Chapter 10

Deployment of Next Generation Cellular Networks

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When discussing the deployment of mobile radio networks two principal flavors have to be addressed. The first flavor is related to the network coverage and is largely independent of the specific system. Hot topics currently under discussion are strategies to reduce the level of electromagnetic exposure while still providing a high level of coverage especially indoors. To achieve that goal new concepts like Femto cells for example are being introduced into various networks. A number of contributions within COST 2100 have been dedicated to these coverage related aspects and are discussed in Section 10.2. The second flavor deals with the optimization of the network, which depends critically on the standard. The two most widespread standards families used in mobile networks are being developed by the third generation partnership project (3GPP) and IEEE 802, which are discussed separately in two different sections. Section 10.3 is dedicated to the 3GPP networks includes optimization techniques mainly for UMTS and LTE presented in COST 2100, whereas section 10.4 deals with the IEEE 802.16 (WiMAX) and IEEE 802.11 (WLAN). It has to be mentioned that the optimization techniques introduced in this chapter are based on classical approach using input data available in radio network planning tools and are different from the approaches described in chapter 11, where optimization makes use of real measurement values.

10.1 Coverage Aspects

Customers of today's mobile radio networks require access to an ever increasing range of advanced, bandwidth-hungry services and applications, and they expect these services to be available anywhere, anytime and irrespective of user speed. Therefore, operators have to deploy an ever increasing number of base stations to meet the customers' expectations in terms of coverage and quality of service. The number of base stations to be deployed is further increased owing to the larger variety of mobile radio and wireless communications systems in operation, as well as to the entry of new operators in the market. On the other hand, the deployment of an increasing number of transmitting antennas causes concern among the population about possible negative effects that exposure to electromagnetic fields could have on human health. For this reason, several European countries adopted strict exposure limits and started monitoring campaigns to verify that these limits are respected. Obviously, the major concerns occur in dense urban areas, where there are a high number of base stations close to homes and working places. Two TDs presented in COST 2100 dealt with these aspects, namely [BWLE07] and [BCG+08].

Paper [BWLE07] provides results from a study, promoted by a major operator, of how different network topologies affect coverage and exposure. Coverage was evaluated by means of a so-called semi-deterministic propagation model described in [WWWW05]. The model is based on the concept of dominant propagation paths and can also account for indoor penetration loss in a semi-empirical way. Performance was evaluated by means of a dynamic 3G system simulator, which collected several performance indicators, including network throughput and call blocking and dropping rates. Simulations were performed for a district of the city of Bonn, Germany, that extends for about 8 km^2 and has about 40,000 inhabitants. Five different network topologies were considered, shown in Table 10.1: In scenarios 1 and 2 base stations were inside the built-up area while in the other three scenarios base stations were placed outside this area.

Finally, four different service classes were considered: voice, video telephony, WWW browsing and a generic high-speed data transfer. As an example of coverage results, Fig. 10.1 shows the portion of area where coverage probability, evaluated with the dynamic simulator, is at least 90% for the 384 Kb/s data service. As might be expected, the covered area decreases for scenarios where the base stations are placed outside the urban area.

Table 10.1: Network scenarios considered in [BWLE07]

Scenario	No. of sites	sectors per site	Antenna height
1	1	6	40 m
2	7	3	25 m
3	1	4	30 or 60 m
4	2	4	30 or 60 m
5	5	3	30 or 60 m

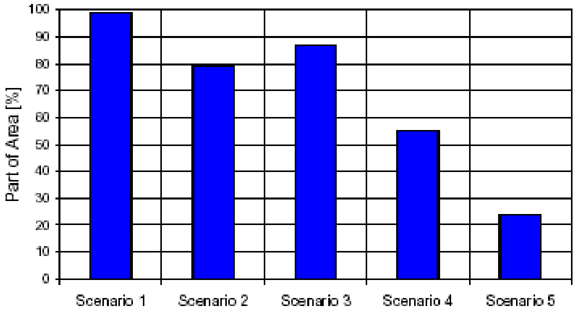


Figure 10.1: Area with at least 90% coverage probability (384 Kb/s data service)

Fig. 10.2 compares the total system throughput (magenta curve) with the 90^{th} percentile of exposure (blue curve). This comparison shows that network topologies with base station sites outside the city yield the lowest exposure, yet at the cost of a large reduction of the network capacity. Scenario 1 yields low exposure values at a reasonable network capacity.

In conclusion, regarding all three aspects (exposure, coverage and capacity), the scenarios with sites within the urban area were shown to be in advantage. Using only one external site yields low exposure but insufficient capacity, while with five external sites the coverage is insufficient, in spite of an exposure comparable to that of scenarios with inner-city sites.

