user.
Chapter 5. Network Design, Dimensioning, and Cost Models

- The access scheme was set as open/hybrid in order to serve the mall’s visitors as well as prioritize access whenever necessary.

- High mobility was a prerequisite to successfully serve the mall visitors moving through the facility and between floors. Therefore we set a requirement for femtocell interconnectivity through the X2 interface to guarantee optimum inter-femtocell handover. The networked mode of the interconnected femtocells can also enable decentralized self-organization features within the RAN.

- Internal traffic had to be handled locally using local IP access (LIPA) and local mobility for cost efficiency, performance and security reasons. The management system was required to be local.

The scenario’s use case and environment share common characteristics with other cases, such as the enterprise scenario, broadening the appliance of the study’s results to some extent.

5.2 Network Design & Dimensioning Model

5.2.1 Parameter Values

For the HeNBs, the following specifications were employed:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAT</td>
<td>LTE</td>
</tr>
<tr>
<td>Spectral efficiency</td>
<td>10 bit/s/Hz</td>
</tr>
<tr>
<td>Coverage</td>
<td>800 m²</td>
</tr>
<tr>
<td>Power consumption</td>
<td>25 W</td>
</tr>
</tbody>
</table>

Table 5.2: HeNB characteristics (average values)

The maximum spectral efficiency of LTE is 16.3 bits/s/Hz. This value is achieved for a single user with high signal to interference plus noise ratio (SINR) which allows for downlink transmission utilizing all available spectrum resources using the highest modulation scheme of 64QAM. To approximate more accurately the capacity delivered for multiple users in indoor environments, where some users experience reduced SINR due to in-band interference or fading, we used an average value of 10 bits/s/Hz for the LTE spectral efficiency.

The average HeNB capacity was calculated as:

$$\text{Average Capacity} = \text{Average Spectral Efficiency} \times \text{Bandwidth}$$

where the average spectral efficiency value was 10 bits/s/Hz as mentioned earlier and bandwidth was dependent on the spectrum type. Following the information presented in Chapter 4, for licensed spectrum we considered 20 MHz blocks, for the TVWS case we considered combination of up to three 8 MHz channels, resulting in an aggregate bandwidth of 24 MHz [31], while for the 2.4 GHz and 5 GHz ISM bands we assumed 40 MHz and 80 MHz bandwidths respectively. Without including coding or overhead considerations, the average HeNB capacity value estimation per spectrum type is presented in Table 5.3 below:
### 5.2. Network Design & Dimensioning Model

<table>
<thead>
<tr>
<th>Spectrum type</th>
<th>Bandwidth (MHz)</th>
<th>Average Capacity (Mbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Licensed</td>
<td>20</td>
<td>200</td>
</tr>
<tr>
<td>Unlicensed 2.4 GHz</td>
<td>40</td>
<td>400</td>
</tr>
<tr>
<td>Unlicensed 5 GHz</td>
<td>80</td>
<td>800</td>
</tr>
<tr>
<td>TVWS</td>
<td>24</td>
<td>240</td>
</tr>
</tbody>
</table>

Table 5.3: Average HeNB capacity per utilized spectrum type

#### 5.2.2 RAN design and dimensioning

Network design and dimensioning are performed at a high level using average values. In our approach, the main RAN design and dimensioning requirements were:

- provide full coverage
- serve the input number of simultaneous users
- deliver the desired input value of average capacity per user.

The capacity demand per user was progressively given values until reaching a maximum of 10 Mbps. The 10 Mbps capacity requirement is much higher than the 2 Mbps Ethernet over copper (EoC) target, making the LTE-femto edge network capable of delivering QoS and over-provisioning of capacity in the short to medium term.

![Figure 5.1: The RAN design and dimensioning approach.](image)

At the time, enterprise HeNB devices can simultaneously serve about 30 users. As this was proven to be a constraint for the network design and dimensioning, this limitation was removed by assuming that HeNBs can support
high numbers of users. This approach was selected to project a future situation where HeNB chipsets have not such strict simultaneous user number limitations.

The input values of simultaneous users were 10, 100, and 1000. By multiplying the average capacity demand per user with the number of users, the aggregate RAN capacity was calculated:

\[ \text{Aggregate RAN capacity} = \text{Average Capacity per User} \times \text{Number of Users} \]

This aggregate capacity was then divided by the average HeNB capacity per spectrum type (Table 5.3) to calculate the number of HeNBs required to deliver the capacity per spectrum type. Taking into account the number of HeNBs needed for coverage, the number of HeNBs for providing both capacity and coverage was derived as:

\[ \text{HeNB Number} = \max(\text{HeNB Number for Capacity}, \text{HeNB Number for Coverage}) \]

### 5.2.3 Backhaul design and dimensioning

#### 5.2.3.1 Backhaul capacity estimation

The backhaul capacity estimation was based on supporting the aggregate RAN capacity. In reality, FAPs will not operate at the same fixed rate as users and traffic are not equally distributed among neither FAPs nor time. Also, traffic peaks are most of the time uncorrelated between sectors (with some exceptions, such as a big event broadcast through the Internet for example). Taking into account these characteristics of the RAN traffic, backhaul capacity could be adjusted at a much lower level than the one needed to support peak rate HeNB operation, resulting in an aggregation gain.

In the present work the backhaul was designed and dimensioned based on a high average capacity at all HeNBs simultaneously, in order to provide an supremum estimation for backhaul capacity and cost values.

#### 5.2.3.2 Backhaul type

Combined with the vast growth in mobile data traffic, the high-capacity LTE RAN is expected to put unexampled tension on the backhaul links, making backhaul a focal point for the successful deployment of 4G services.

The high-throughput LTE RAN poses the need for low-OPEX high-capacity backhaul, a requirement that can no longer be met by legacy TDM circuits. The numbers of needed T1/E1 links are growing fast for high-volume traffic values, rendering the TDM solution obsolete for supporting the LTE 4G RAN technology. Instead, IP-based fiber, copper, and E-band radio-link solutions were considered in the present work as most adequate for the last mile backhaul.

In the present work the backhaul was designed and dimensioned based on the available transport infrastructure, in order to provide an supremum estimation for backhaul capacity and cost values. The examined backhaul type arrangements are presented below:
5.3 Cost Structure Model

(a) **built fiber** involves high capital and time resources, especially in dense urban environments where there are physical and legal obstacles to overcome. A single mode fiber with 10 Gigabit small form factor pluggable (XFP) transceivers can deliver capacity of 10 Gbps, while wave division multiplexing techniques can further increase the achieved capacity values.

(b) **leased fiber capacity** is an OPEX-intensive arrangement, with low CAPEX as well as small deployment time if there is fiber availability in the premises’ area. The leasing fees are capacity-dependent.