Authors of [BCG$^+$08] concentrated mainly on the usage of microcells to provide coverage in an urban area, both outdoors and indoors. The studied area was a central district of the city of Bologna, Italy, of about 500 x 500 m; this area could be covered either by a single, three-sectored macrocellular, or by 28 microcells, or by a combination of the two techniques. The macrocel-

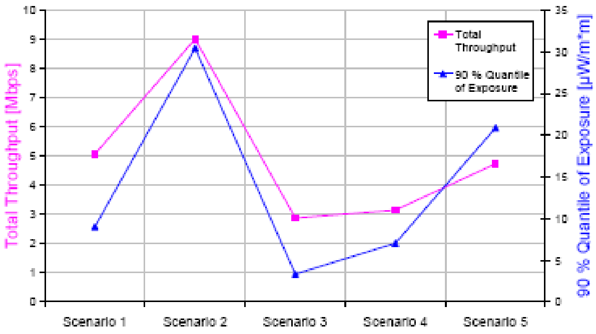


Figure 10.2: Comparison of exposure and capacity for all scenarios

lular site was supposed to be 30 m high, while microcells were at 3 m above street level. A three-dimensional ray-tracing tool was used for propagation, and a penetration loss of 14 dB was assumed. Coverage was considered satisfactory if at least 90% of locations, both outdoors and indoors, were covered; furthermore, it was required that the electrical field should not exceed the limit imposed by the Italian law (i.e. 6 V/m). The paper shows that using only microcells would provide poor indoor coverage, especially at higher floors. This could be overcome by increasing the microcell power, but it would cause excessive field exposure outdoors, where the limit would be exceeded in a non negligible fraction of locations. On the other hand, using only the macrocellular site would not allow sufficient coverage at lower floors of buildings. The authors found that a combination of the two techniques would lead to excellent coverage both outdoors and indoors while respecting the exposure limits, as shown in Table 10.2.

Table 10.2: Indoor coverage (% of locations) by floor according to [BCG+08]

Floor	Microcells only	Macrocells only	Both
0 (ground floor)	83.5	2.9	91.2
1	82.6	91.6	100
2	82.8	97.7	99.5
3	82.3	100	100
4	80.4	100	100
5	79.9	100	100

It was shown how an optimal outdoor coverage at street level does not guarantee a sufficient coverage of indoor environment as well, particularly in high buildings with several storeys.

This topic was also addressed in [dlRZ09], which presented the main issues to be considered within the European project CWNetPlan, that at the time of writing was about to start. As a matter of fact, major operators verify that nowadays most of wireless communications take place when at least one of the terminals is indoor, as authors of [dlRZ09] point out. For this reason, indoor radio coverage optimisation is going to be a key challenge for operators in upcoming years. To fulfill indoor service requirements, operators may follow two main roads:

- The first consists in increasing the indoor radio coverage by modifying the outdoor network, e.g. by adding new base stations or by increasing their output power. This solution has drawbacks such as high costs and the difficulty to plan the network as well as health issues and exposure limits that have already been recalled in [BWLE07] and [BCG$^+$08].

- The other possibility consists in adding low power base stations directly inside the buildings. They can be
  - picocells, i.e. operator-owned and managed base stations, generally deployed in public premises such as shopping malls or airport concourses or
  - femtocells, i.e. user-owned and installed base stations, consisting of small units that need only to be plugged onto the customer's internet connection.

The widespread availability of femtocells ”off the shelf” will mean that operators will lose the complete control of the network structure. The first femtocell deployments are expected to occur in a closed access mode, i.e. only authorised users will be allowed to connect to the femtocell, all the other calls being redirected to the macrocell. This will produce interference when unauthorised users will pass across or close to the coverage area of the femtocell. A possible way to solve this problem is to endow picocells with self-configuration and self-optimisation capabilities (see also section 11.3). Fig. 10.3 shows an example of the benefits achievable with self-optimisation of antenna patterns. We notice that it allows a remarkable decrease of the interference area, shown in red, as well as it favours the reduction of the *ping-pong* effect.

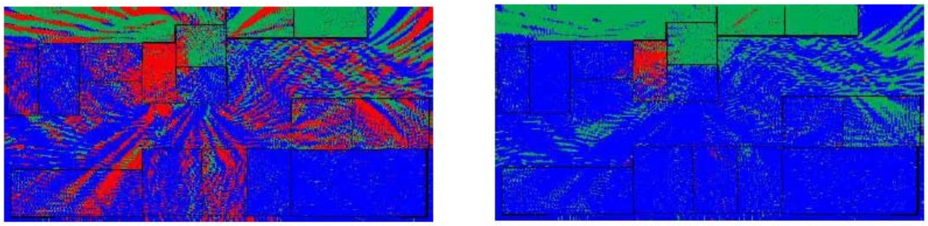


Figure 10.3: Service areas of 3 open access femtocells without (left) and with (right) antenna pattern optimisation. Mutual femtocell-macrocell interference area is shown in red.

In the discussion above we have seen the key role played by propagation prediction tools in wireless systems planning and optimisation. It is well known that models based on ray optics yield accurate field prediction in urban environment, owing to their capability of taking into account the characteristics and the topology of the urban environment.

The paper [OM08] discusses some key research challenges to be solved in order to favour the widespread adoption of ray-based tools by the operator community. Actually, current tools are more suitable for scientific work and for case studies, rather than for the massive computation effort required to simulate a whole network and to optimise base station parameters in order to improve the system performance.