(c) the operator can distribute the signal from the PoP to the femto RAN premises through **E-band point-to-point (PTP)** radio-links in the 71-76 GHz, 81-86 GHz frequencies. The major advantages of E-band wireless backhaul are its fast installation and high spectrum resource availability which can achieve Gbps capacity. License fees are also involved and considered for establishing the radio link. Roof top deployment is assumed in all cases.

Among the alternatives examined was also the facility’s digital subscriber line (DSL) connection which could be used to backhaul data to the CN through the internet cloud. Very-high-bit-rate DSL2 (VDSL2) exploiting multiple copper connections with bonding and vectoring techniques can achieve high capacity values close to 500 Mbps. This value was not adequate to support all investigated traffic volumes, hence the DSL alternative was excluded.

5.3 Cost Structure Model

The cost structure consisted of two parts: CAPEX refer to all the infrastructure and network element investments, including implementation costs for building the network. OPEX represent the costs needed to keep the network up and running. The combination of CAPEX and OPEX led to the estimation of the total cost of ownership (TCO) for each scenario for a study period of 10 years. The parameters and assumptions used in the cost model are gathered below:

- While advantageous market placements or large procurement sizes can guarantee reduced prices, no such factors were taken into account.
- All region-dependent parameters were chosen to consort with the specifications applied in Sweden.
- Component price values were assigned according to pricings in Swedish market.
- The time frame for the evaluation of the TCO was 10 years.
- A 10% yearly depreciation in operational costs was considered.

The cost structure focused on the RAN part of the mobile network, excluding CN costs. Nonetheless, the integration of femtocells into the network would pose the need for additional physical/logical entities such as a femtocell HeNB-GW, servers for synchronization and location determination, and O&M subsystems, which were considered.

The cost components considered were the following:
• **License fees** (CAPEX). The fees buy the right for exclusive usage of auctioned spectrum. The spectrum license cost value was estimated at €0.5 / MHz / pop based upon the Swedish 800 MHz band auction held in 2011 [32]. The price metric is spectrum price normalized to the number of MHz and the country population.

• **Radio equipment costs** (CAPEX). As HeNBs have not reached mass-market yet, there was a degree of uncertainty around their price level. This uncertainty was intensified by the manufacturer’s reluctance to reveal HeNB in an effort not to give away their marketing strategies and possible competitive advantages. 2010 announcements stated that the price for residential HeNB has dropped under $100. For enterprise HeNBs carrying more advanced features we assumed a price of €700. However, the cost of CR-enabled FAPs is still unclear. For the CR femto devices an additional cost of 20% was assumed.

• **Installation and deployment costs** (CAPEX). A common remark made by the interview respondents was that site ownership can lead to reduced prices. For the FO, which is the only actor with the site ownership asset, we assumed a 40% discount on installation and deployment costs.

• **Backhaul** (CAPEX, OPEX). CAPEX: Regarding the last mile backhaul, capital investments included installation and deployment, connection setup, procurement of equipment such as transceivers and antennas.

  OPEX: Running costs included transmission and O&M costs, as well as leasing fees for the leased fiber case.

• **Synchronization** (CAPEX, OPEX). CAPEX: The cost bound to the synchronization function is relative to the chosen implementation method. We assumed network-based applications relying on NTP for synchronization. A single NTP server was assumed able to support up to 100,000 users.

  OPEX: The average cost for accessing the server per HeNB.

• **Electricity** (OPEX). Electricity bills are running costs chargeable to the site owner. While power consumption-associated costs are small compared
to other cost drivers and are not taken into account in most related studies, we considered them as they differentiated the actor-specific cost structures.

- **Operation and Maintenance** (CAPEX, OPEX).

  CAPEX: Initially, an investment for new or additional O&M subsystems is needed to integrate the femtocell network according to the actor's infrastructural assets. The most important O&M operational cost driver is the management system. In our scenario, the management system was assumed to be deployed locally within the shopping mall premises.
Chapter 6

Preliminary Analysis

6.1 Actor presentation

This section introduces the actors qualified for having a substantial business case to operate a femto RAN within the shopping mall facilities, providing information acquired during the literature research and interview sessions.

6.1.1 MNO

Mobile network operators are traditional stakeholders dominating the mobile business domain. They provide services for mobile phone subscribers operating infrastructure in license-protected frequency bands. Besides having established strong customer bases, MNOs maintain due to their central position long-standing relationships with a diversity of actors: mobile virtual network operators, Wi-Fi operators, ISPs, telecom equipment vendors, handset vendors, service application providers, regulatory authorities, and consumers.

Main RAN assets

- Macro layer infrastructure
- Core network infrastructure
- Backhaul infrastructure
- Spectrum license

Infrastructure. MNOs typically own dense macro and micro BS deployments which enable national level urban coverage. The MNOs circuit-switched, voice-oriented legacy CN infrastructure is currently flattening to efficiently incorporate high volume data services. A substantial number of operators has already started deploying OFDMA RATs, i.e. LTE or WiMAX infrastructure.

Most significantly, the MNO possesses dedicated backhaul network serving the macro layer deployments.

Spectrum. The long term licensing policy gives MNOs the right to utilize spectrum blocks exclusively and the opportunity to keep new competitors out of the market. As the licensing spectrum strategy bears high-volume capital
expenses, MNOs always favor activities leveraging their costly investments in spectrum licensing.

“Operators see the CR system as a threat to their business”, stated Marja Matinmikko, VTT at the technical research center of Finland. The attachment of MNOs to the out-of-date long term licensing system gives a strong interest in examining whether the licensed path is the best option for the femto layer operation compared to unlicensed and TVWS arrangements.

Motivation. As IP backhauling significantly cuts operational costs, femtocell local area networks (LAN) promise to absorb macro layer traffic in a cost-efficient manner, delaying costly investments in macro BSs at the same time. As a collateral benefit, wide-to-local area offloading can redirect freed resources to provide better QoS towards outdoor high-mobility users. There is a twofold gain for MNOs: enhanced capacity and five-bar reception indoors, more resources allocated outdoors. Amongst the benefits most mentioned in studies are: decreased customer churn, increased customer loyalty, delivery of location-enabled services and bundled offerings, proliferation of customer lifetime value.

6.1.2 WISP

WISPs have been established in the mobile market as providers of local area broadband access operating IEEE 802.11 Wi-Fi unlicensed band technologies. Their competitive advantages are cost-effectiveness attributed to the unlicensed IP-based network operation, and backhaul provisioning. Operators of this type follow a ‘demand-pull’ model, offering nomadic WLAN service where there is concentrated demand, e.g. in public hotspots, hotels, restaurants, and trains, or in places out of wired broadband coverage. The fact that the nomadic access offering does not establish large revenue streams has led WISPs to developed cost-effective ways of deploying and operating their WLANs.

Main RAN assets

- Wi-Fi RAN infrastructure
- Backhaul infrastructure

From a business perspective, the femtocell venture shows proximity to the existing WISP business schemes. WISPs have also experience in making revenues operating IP-centric network architectures, which makes adaptation easier for them.

Infrastructure. Wi-Fi operators deploy WLANs that span over enterprises, residencies and hotspots to form often quite dense aggregate networks.

Spectrum. WISPs have based their operation in unlicensed RAT, such as the ubiquitous IEEE 802.11 Wi-Fi.
6.2. Qualified Scenarios

6.1.3 FO
As mobile Internet is becoming a mass service, the provisioning of high quality mobile broadband can become a feature important for customer satisfaction. Site ownership and direct access to customers is the starting point for the FOs involvement in the mobile business.

Main RAN assets.

- Site operation
- Access to reduced installation and deployment costs

The major asset of the FO is the site operation which strengthens its bargaining position and significantly reduces installation and deployment costs. End-users can be customers established from the FOs core business (e.g. hotel) or passing by the site location (e.g. mall).

Infrastructure. FOs can deploy and operate their own RAN or authorize a third party to deploy infrastructure within their premises.

Spectrum. All spectrum alternatives are open.

6.1.4 TVWSO
While the TVWS secondary usage alternative gathers interest due to the spectrum resource scarcity, its business perspective has not been well-defined yet. The TVWSO operator is a hypothetical entity introduced to investigate the potential of operating CR equipment over TVWS.

The TVWSO will face fierce competition from established rivals of bigger caliber (MNOs, WISPS, ISPs). The major obstacle for the TVWSO is the required market entry; as the cost structure is RAN oriented, market entry expenses are not going to be considered.

Infrastructure. For the economy of the research, we assume that the TVWSO has deployed LTE EPC infrastructure able to support all RAN traffic at all times.

Spectrum. TVWSO networks are entirely based upon TVWS spectrum, which is the core of the operator’s business concept.

6.2 Qualified Scenarios
The scope of the scenario assessment was to filter all possible actor and spectrum type combinations in order to qualify the scenario cases that combine business feasibility with strong motivation for investigation. The scenarios that were qualified and investigated are gathered in the table below:

Each spectrum alternative refers to different frequency bands. Licensed spectrum refers to the main 1.9 GHz band, unlicensed spectrum is examined for the
2.4 GHz and 5 GHz ISM bands, and TVWS spectrum contains interleaved frequencies allocated between 470 MHz and 790 MHz.

As a standard case, the WISP is considered to base its business on unlicensed spectrum operation; the FO has all options open; the TVWSO exclusively operates over TVWS; the MNO is the only actor holding spectrum licenses. As shown in Table 6.1, the TVWS path was examined for all actors since investigating its potential is one of the main tasks of the research.

### 6.3 Impact of spectrum path on the RAN and cost structure models

The impact of using different frequency bands on some key parameters was examined next:

- **Coverage.** While lower frequencies have better propagation characteristics leading to larger area coverage, in our indoor deployment case we assumed no significant differentiation in coverage radius when changing spectrum bands.

- **Power consumption.** Power consumption is not only a weak cost driver, but also fluctuates insignificantly for different operating frequencies and negligible cost differences would be observed. Therefore, a common value was used in all cases.

- **Femtocell device cost.** Circuit complexity and costs of baseband and radio frequency chipsets, which are the main manufacturing cost drivers, are essentially the same for devices operating in different frequencies. What is going to increase the cost of the femto equipment is the integration of CR capabilities.

- **Bandwidth.** Bandwidth availability was the major factor differentiating the spectrum alternatives. Licensed spectrum bandwidth is strictly defined by the signed license agreement with typical values of 10-20 MHz. Conversely, unlicensed and TVWS bands can provide for wider bandwidth channels delivering higher capacity. As already mentioned in Chapters 4 and 5, the bandwidth values used were 20 MHz for the licensed band, 24 MHz for TVWS, 40 MHz for the 2.4 GHz ISM band, and 80 MHz for the 5 GHz ISM band.
6.4 Actor Assets

The cost structure varies for each actor not only according to the spectrum path followed; the component costs an actor confronts are relative to the actor’s resources and infrastructure. The assets connected to the cost structure are gathered in the following table:

<table>
<thead>
<tr>
<th>Component</th>
<th>MNO</th>
<th>WISP</th>
<th>TVWSO</th>
<th>FO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectrum licenses</td>
<td>✓</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Technicians</td>
<td>✓</td>
<td>✓</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Backhaul network</td>
<td>✓</td>
<td>✓</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CN infrastructure</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>-</td>
</tr>
<tr>
<td>Site ownership</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>✓</td>
</tr>
</tbody>
</table>

Table 6.2: Availability of cost structure related assets

**Spectrum licenses.** An operator that does not own spectrum in advance has to allocate budget for licensing spectrum blocks or operate in unlicensed bands. The only actor in possession of licensed spectrum is the MNO.

The FO constitutes a particular case; we considered that the FO will not pay for occupying licensed spectrum resources as part of the agreement with the MNO for the femto network deployment.

**Qualified Personnel - Technicians.** The deployment of the femtocell LAN can be substantially cheaper if the actor employs personnel specialized in small cell or WLAN installations. Deployments in large premises, such as large enterprises or malls, are likely to require on-site calibration in order to optimize the network performance coverage and minimize leakage out of the facility. Actors with this type of asset are MNOs, WISPs.

**Backhaul.** The possession of backhaul network was proclaimed by the interview sessions and literature study one of the major assets that can be activated in the femto RAN undertaking. The actors assumed to have available proprietary transport network are the MNO and the WISP, while the TVWS was assumed to lease transport capacity.

**CN infrastructure.** It is possible that mobile actors have already deployed LTE core infrastructure for their macro networks or core network elements that can be exploited in LTE operation. In contrast, operators typically do not possess infrastructure that can be re-used or upgraded when transitioning from a legacy network to an OFDMA LTE network.

In the CN, apart from some authentication, authorization, and accounting (AAA) or billing systems that can remain common in both network environments, the network components that can be reused are few. A MNO for instance could have wideband code division multiple access (WCDMA) 3G core infrastructure which is structurally similar to the LTE EPC and thus certain elements could be reused in the LTE network.

For the economy of the research, all operators are assumed to have existing LTE CN infrastructure, such as MMEs, SGWs and HeNB-GWs, with the exception of the FO which was assumed incapable of deploying costly EPC in-
frastructure on its own and would require partnership with a 3rd operator. The cost estimation of deploying and running the LTE EPC is outside of the Thesis scope.

**Site ownership.** The only actor with this asset is the FO. Other actors must lease the site or come to some kind of agreement with the FO in order to deploy the femto RAN, as the FO will claim some profit for allowing 3rd party deployment in the property. The FO has the unique advantage of deploying the RAN with reduced costs.
Chapter 7

Results

7.1 Cost structure sensitivity analysis results

The sensitivity analysis examines how the cost structure behaves using the number of users and the average capacity per user as independent variables. The average capacity is given values up to 10 Mbps per user, while simultaneous mobile broadband users take three values: 10, 100, and 1000. As presented in section 5.2.2, the number of deployed HeNBs was the maximum between the number of HeNBs needed to deliver the input capacity per user and the number of HeNBs needed to provide coverage in the facility premises.