The main requirements of a ray-based propagation tool, from an operator's point of view, are the following:

- improved accuracy justifying the effort in developing or adopting the propagation model and procuring an adequate topographic database
- a computation time allowing excessive usage of the tool
- the integration of statistical with deterministic models including outdoor-to-indoor modeling
- allowing wideband characterisation

The authors show the main research challenges to be tackled to meet the above requirements.

- The integration with the existing statistical models shall be pursued by developing modules able to interface with any statistical model, without the need to adapt to any proprietary tool.
- Computation time can be significantly reduced by a simplification of the data-base that is generally obtained by aerial or satellite photographs, reducing the number of surfaces and of edges to be considered.
- Outdoor-to-indoor prediction accuracy can be improved by using information about the internal structures of the buildings, the position of the user terminal within the building and the angles of arrival of rays at the building external surfaces.
- Wideband predictions can be improved by refining the models, and particularly by also considering diffuse scattering phenomena.

Combining the four challenges above leads to the propagation model architecture shown in Fig. 10.4, where the research challenges are indicated as four separate blocks.

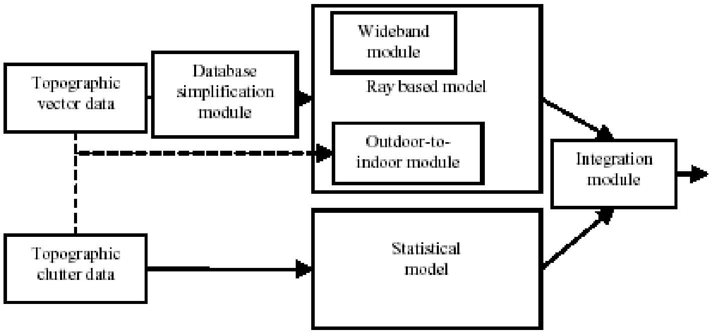


Figure 10.4: Architecture of a propagation model combining a statistical and a ray-based component.

10.2 3GPP Networks

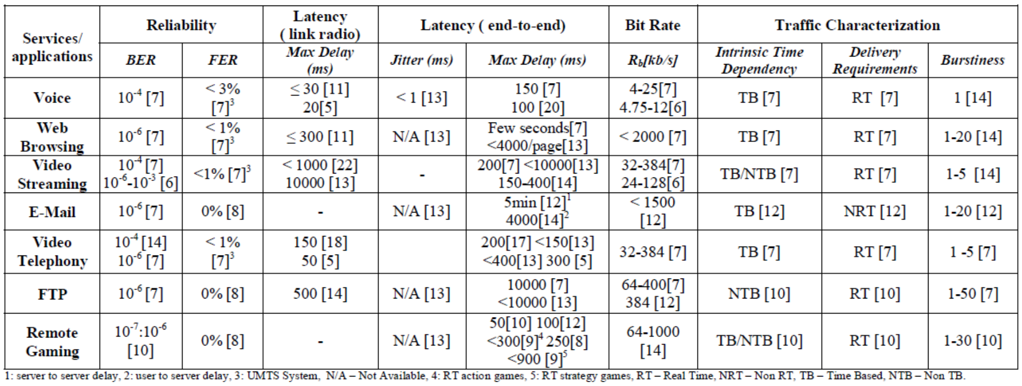
The initial deployment of a network and its subsequent expansions have always and are still posing considerable challenges to a network operator. Throughout the lifetime of a network, its radio coverage and capacity are important quality metrics. These two dimensions can largely be considered in isolation for Global System for Mobile Communications (GSM) networks. This is because GSM uses time-division multiple access (TDMA) and Frequency Division Multiple Access (FDMA) in such a way that interference can ideally be controlled by means of a proper frequency allocation.

The increasing service diversity over the recent years, however, has rendered the traditional capacity notion in terms of Erlang hardly effective. In addition, strongly interference-limited technologies such as Code Division Multiple Access (CDMA)-based Universal Mobile Telecommunications System (UMTS) and Orthogonal Frequency-Division Multiple Access (OFDMA)-based 3GPP-Long Term Evolution (LTE) come with a coupling of coverage and capacity that makes it futile to look at one dimension only while ignoring the other.

This section addresses the following aspects related to the deployment of 3rd Generation Mobile Group (3GPP) networks. First, examples of service requirements are reviewed, which can be used in the design of cost-effective network layouts. Second, results on network capacity optimization by means of cell/sector configuration are presented. Third, options of increasing network capacity through the use of smart antennas or Multiple-Input Multiple-Output (MIMO) antenna systems are reported. Finally, results on the use of a cognitive radio system as an underlay to a GSM network are given.

10.2.1 Quality Requirements and Profit Maximization

Both, network technology design as well as network planning depend on a clear understanding of the capabilities that a network shall have. A prominent driver for recent and future network generations is service beyond speech telephony. Such services include web browsing, video streaming, e-mail, video telephony, file transfer, and remote gaming. The requirements for supporting such services in terms of the reliability of the transport, the maximum latency, and the desired bit rate have been considered by various research teams as well as standardization bodies. In an effort to create one single reference for these seven services (including speech telephony), contribution [AMCV07]



Services/ applications	Reliability		Latency (link radio)	Latency (end-to-end)		Bit Rate	Traffic Characterization		
	BER	*FER*	*Max Delay (ms)*	*Jitter (ms)*	*Max Delay (ms)*	*R_b[kb/s]*	*Intrinsic Time Dependency*	*Delivery Requirements*	*Burstiness*
Voice	10^{-4} [7]	< 3% [7]^3	≤ 30 [11] 20[5]	< 1 [13]	150 [7] 100 [20]	4-25[7] 4.75-12[6]	TB [7]	RT [7]	1 [14]
Web Browsing	10^{-6} [7]	< 1% [7]^3	≤ 300 [11]	N/A [13]	Few seconds[7] <4000/page[13]	< 2000 [7]	TB [7]	RT [7]	1-20 [14]
Video Streaming	10^{-4} [7] 10^{-6}-10^{-3} [6]	<1% [7]^3	< 1000 [22] 10000 [13]	-	200[7] <10000[13] 150-400[14]	32-384[7] 24-128[6]	TB/NTB [7]	RT [7]	1-5 [14]
E-Mail	10^{-6} [7]	0% [8]	-	N/A [13]	5min [12]^1 4000[14]^2	< 1500 [12]	TB [12]	NRT [12]	1-20 [12]
Video Telephony	10^{-4} [14] 10^{-6} [7]	< 1% [7]^3	150 [18] 50 [5]		200[17] <150[13] <400[13] 300 [5]	32-384 [7]	TB [7]	RT [7]	1 -5 [7]
FTP	10^{-6} [7]	0% [8]	500 [14]	N/A [13]	10000 [7] <10000 [13]	64-400[7] 384 [12]	NTB [10]	RT [10]	1-50 [7]
Remote Gaming	10^{-7}:10^{-6} [10]	0% [8]	-	N/A [13]	50[10] 100[12] <300[9]^4 250[8] <900 [9]^5	64-1000 [14]	TB/NTB [10]	RT [10]	1-30 [10]

1: server to server delay, 2: user to server delay, 3: UMTS System, N/A – Not Available, 4: RT action games, 5: RT strategy games, RT – Real Time, NRT – Non RT, TB – Time Based, NTB – Non TB.

Table 10.3: Overview of service characteristics and requirements from [AMCV07, Table 2] including references, where the references translate as follows: [5] → [EU98], [6] → [EU03], [7] → [Pro03], [8] → [3GP03], [9] → [AL03], [10] → [Fer02], [11] → [Mon05], [12] → [Vel00], [13] → [LWN02], [14] → [Fer03], [18] → [HAS96], [20] → [Kwo95], [22] → [Ant04].

compiles information into an overview that is reproduced in Tab. 10.3.

The deployment and operation of a radio network for the mass market incurs high costs that are to be paid up by (future) revenues. Optimizing the roll-out of a network according to a cost/revenue trade-off – or more general, according to expected profit – is therefore a common goal in practice. Achieving this goal is by no means trivial in the presence of various sources of uncertainty, such as future service types, service demand, operating cost, and equipment prices. Nevertheless, the paradigm of cost-effective investments prevails roll-out in practice. Scientifically, the topic has yet received less attention than one might expect. This is possibly due to the intrinsic complexity of network planning without considering uncertainty as well as the various (partially related) sources of uncertainty.

The contribution [VCMV10] studies a cost/revenue trade-off for a UMTS network in a business city center. The scenario entails a service mix of demanding data services, a Manhattan grid layout, micro-cellular base stations with omni-directional antennas at the crossings, and pedestrian outdoor users. The desired grade of service is defined via a metric that measures call blocking and handover failure probability and a target value of 1%. Simulations for the Down-Link (DL) only are performed using a system-level simulator based on NS-2. Several variations are analyzed, which differ in the amount of capital expenditure and operational expenditure required for building and maintaining the network. In the context of a simple (and fixed) economic model, this analysis provides insights into how service demand, expected revenue per megabyte, quality requirements, cell sizes, license and equipment costs may influence operating profit.

10.2.2 Maximizing Cell Capacity

Capacity maximization in interference-limited networks is strongly related to the management of interference by the system at run-time as well as by the operator during network planning and optimization. As part of the deployment of a network, cell sectorization, the choice of antennas, and azimuth/downtilt of antennas are decided. Each of these parameters may have a strong impact on interference.

The authors of [PSN07] study means to optimize the sector configuration of a multi-sector cell in a CDMA network as to maximize the overall cell capacity. A necessary and sufficient optimality criterion for the sector configuration is known for perfectly homogeneous environments in the case of networks consisting only of one multi-sector cell. The criterion basically states that each sector shall serve the same amount of traffic. In order to be able to exploit this criterion under non-homogeneous environment conditions, the authors propose a transformation function that maps the cell power vector of a multi-sector cell operating in a non-homogeneous environment into a cell power vector for an "ideal" network in a homogeneous environment. Based on this transformation, the same optimality criterion and optimization procedure as in the homogeneous case shall become applicable, see [PSN07] for details.

The author of [Pom09] proposes an approach to identifying an optimal site sectorization in CDMA networks. He also argues that realistic multi-site scenarios can be appropriately captured using the method from [PSN07] for single multi-sector cell networks.