Due to the high average spectral efficiency value of 10 bits/s/Hz the HeNBs deliver high average capacity values (Table 5.3). As a result, the 25 HeNBs required for coverage can satisfy extremely high capacity demand values for 10 and 100 users.

<table>
<thead>
<tr>
<th>Spectrum type</th>
<th>Capacity achieved for 25 HeNBs (coverage requirement) (Mbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10 users</td>
</tr>
<tr>
<td>Licensed</td>
<td>200</td>
</tr>
<tr>
<td>2.4 GHz ISM</td>
<td>400</td>
</tr>
<tr>
<td>5 GHz ISM</td>
<td>800</td>
</tr>
<tr>
<td>TVWS</td>
<td>240</td>
</tr>
</tbody>
</table>

Table 7.1: Average capacity per user achieved per spectrum type by the 25 HeNBs required for coverage

The numbers of required HeNBs begin to differentiate between spectrum paths only after exceeding the average capacity value per user of 5 Mbps for 1000 simultaneous users, as show by Table 7.1. Thus, all cases for 10 and 100 users are masked by the coverage requirement and all calculations refer from now on to the 1000 simultaneous users case.

For delivering the desired input capacity, the numbers of HeNBs per spectrum type have as follows:
### Chapter 7. Results

#### Capacity demand

<table>
<thead>
<tr>
<th>Capacity demand per user (Mbps)</th>
<th>Number of HeNBs required per spectrum type (capacity only)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Licensed</td>
</tr>
<tr>
<td>5</td>
<td>25</td>
</tr>
<tr>
<td>6</td>
<td>30</td>
</tr>
<tr>
<td>7</td>
<td>35</td>
</tr>
<tr>
<td>8</td>
<td>40</td>
</tr>
<tr>
<td>9</td>
<td>45</td>
</tr>
<tr>
<td>10</td>
<td>50</td>
</tr>
</tbody>
</table>

Table 7.2: Number of HeNBs required for ascending capacity per user demand values per spectrum type

Taking into account the number of 25 HeNBs required to provide coverage, as calculated in section 5.1, the previous table becomes as follows:

<table>
<thead>
<tr>
<th>Capacity demand per user (Mbps)</th>
<th>Number of HeNBs required per spectrum type (capacity and coverage)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Licensed</td>
</tr>
<tr>
<td>5</td>
<td>25</td>
</tr>
<tr>
<td>6</td>
<td>30</td>
</tr>
<tr>
<td>7</td>
<td>35</td>
</tr>
<tr>
<td>8</td>
<td>40</td>
</tr>
<tr>
<td>9</td>
<td>45</td>
</tr>
<tr>
<td>10</td>
<td>50</td>
</tr>
</tbody>
</table>

Table 7.3: Number of HeNBs required for capacity and coverage per spectrum type

The number of HeNBs over the unlicensed spectrum still is defined by the coverage requirement of 25 HeNBs. For this reason, the 2.4 GHz and 5 GHz ISM bands are considered as one merged case.
7.1. Cost structure sensitivity analysis results

7.1.1 MNO TCO

The results indicate that the LTE-femto RAN TCO is CAPEX intensive. CAPEX represent 76.1% to 83.2% of the TCO.

Running expenditures grow faster than capital investments when more HeNBs are added to the RAN.

Licensed operation bears more expenses due to licensed fees and the narrower bandwidth that results in deployment of more additional HeNBs.

Comparing the licensed and TVWS cases, the narrower licensed bandwidth leads to higher number of HeNBs in the RAN. As a result, the licensed case expenditures grow faster than the TVWS case expenditures, showing that the 20% larger bandwidth compensates the assumed 20% higher CR-equipment prices as the RAN traffic grows.

TVWS offers a TCO reduction fluctuating from 13.2% to 16.9% compared to the licensed case.

Unlicensed operation is the most cost-effective solution delivering significant cost reductions. The unlicensed case MNO TCO is 18.2% to 42% lower in comparison to the licensed case, and 4.6% to 30.3% lower compared to the TVWS case.

The RAN operating in the ISM bands can satisfy all demand values up to 10 Mbps with no need for any additional network elements and costs remain unaffected by the examined traffic values.

Figure 7.1: TCO for the MNO per spectrum path (1000 users)
7.1.2 WISP TCO

- The RAN TCO is CAPEX intensive. CAPEX represent 76.1% to 80.7% of the TCO.
- Running expenditures grow faster than capital investments when more HeNBs are added to the RAN.
- RAN implementations over the ISM bands can satisfy all demand values up to 10 Mbps with no need for any additional network elements and costs remain unaffected by the traffic increase.
- The TVWS arrangement on the other hand needs to incorporate more HeNBs when the average capacity per user demand exceeds 6 Mbps.
- Unlicensed operation features reduced expenditures compared to the TVWS case, from 5% up to 30% as we move from 5 Mbps to 10 Mbps average capacity per user.
7.1.3 FO TCO

![Graph showing TCO for FO per spectrum path (1000 users)](image)

- The RAN TCO is CAPEX intensive. CAPEX represent 67.4% to 75.6% of the TCO.
- Taking into advantage its unique asset of site ownership the FO exploits low installation and deployments costs presenting substantially reduced CAPEX, also confirmed by the decreased CAPEX attribution to the TCO.
- Running expenditures grow faster than capital investments when HeNBs are added to the RAN.
- Licensed operation bears more expenses due to licensed fees and the narrower bandwidth that results in deployment of more additional HeNBs.
- TVWS operation starts with 6% higher TCO compared to the licensed case due to the increased CR equipment prices, but then the licensed operation TCO surpasses the TCO of the TVWS case as expenditures in the licensed case grow faster. After the 6 Mbps average capacity per user value, the TCO in the TVWS case appears 4% to 5.9% lower than the TCO of the licensed RAN.
- Unlicensed operation TCO is up to 36.8% lower than the licensed operation TCO and 5.2% to 32.9% reduced compared to the TVWS case.
- The RAN operating in the ISM bands can satisfy all demand values up to 10 Mbps with no need for any additional network elements and costs remain unaffected by the capacity increase.
7.1.4 TVWSO TCO

- The RAN TCO is CAPEX intensive. Capital investments represent 76.1% to 80.7% of the TCO.
- Running expenditures grow faster than capital investments when more HeNBs are added to the RAN.
- Additional HeNBs are needed after the average capacity demand per user exceeds 6 Mbps.

Figure 7.4: TCO for the TVWSO using TVWS (1000 users)
7.1.5 Actor standard case TCO comparison

Next, to further facilitate comparison between actors we present the TCO breakdown into RAN and CN expenditures in the case where involved actors follow the spectrum path closest to their established operational schemes: MNO chooses the traditional licensed path, WISP the trivial unlicensed path, FO the unlicensed path to cut down expenses, and TVWSO the TVWS.

![Figure 7.5: TCO breakdown per actor (1000 users)](image)

- The cost structure results reflect the importance of bandwidth size. Unlicensed spectrum usage leads to reduced TCO (WISP, FO), followed by TVWS (TVWSO) while licensed operation involves the highest expenses.

- Expenditures escalate faster for narrower bandwidths (licensed) and slower for larger bandwidths (TVWS). In fact, in the unlicensed ISM operation of the WISP and the FO, the RAN and CN expenditures remain stable, as the number of HeNBs required for providing coverage can deliver up to 10 Mbps capacity to 1000 simultaneous users.

- However, the increased traffic requirements reflect directly on the licensed and TVWS RAN TCO after the capacity demand exceeds 5 Mbps and 6 Mbps respectively, which are already high values.

- The MNO and the TVWSO have similar expenditure fingerprints due to the close bandwidth values (20 MHz and 24 MHz). The MNO has higher capital expenditures due to the spectrum license fees.

- The FO has the smallest TCO. Thanks to the site ownership, FO enjoys the privilege of reduced installation and deployment prices. The fact that installation and deployment costs represent a fraction of approximately 20% of the RAN CAPEX, highlights the importance of site ownership in the cost structure, translated into a 10% reduction in total CAPEX.
• On the other hand, the FO is charged with power bills. Their extend is not so significant though and appears as a slight increase in OPEX.

• Licensed operation bears more expenses due to licensed fees and the narrower bandwidth that results in deployment of more additional HeNBs. For these same reasons, the MNO licensed RAN is the most costly solution among all actor and spectrum type pairs.

• The RAN segment is a stronger cost driver than the CN.

• CN elements can support high numbers of HeNBs without need for additional elements leading to stable capital investments. In contrast, RAN CAPEX are bound to the number of deployed HeNBs.

• CN operational costs are substantially lower and escalate slower than RAN operational costs.

7.1.6 Backhaul results

In this section’s sensitivity analysis, last mile backhaul costs are presented as a function of aggregate RAN capacity, considering built fiber, leased fiber capacity, and E-band PTP links.

![Backhaul CAPEX and OPEX](image)

Figure 7.6: CAPEX and OPEX per backhaul type as a function of backhaul/aggregate RAN capacity
• Built fiber deployment CAPEX are significantly high, 56 times higher than leased fiber CAPEX and 2.6 to 17.6 times higher than E-band radio link CAPEX. These high initial investments are compensated by the limited and insensitive to the capacity increase operating costs.

• Built fiber expenditures remain unaffected by the backhaul capacity increase. A single-mode fiber with XFP transceivers for instance is capable of delivering 10 Gbps supporting the aggregate RAN capacity under all examined cases.

• Leased capacity involved minor capital investments, 56 times lower than built fiber and 3.2 to 21.8 times lower than E-band PTP backhaul.

• Fiber leasing fees increase sharply with the aggregate RAN capacity increase, causing extreme operating costs and unsustainable TCO levels for backhaul capacity values over 1 Gbps.

• The E-band PTP CAPEX and OPEX values lie between the equivalent values of the built and leased fiber arrangements. E-band PTP OPEX are 10.3 to 40 times lower than leased capacity, while they begin 10.3 times lower than the built fiber OPEX, it shows almost equal OPEX to built fiber for the 1 Gbps backhaul capacity value, after which they exceed the built fiber OPEX 1.9 to 9.7 times.

• Leasing capacity involves 4 to 100 times higher OPEX than built fiber.

7.1.7 Comments and conclusions on TCO
The results proclaim bandwidth as the preminent factor that defines the RAN TCO. The TCO results indicate that the licensed spectrum usage involves higher deployment and operation expenditures for the LTE-femto RAN. Unlicensed RANs are the most cost-efficient, while TVWS-based RANs lie at an intermediate position.

<table>
<thead>
<tr>
<th>RAN TCO</th>
<th>Spectrum type</th>
<th>Licensed</th>
<th>Unlicensed</th>
<th>TVWS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actor</td>
<td>Spectrum type</td>
<td>Licensed</td>
<td>Unlicensed</td>
<td>TVWS</td>
</tr>
<tr>
<td>MNO</td>
<td>Licensed</td>
<td>-</td>
<td>+18%</td>
<td>+13%</td>
</tr>
<tr>
<td></td>
<td>Unlicensed</td>
<td>-18%</td>
<td>-</td>
<td>-5%</td>
</tr>
<tr>
<td></td>
<td>TVWS</td>
<td>-13%</td>
<td>+5%</td>
<td>-</td>
</tr>
<tr>
<td>WISP</td>
<td>Unlicensed</td>
<td>-</td>
<td>-</td>
<td>-5%</td>
</tr>
<tr>
<td></td>
<td>TVWS</td>
<td>-</td>
<td>+5%</td>
<td>-</td>
</tr>
<tr>
<td>FO</td>
<td>Licensed</td>
<td>-</td>
<td>+1%</td>
<td>-6%</td>
</tr>
<tr>
<td></td>
<td>Unlicensed</td>
<td>-1%</td>
<td>-</td>
<td>-5%</td>
</tr>
<tr>
<td></td>
<td>TVWS</td>
<td>+6%</td>
<td>+5%</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 7.4: RAN TCO comparison between spectrum types for the base case deployment (25 HeNBs) per actor

We observe that under all actor cases the RAN TCO is CAPEX intensive. Even for basic configuration deployments we can observe that the femto RAN deployment involves substantial costs due to the first-time introduction of the
required network elements. This finding is of high importance considering the high numbers of LTE-femto RANs the operator will need to deploy at a large scale.

Running costs increase more sharply than capital investment costs as the number of HeNBs increases. The model predicts that OPEX escalate faster than infrastructure related costs, confirming what was also stressed out during the interview sessions and literature study.

As far as it concerns the traffic’s impact on the network related expenditures, it is shown that the traffic increase puts direct tension on the backhaul segment expenditures. RAN expenditures come second, being sensitive to the traffic increase in a manner reversely connected to bandwidth. CN costs move more slowly as its elements are capable of handling large volumes of HeNB traffic.

Regarding the backhaul type, it is reflected in the sensitivity results that the built fiber is the superior option as it can handle extremely high capacity volumes at stable costs. The drawback is that it requires a considerable initial investment, which is compensated in the long term though. Leasing capacity on the other hand incurs very limited initial investments enabling actors to bring up the network fast when there is fiber availability in the premises area, but leads to unsustainable operational costs for high traffic volumes. Finally the E-band PTP solution compromises CAPEX and OPEX, making a good approach for mid-term transition to proprietary fiber.