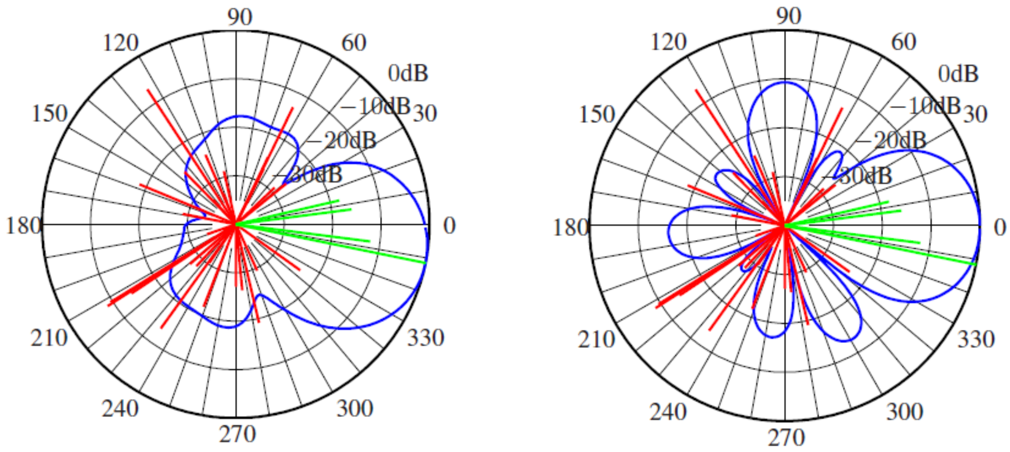
During network planning and optimization, the cell capacity of UMTS networks can be improved by explicitly designing for minimal interference. The contribution of [EG08] is to introduce planning methodologies that allow to minimize interference overhead while maintaining the established network coverage. Tab. 10.4 shows computational results for the two public scenarios Berlin and Lisbon from the Models and Simulations for Network Planning and Control of UMTS (MOMENTUM) library [EGT05] as well as for the two scenarios Turin and Vienna from the COST 293 Mobile Radio Access Network

		uncovered load [%]	total TX power [W]	avg. cell load [%]	max cell load [%]	other/own cell intf. ratio [%]	blocked traffic [%]	congested cells [#]
Berlin	initial	1.4	773.2	35.9	63.4	114.7	5.96	42
	optimized	0.2	647.9	30.1	49.5	89.2	1.87	14
Lisbon	initial	1.3	469.8	24.5	60.0	81.8	2.52	12
	optimized	0.9	422.6	22.1	51.6	65.8	0.99	6
Turin	initial	35.1	998.3	37.6	63.0	234.4	1.02	14
	optimized	35.3	854.4	32.2	57.1	208.5	0.41	6
Vienna	initial	5.2	2257.1	31.3	56.0	191.6	1.59	24
	optimized	5.3	2173.6	30.2	54.5	173.0	1.08	11

Table 10.4: Computational results for coverage and capacity optimization of realistic UMTS network scenarios [EG08]: uncovered traffic lacks pilot power or quality; other-to-own-cell interference ratio represents cell coupling, and "congested" cells have $\geq 2\,\%$ blocking

Reference Scenarios (MORANS) library. Furthermore, the authors present the first practicable approach to assess how well a network is configured with respect to interference avoidance. One benchmark is derived from the revised pole equation [EG07], another one comes from homogenized versions of the scenarios. A comprehensive treatment of these topics can be found in [Gee08].

LTE cell capacity is limited by interference, like in all modern radio network systems. The main approach to mitigating inter-cell interference is soft frequency reuse: demanding users at cell edges follow a frequency reuse pattern, whereas users with low power requirements, e.g., those at the cell center, can freely use all resources. The reuse pattern is prescribed by power masks. The authors of [BEGT09] use equation systems that describe interference coupling among cells – previously established in the context of CDMA/UMTS – as a tool for adapting power masks to traffic demand. A concise model is introduced that allows to efficiently evaluate alternative power masks w.r.t. their impact on inter-cell interference. Based on this model, the authors propose a simple algorithm that optimizes power masks for a given user demand distribution. Results from dynamic simulations suggest that adaptive power masks beat uniform, hard, and fixed static reuse patterns in terms of total cell throughput as well as weakest users' performances.



(a) SNR

(b) SINR

Figure 10.5: The radiation patterns are optimized for an example link using SNR- and SINR-based metrics. The green and red lines indicated the paths to the desired and non-desired MSs, respectively. Line lengths correspond to path gain [BHC07, Figures 4, 5]

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10.2.3 Advance Radio Systems

The authors of [CGV09] investigate aspects of using beamforming antenna arrays with four commercial antennas per sector in a 3-sectorized UMTS-Frequency-Division Duplex (FDD) network. They study the impact of array positioning and alignment errors as well as the influence of alternative feasible methods of obtaining the covariance matrix used for beamforming. The variations in the ability to support users in the DL is analyzed in a wrap-around scenario with seven cells using Short-Term Dynamic (STD) system-level simulations. The key observations are that limitations in properly estimating the required DL covariance matrix have a considerable impact on the capacity of the network. Moreover, poor vertical alignment of the antennas within an array causes significant degradations in the achievable capacity. In contrast, horizontal alignment and the type of array (uniform circular or uniform triangular) do not show a strong influence on the metric. In case beamforming is performed at each base station separately, then using the Signal-to-Noise-Ratio (SNR) instead of the Signal to Interference plus Noise Ratio (SINR) performs better, see Fig. 10.5.