Of course, not all operators own a proprietary transport network. When leased capacity is the only option, it is clearly shown that the current pricing policy will prove inadequate for serving very high traffic levels and backhaul could become a point of friction between RAN operators and backhaul providers.
7.2 Qualitative analysis results

7.2.1 Spectrum analysis

7.2.1.1 Licensed spectrum

This section refers to the MNO as it is the unique spectrum license holder. The key advantage of licensed operation is the exclusive management of the spectrum resources which guarantees the delivery of QoS. The licensed path offers the opportunity for full femto integration to the existing network at the cost of strict engineering planning requirements for interference management or the use of a dedicated channel.

Deployment strategy

**Integrated deployment.** Provides for QoS, integrating the femto overlay into the existing macro layer with frequency planning to manage interference. There are two options for the femto layer integration into the network:

(a) **Licensed co-channel deployment.** Achieves high frequency efficiency, and cost-finess due to carrier sharing. Introduces heavy interference management requirements that become quite complex at a large scale. Under this strategy, the femto overlay can cause coverage holes in closed access scheme and degradation to the macro layer performance.

(b) **Licensed dedicated spectrum.** Dedicating a spectrum chunk exclusively to the femto layer avoids cross-layer interference and macro layer degradation, but is a more costly arrangement.

**Island deployment.** Deploying FAPs in an ad-hoc Wi-Fi-like fashion provides no QoS guaranty and limited managing power over the femto networks which rely largely on their SON features. Therefore, it is not suitable for the scenario deployment examined in this work.

Under both cases, the licensed spectrum RAN works with single mode handsets.

7.2.1.2 Unlicensed spectrum

Under the presence of a macro layer, deploying the femto network over the ISM band means that macro and femto frequencies are separate; therefore, there is no cross-layer interference and no macro layer degradation.

As analyzed in section 4.2, the main drawback of operation in ISM unlicensed bands is the high congestion and lack of interfaces between LTE and WLAN systems that makes interference mitigation and QoS provisioning hard to accomplish.

In our case however, where the premises are managed by a single entity, it is reasonable to assume central RRM and controlled interference levels within the facility, e.g., radio emissions over the ISM bands from sources other than the femto RAN are minimized, so that the mobile broadband service is protected and QoS guarantees can be made. Under this condition, the increased pool of
radio resource blocks can be exploited and lead to high system capacity and over-provisioning, as shown by the RAN dimensioning results.

The usage carriers different than the legacy ones poses the need for handset modification or dual-mode handsets.

### 7.2.1.3 TVWS

Similarly to the ISM band case, secondary access of TVWS provides isolation of the macro and femto layers and thus delivers a RAN free of cross-layer interference. The advantage of the TVWS is that in indoor environments it can promise higher bandwidth availability than the licensed 20 MHz channel.

Furthermore, with the TVWS secondary usage standardization still open, it is possible to see QoS support for secondary TVWS systems. Recent works propose new RRM techniques that can achieve QoS over TVWS with less resources than those needed over legacy carriers [28, 29, 30].

The usage of carriers different than the legacy ones poses the need for handset modification or dual-mode handsets.

The following table summarizes the technical advantages and disadvantages of the four examined spectrum modes.

<table>
<thead>
<tr>
<th>Spectrum Mode</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Licensed</td>
<td>Advanced network configuration capabilities, QoS guarantee</td>
<td>Cross-layer interference and macro-layer degradation considerations</td>
</tr>
<tr>
<td></td>
<td>No dual mode handset</td>
<td></td>
</tr>
<tr>
<td>ISM bands</td>
<td>No cross-layer interference</td>
<td>Network planning required to contain co-layer interference and provide QoS</td>
</tr>
<tr>
<td></td>
<td>Largely increased bandwidth</td>
<td>Modified/dual mode handsets</td>
</tr>
<tr>
<td></td>
<td>Possibility for QoS</td>
<td></td>
</tr>
<tr>
<td>TVWS</td>
<td>No cross-layer interference</td>
<td>LTE operation and RRM over TVWS not defined</td>
</tr>
<tr>
<td></td>
<td>Increased bandwidth</td>
<td>CR-enabled BSs</td>
</tr>
<tr>
<td></td>
<td>Possibility for QoS</td>
<td>Modified/dual mode handsets</td>
</tr>
</tbody>
</table>

Table 7.5: Spectrum type advantages and disadvantages

### 7.2.2 Backhaul analysis

**Built fiber.** The TCO analysis promotes built fiber as the most cost-effective solution in the long term. The price paid is high capital and likely time resources.
Leased capacity. Minor capital investments and sharply raising leasing fees make leased capacity an option more suitable for bringing the a low-to-medium capacity RAN up and running, assuming there is direct fiber availability at the premises’ area. From an operational point of view, leasing fiber inserts 3rd party dependency to the backhaul provider. End-to-end QoS provisioning becomes complex and requires the establishment of service level agreements (SLA) with the backhaul provider. IPsec must be used to secure the femto-CN communication, adding overheads and computational effort to the network elements.

E-band PTP. The E-band PTP radio link solution compromises between CAPEX and OPEX. In contrast to the fiber arrangements, the radio link deployment is immediate. The main drawback of the E-band PTP is that it is a capacity-limited solution.

Building fiber or deploying E-band PTP links to connect the facility premises to the nearest macro cell site hub point can leverage an existing transport network, result in no 3rd party dependency, and allow for end-to-end QoS provisioning and network management. Moreover, if no tampering is possible over the proprietary transport network and LTE payload is encrypted, IPsec can be disabled lightening the network from overheads and tunneling processing load.

In all above last mile arrangements, the traffic is directed towards the CN through the operator’s dedicated transport network which means all traffic passes through the CN. While the macro network gets offloaded, SIPTO is not applicable for CN offloading that would be extremely beneficial at a large scale.
7.3 Actor-specific SWOT analysis

In this section we perform an actor-specific, business-oriented SWOT analysis for the LTE-femto venture.

7.3.1 MNO

The MNO stands at a powerful position, having the most complete arsenal and a full set of options for deploying and operating indoor femto networks. Most importantly, the MNO has the unique asset of macro coverage which combined with the indoor femto layer can give the superior offering of true ubiquitous mobile broadband.

The cost structure results confirm that LTE-femtocell LANs can absorb extremely high volumes of mobile traffic in a cost-efficient manner which makes them an excellent solution for macro to local area offloading. The femto layer presence can create a twofold gain for the MNO: superior capacity and five-bar reception for indoor users on one hand, more macro layer resources freed and redirected to deal with wide-area high-mobility users on the other hand. By introducing indoor capacity where there is concentrated demand, MNOs have the opportunity to slow down costly extensions of the macro layer and to optimize their existing wide area network investments.