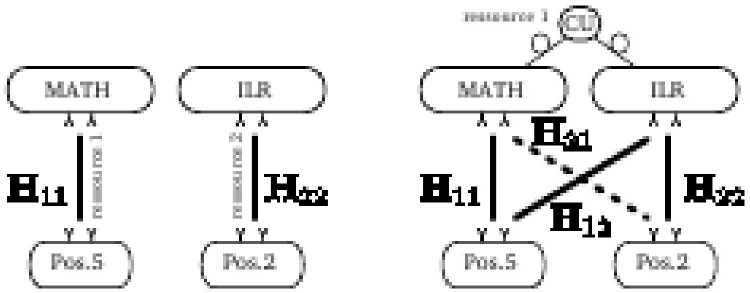

Figure 10.6: In the traditional setup (left), two users are served from different sites (MATH, ILR) using distinct resources. In the cooperative approach (right), the same users are served from the same sites on a shared resource. The benefit comes from a joint (central) processing (CU).

The contribution [JJJ+09] reports on radio measurement campaigns at 5.2 and 2.53 GHz in outdoor multi-cell environments from Berlin and Dresden (Germany). The performance of cooperative multi-cell systems is under study. The authors experimentally present evidence that cooperation enhances the rank of the compound channel matrix (see Fig. 10.6). This allows to exploit new spatial degrees of freedom. While in traditional settings, cell capacity decreases when sharing the same spectrum among cells, cooperation allows to raise the capacity even beyond the mean capacity of isolated cells.

10.2.4 Spectrum Re-use by Cognitive Radio Systems

The authors of [CGV09] consider alternative approaches to implement a cognitive radio system as an unlicensed user in the GSM licensed frequency bands. Two proposals, an interweaved frequency use and an underlay approach, are considered [GJMS09]. The latter approach is favored and studied in more detail. An algorithm for the selection of frequency resources by the cognitive radio system (secondary system) operating according to the underlay approach is presented and its impact on the primary system, GSM in this case, is investigated. This investigation is based on a realistic network scenario in the city of Bologna, Italy, that is analyzed in a detailed simulation environment. The preliminary results suggest that a secondary usage is indeed possible without causing harmful interference to GSM.

10.3 IEEE 802 Networks

10.3.1 IEEE802.16 WiMAX

Worldwide Interoperability for Microwave Access (WiMAX) was designed by the WiMAX forum in 2001. It is a technology based on the IEEE 802.16 standard (also called Broadband Wireless Access) [Zha08]. It was initially developed as a last mile connectivity solution, i.e. a solution to efficiently bring the internet in areas where no copper is deployed. WiMAX is also a possible replacement candidate for cellular phone technologies and the future release is candidate for the Fourth Generation (4G).

Advantages of WiMAX

WiMAX covers long distances and it uses unlicensed spectrum to provide access to a network. It can be deployed for Point to Point (PTP) or Point to Multi-points (PTM) links [MAR$^+$07b]. WiMAX uses OFDMA, where individual users are assigned to different subsets of sub-carriers, in order to achieve higher data rates and reduce interference. Thus, it is important, when deploying a WiMAX network, to carefully plan not only the radiated power, but also the distribution of the sub-carriers.

As explained in [MAR$^+$07b], different received power levels correspond to different physical bit rates, and modulation and coding schemes. Thus, a WiMAX receiver can automatically choose its modulation from binary phase shift keying (BPSK) until 64 state Quadrature Amplitude Modulation (QAM), displaying its ability to overcome Quality-of-service (QoS) issues with dynamic bandwidth allocation over the distance between the base station and the mobile user. In IEEE 802.16-2004, channels of 3.5, 7 and 10 MHz are defined. This ability to ensure a good QoS is one of the best characteristics of WiMAX and makes it suitable to support multimedia and IP (Internet Protocol) communications, e.g., videoconference, voice over IP, and communication of high resolution video/image.

In [MAR$^+$07b], the deployment of a PTP link is presented. Such deployment is performed using relays, and it is important to verify that there is a line of sight between the transmitters for the placement of the repeaters and absence of obstructions to the first Fresnel ellipsoid. Five different scenarios were tested, covering distances from $5km$ until $20km$. The field trials fit very well the Friis formula, and it is also verified that the beam width, which is

Table 10.5: Coverage and interference areas for the whole region of Beira Interior.

Type of antenna	Covered area	Area of interference	Non-covered area
Omnidirectional	50.8%	36.4%	12.8%
Sectorial	86.9%	0.3%	12.8%

small in such PTP links, can have a negative impact if it is not perfectly oriented. PTM networks have also been tested and the covered distance was up to $5km$. In such a scenario, the impact of the antenna is also very important. As represented in Table 10.5 it was verified, when covering the whole region of Beira Interior in Portugal, that using sectoral antennas improves the radio coverage and reduces interference.