With all spectrum arrangements available, the MNO can select the optimal from a cost and technical perspective solution. However, MNO decision making is largely business-driven and the MNO rule of thumb of protecting spectrum investments and maintaining solid high suppliers often outweighs techno-economic aspects.

![SWOT MNO Diagram]

Figure 7.7: MNO SWOT analysis
Even in purely techno-economic terms, the licensed path might be outperformed in TCO metrics according to the research findings but it still constitutes the safest option. At the time, QoS is not guaranteed in the unlicensed and TVWS bands, LTE operation has not been extended over unlicensed and TVWS bands, and availability of TVWS resources has not been quantified yet.

### 7.3.2 WISP

WISPs target at the mobile market through the new entry channels opened. The WISP femto offering is nomadic, showing proximity to the Wi-Fi-based business model currently run by the WISP. As 4G mobile networks are going to be built mostly on top of LTE, there is a clear motivation for shifting to LTE for reaching mobile end-users.

On the down-side, this shift involves large investments in infrastructure. Nevertheless, the biggest challenge for the WISP is how to transit from a best-effort service provider to deliver competitive QoS offerings against MNOs. Competing with the MNOs over indoor mobile broadband involves high business risks. Therefore, partnering up with MNOs as offload providers could be a safer approach for the WISPs.

### 7.3.3 FO

Owners of facilities such as malls, or hotels can strengthen their core business and gain edge over rivals as mobile broadband becomes increasingly valued.
Furthermore, they can increase profitability by offering broadband access as a value-added service to their core business customers or to mobile subscribers after reaching agreements with MNOs.

**SWOT – FO**

<table>
<thead>
<tr>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Site ownership</td>
<td>• Cannot operate independently</td>
</tr>
<tr>
<td>• Strong negotiating base</td>
<td></td>
</tr>
<tr>
<td>• Partner-up flexibility</td>
<td></td>
</tr>
<tr>
<td>• Direct access to customers</td>
<td></td>
</tr>
<tr>
<td>• Reduced deployment and installation costs</td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th>Opportunities</th>
<th>Threats</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Mobile broadband access becomes valued</td>
<td>• Wi-Fi competing RAT</td>
</tr>
</tbody>
</table>

Figure 7.9: FO SWOT analysis

The FO has the main advantage of site ownership which gives significant bargaining power and flexibility in forming partnerships to exploit its facility, direct access to customers, as well as optimal installation and deployment costs. Unable to undertake the huge investments to operate the network independently, the FO must rely on cooperative business schemes.

### 7.3.4 TVWSO

The TVWSO stands at a disadvantageous point as it has to make a market entry and compete with incumbent operators for the mobile broadband provisioning. The CR ecosystem is in the growth phase where standardization and CR equipment certification are still ongoing procedures.

The cost structure results suggest that the secondary use of TVWS bands for indoor mobile broadband services is a feasible case. Nevertheless, the business viability of delivering QoS offerings over TVWS is uncertain due to the multitude of uncertainties in resource availability, standardization, equipment certification and price levels, and QoS mechanisms and LTE operation over TVWS. Until the CR and TVWS ecosystems mature, it is very unlikely that an operator will go for the TVWS approach, especially for startups where market entry expenses are added.
7.3. Actor-specific SWOT analysis

Figure 7.10: TVWSO SWOT analysis

Cognitive radio-enabled LTE is not the only candidate RAT for exploiting TVWS resources. The 802.12af ‘Wi-Fi over TVWS’ standard is another plausible candidate which perfectly fits the WISP business and operational frame, also IP-based and without the need for costly investments in EPC infrastructure.

7.3.5 LTE-femto vs Wi-Fi access points

A common threat for the LTE-femto venture under all operator cases is Wi-Fi. While the operational maturity of LTE-femtocells is not clear yet, the pros and cons of Wi-Fi are already well known.

Putting technical facts down, the LTE architecture is flatter and simpler to implement but bears large infrastructural investments. OFDMA-based LTE delivers much better co-layer and cross-layer interference mitigation attributed to the use of sub-channels. The extension of LTE operation over TVWS can be expected to integrate a more efficient access control as compared to the suffering Wi-Fi CSMA/CA air interface. In contrast, half-duplex Wi-Fi APs and terminals transmit and receive on the same channel and the distributed coordination function (DCF) which implements CSMA/CA is performing poorly in crowded shared spectrum environments. This is the reason that Wi-Fi usage has been restricted to local best-effort services. For delivering real time, delay sensitive services such as video and voice, QoS becomes a neuralgic parameter to be taken into account. Latest Wi-Fi standards such as 802.11e incorporate Wi-Fi multimedia extensions (WMM) to implement granular QoS mechanisms that can prioritize traffic on a per packet basis.

This conflict has not only technical, but also strong business aspects. The huge asset of Wi-Fi is its ability to immediately reach mass-market as it has
access to practically any mobile user: almost all handsets, pads, and laptops presently come equipped with Wi-Fi adapters. In contrast, the LTE-handset penetration is growing at a fast rate but still not close to the ubiquitous Wi-Fi levels. Furthermore, the requirement for dual or triple mode LTE handsets can be a serious impediment to the fast adoption of the unlicensed and TVWS LTE-femtocell solutions.
Chapter 8

Conclusions and Future Work

In this final Chapter we answer the research questions formulated in section 1.2 and highlight the most important findings of the research, discussing at the same time its weaknesses and possible future work directions.

8.1 Research questions discussion

- Which key network benefits and handicaps does each spectrum alternative offer?

The TCO sensitivity analysis results indicate that all TVWS, 2.4 GHz and 5 GHz ISM band alternatives outperform the licensed LTE-femto RANs in terms of TCO metrics. Taking into account the large scale of the MNO femto deployment, this finding could perhaps put under question the justification of the MNOs’ persistence to follow the licensing policy path.

However, this result is closely related to the highly optimistic assumptions made for the unlicensed and TVWS bands’ spectrum resource availability as the 2.4 GHz ISM band, 5 GHz ISM band, and TVWS band RANs were assumed to fully utilize bandwidths of 40 MHz, 80 MHz, and 24 MHz respectively. In reality, unlicensed and TVWS approaches confront substantial problems in delivering QoS and spectrum utilization cannot reach the assumed values at present. The licensed spectrum alternative is the only one currently guaranteeing QoS and makes the safest option.

- Is it feasible to deploy and operate LTE-femto RANs over TVWS?

The research’s results show that operation in TVWS is a feasible venture from a cost perspective. The operation over TVWS brings reduced TCO compared to the licensed spectrum case taking advantage of the unlicensed TVWS regime and the assumed high spectrum resource availability. Next to the ISM band operation though, the TVWS solution is outperformed in terms of both bandwidth and TCO.
While the TCO results are promising, as mentioned earlier the real barriers to the secondary usage of TVWS lie underneath. With unquantified availability of spectrum resources and uncertainty in QoS delivery, actors are not likely to choose the TVWS alternative. Even if adequate spectrum resource availability is proven, the TVWS solution will need a significant amount of time to become technically mature, establish stable value chains, and form a developed ecosystem able to reach mass market at reasonable equipment costs.

- How does traffic increase impact on the structure and cost of the actor-customized RANs?

Regarding the RAN segment, the sensitivity analysis results show that the high LTE spectral efficiency enables all RAN arrangements to serve high traffic volumes under stable costs until the aggregate RAN capacity reaches the breakpoint value of 5 Gbps for licensed spectrum, and 6 Gbps for TVWS. The breakpoint value for the 2.4 GHz band is 10 Gbps, and for the 5 GHz band 20 Gbps, out of the sensitivity analysis’ reach. After these points, the traffic growth affects the RAN TCO in a way inversely connected to bandwidth. The same applies for RAN marginal costs, which are higher for the licensed case, followed by the TVWS case, and acquiring their lowest values for the unlicensed spectrum case. The main conclusion is that large bandwidths shield RANs from adding network elements and thus costs in TCO.

Looking at the big picture, the traffic growth appears to influence more strongly costs at the backhaul segment. Backhaul CAPEX and OPEX can become many times higher than those of the RAN and CN parts, pointing out that the high data-rate LTE-femto RAN will put stress on the backhaul capacity and pricing requirements. This result agrees with the interview feedback that distinguished proprietary transport network as one of the most substantial assets for indoor mobile broadband provisioning.

8.2 Conclusions

The LTE-femtocell and TVWS concepts were seen through the prism of established and potential actors in order to reach a comprehensive understanding of their potential in indoor mobile broadband provisioning.

Under all actor cases the deployment of LTE-femtocell networks able to handle vast amount of traffic has been shown to be economically feasible. The sensitivity analysis results proclaimed bandwidth as the most influential parameter for the RAN TCO. Licensed operation involves the highest expenditures because of its narrower bandwidth, TVWS secondary usage comes next, and the ISM bands with assumed large bandwidths are practically unaffected until extreme traffic volumes are confronted.

Another major finding of the research was that traffic growth is going to put a stress on the backhaul segment first, rendering capacity leasing unsustainable under current fee levels. RAN and CN costs escalate at a significantly lower rate.

When it comes to providing mobile broadband as a secondary service over
8.3 Discussion and Future Work

TVWS, it is concluded that it is not only feasible but also bears cost reduction benefits compared to the licensed spectrum path. Notwithstanding, the current work employed bold assumptions over key issues that can determine the success of TVWS secondary usage, namely guaranteed high spectrum resource availability and standardized CR technology. Until these issues are addressed, the TVWS secondary exploitation for indoor mobile broadband services is characterized as a high-risk business decision, for both incumbent and emerging operators.

8.3 Discussion and Future Work

The TCO sensitivity analysis results showed that bandwidth has a key role in shaping the expenditures for the LTE-femto RAN deployment and operation. However, interpreting this finding brings up a substantial dilemma: should operators intensify their efforts in purchasing spectrum or should the wireless community focus on rendering free spectrum more effectively re-usable in a local area fashion?

Even if the radio access control is significant for the delivered throughput and QoE, backhaul is argued as the key issue that might become the bottleneck for future mobile networks. In the present work high capacity requirements were examined attempting to look into the mid-term future, but the truth is no one can know what end-to-end and segment-specific requirements to expect one decade from now. The researcher has strong confidence in network engineering, which can implement prescient caching, smart scheduling, or multi-cast techniques to relieve the backhaul segment from unnecessary stress and thus constrain backhaul capacity requirements, forming a reality far from this pessimistic scenario.

Modeling the cost of deployment and operation components of the LTE-femto RAN has been a rather challenging task as actual implementations are missing from the Swedish market. Most importantly, device manufacturers and operators are reluctant to share cost related information because these are considered an integral -hence confidential- part of their strategy. Even worse, such values are not available for CR-enabled equipment yet. Therefore, more explicit primary data input would certainly enhance the suggested methodology’s quantitative output.

As far as it concerns other promising alternatives not considered in this work, the literature study indicated the existence of local LTE EPC-emulating solutions for facility owners. If this is the case, facility owners could be allowed to operate the femto RAN on their own, leveraging their site ownership asset even more.

When it comes to cognitive radio, the fact that cognitive radio is an enabler for secondary operation in TVWS does not mean it is a TVWS-exclusive technology. CR features could be integrated in licensed and unlicensed bands as well in numerous ways to enhance overall spectrum utilization. It would make perfect sense for example that a MNO enables opportunistic access over its licensed spectrum to increase overall spectrum utilization and thus profitability of its investment. From that perspective, the TVWS-related cost structures could provide an estimation basis for such resembling cases.
All above considerations indicate that the proposed method of designing and techno-economically evaluating tailor-made RAN models can be enhanced in several ways. Hopefully a small step forward has been made, followed by many others yet to come.
Bibliography


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Appendix A

Interview questions

A.1 General

Do companies shift to mobile over fixed broadband in their premises? Which are the main reasons?

How does the traffic growth affect mobile operators?

Which are the advantages and disadvantages of using small cell deployments?

What is the demand for LTE solutions?

A.2 Assumptions and parameters

Which are the technical specifications of enterprise LTE-femtocells regarding data rates, coverage, simultaneous users, and power consumption?

A.3 Cost-related

What is the wholesale price of an enterprise LTE-femtocell?

Does operating frequency affect manufacturing costs and power consumption?

What are the installation and deployment costs for deploying an indoor femtocell network? Which are the major cost components?

What management costs are involved for femtocell deployments?

What kind of costs does a network-based synchronization solution such as NTP and PTP bear?
Appendix A. Interview questions

Which are the costs for deploying and leasing fiber?

Which are the main cost drivers in an end-to-end mobile broadband service?

A.4 Design and dimensioning

What is the typical indoor area an indoor FAP can cover?

Backhaul design based on mean traffic (during ‘busy’ hours) can cause bottlenecks, while based on peak traffic (during ‘quiet’ hours) can lead to under-utilization. Under which circumstances is each approach most suitable?

Are backhaul requirements moving towards peak-rate values?

A.5 Actor-specific

Which are the main assets MNOs and WISPs can activate in deploying and operating femto RANs?

How important is site ownership in deploying an indoor network and what other assets does a FO have?

Does mobile broadband over TVWS sound promising / feasible? For which reasons?

How can mobile operators integrate femtocells into their networks? Under which circumstances is each strategy more suitable?

Which factors are taken into account when an actor considers an investment? How much do technical and business criteria affect these decisions?

Is on-site calibration needed for a femto RAN deployed in a large facility environment?

A.6 Spectrum-related

Is it possible to deliver QoS over unlicensed bands?

Is it possible to deliver QoS over TVWS?

Is spectrum licensing becoming obsolete as a management policy?