In order to compare the performance of WiMAX with a more traditional approach such as Wireless Local Area Network (WLAN), an isolated village scenario has been considered [FCFN08]. First, as represented in Figure 10.7 (left), a mesh network of IEEE 802.11 access points, also called Mesh Access Points (MAPs), was deployed. The fixed Internet gateway was connected to a wireless Mesh Point Portal that established communication with MAPs spread over the village, each of them providing connectivity to nearby users. MAPs were equipped with two wireless interfaces: one acting as a classical 802.11g infrastructured access point, with a rate of $11Mbps$, transmission power of $5mW$ and sensitivity of $-95dBm$, another as an 802.11a mesh router, communicating at $54Mbps$, with a transmission power of $1W$ and a sensitivity of $-82dBm$, recurring to directional antennas that enable high communication ranges.

Then, as represented in Figure 10.7 (right), a single WiMAX base station was installed in the village. Mobile terminals were equipped with WiMAX interfaces. A bandwidth of $20MHz$ and 2048 sub-carriers was considered. From these, 367 were guard sub-carriers. In DL, clusters of 28 sub-carriers were defined, with 4 pilot sub-carriers. This resulted in 1440 data sub-carriers for DL. For Up-Link (UL), tiles of 12 sub-carriers with 4 pilots were considered. This resulted in 1120 data sub-carriers. A transmission power of $500mW$ was chosen for both the base station and mobile users.

From these two deployments, it was verified that the solution based on WiMAX could cover a higher number of users, since it could support up to 555 voice sessions, whereas the mesh network of Wireless Fidelity (WiFi) access points could only serve up to 41 voice sessions. However, it was also pointed out that a WLAN based solution is still a cheaper and less complex solution compared to WiMAX, that is why WLAN could be sufficient for small villages with low density of users.

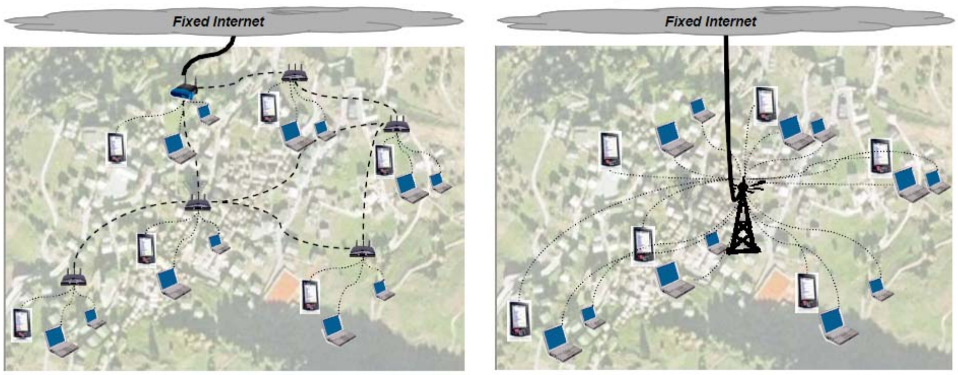

Figure 10.7: Solutions to cover a village, using WiFi mesh network (left), or WiMAX (right).

If WiMAX seems to be an optimal approach to cover large distances, many parameters such as the positions of the emitters, the type of antennas, or the distribution of the sub-carriers have to be optimised. Hence, before deploying such network, it is helpful to perform on-site measurements or off-line simulations using planning tools.

On-site Measurements

Field trials are very important to help deploy a WiMAX network. In [MAR$^+$07a], PTP links were established using relays. First measurements were performed to check the validity of the Friis formula. But if radio measurements are useful, it is also necessary to check the real throughput. Therefore, two computers, one as a server and one as a client, were connected and used to transmit data. Different tests were performed, one of them consisted in sending a large $40Mb$ file. The performance of such a file transfer is summarised in Table 10.6. In these field trials, it was verified that the measured data rate (throughput) and C/N decrease with the increase of the distance between the antennas (except in one case). The tests also demonstrated that WiMAX performs well for large distances.

As described in [VSaC$^+$09a], more measurement campaigns were also

Table 10.6: WiMAX Field trial results.

Distance (km)	Data rate (kbps)	C/N (dB)	Modulation	Time (s)
5.9	9 774	24	8	46
14.9	9 448	15	6	47
17.6	7 584	15	6	49
17.9	9 407	17	6	47
20.9	7 016	15	6	49

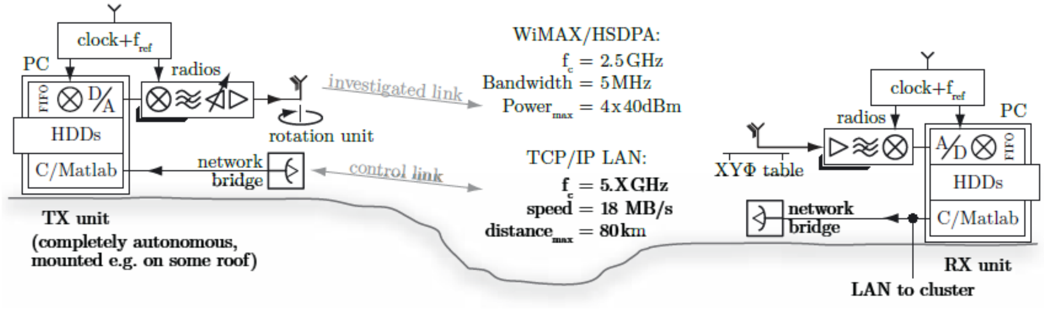

Figure 10.8: MIMO WiMAX measurement setup.

performed using a spectrum analyzer and a LabVIEW application especially designed to load the measurement data into the computer.

Other WiMAX field measurements are reported in [CMLR10] in the context of MIMO. Such measurements are usually time and money consuming, that is why a simple approach was proposed to study static scenarios, where only the physical layer was analyzed and a maximum of 4 antennas (at both receiver and emitter) was used. The scenario was evaluated on a block-by-block basis in real-time, with a flexible Matlab code. The measurement setup is represented in Figure 10.8.

The advantage of such measurement platform is that, when it is deployed, it is easily reconfigurable (by changing either the code or the position of the receiver) and many measurements can be carried out. For example, with such a system it was possible to verify that in different scenarios (alpine or urban), the turbo codes outperform the convolutional codes by about $3dB$. Moreover, an additional gain of about $1dB$ was achieved when implementing LDPC channel coding. However, at low SNR, the performance of the turbo code was worse than the convolutional one.

WiMAX Planning tools

When deploying WiMAX networks, another approach is to use planning tools. Even if field trials will always perform better than simulation, simulators are helpful to plan the pre-configuration of the network, and to study dense networks. First, such tools must be based on accurate radio coverage prediction, that is why measurement campaigns are always necessary to calibrate them. In [VSaC$^+$09b], the Friss model is modified to model different propagation environments by different propagation exponents α, e.g. $\alpha = 2$ for free space, $\alpha = 3$ in urban areas, and $\alpha = 4$ in shadowed urban areas. In [dlRVLP$^+$08], a more accurate propagation is proposed, based on an FDTD model. The advantage is that such a model can lead to a higher accuracy, but a very accurate database of the scenario must be available, containing the position of the walls and their materials. Hence, the propagation models must be carefully chosen depending on the scenarios and the requirements.

In [VSaC$^+$09b], the challenges when deploying a WiMAX network are investigated and illustrated using simulations. It is explained that planning tools are needed for operators to optimise both cost and revenues:

- Cost comprises the fixed cost (e.g. spectrum licenses) plus costs proportional to the number of cells, and the number of transceivers. It usually depends on the size of the cells and on the reuse pattern.

- Revenues depend on the throughput and the prices and are sensitive to the number of supported users.

In [VAH10], a cost/revenue function which incorporates the cost of building and maintaining the infrastructure and the effect of the available resources on revenues is proposed. In order to reach these objectives, operators will have to carefully implement interference cancellation techniques, as simple interference avoidance design presents limitations. In OFDMA, the amount of interference depends on how the sub-channels (subsets of orthogonal subcarriers) are allocated. For example, it was verified with this tool [VSaC$^+$09b] that with a reuse pattern K = 7, cell throughputs near the maximum are only achieved in the UL if sub-channelisation is used together with sectorization.

As explained in [LPGSZ$^+$08], the number of available sub-channels depends on the channel bandwidth and the permutation scheme (which indicates how the sub-channels are formed), since the sub-carrier spacing is fixed.

The sub-channels may be built by using contiguous or pseudo-random distributed sub-carriers. Sub-channels using contiguous sub-carriers, e.g. Adaptive Modulation and Coding (AMC), enjoy multi-user diversity (appropriate for static and nomadic traffic), while sub-channels using distributed sub-carriers, e.g. Partial Usage of Sub-channels (PUSC), enjoy frequency diversity (appropriate for mobile traffic).

To choose between the different allocation strategies, a good approach is to use system level simulators where the performance of the users is evaluated depending on the parameters of the network.

Hence, in [LPGSZ$^+$08] the implementation of a WiMAX system level simulator is described. The simulator takes multiple Monte Carlo snapshots to observe the network behaviour over long time scales. The Monte Carlo snapshots are independent one from each other since the users are randomly spread over the planning area with different requirements for throughput and QoS. The simulator takes four steps to calculate the final users and cells performance in each snapshot:

- The network configuration such as users, sectors, services and traffic map parameters is read in.
- The path loss for each user is calculated and the best server for each user is computed.
- The admission queue is created, according certain admission policies. Subsequently, DL and UL are analyzed separately
- Power control is carried out and the results of both downlink and uplink are calculated.

Different experiments have been carried out to evaluate the behaviour of the simulator and the performance of Mobile WiMAX networks.

Case study: deployment of WiMAX femtocells

In [dlRVLP$^+$08], simulations of WiMAX femtocells have been performed. Femtocells [ZdlR10] are very small base stations directly installed by the users inside their home. Since such devices have just started to be commercialised, there is no large scale femtocell deployment at the moment. That is why planning tools are very useful in this case. Different sub-channel allocation strategies have been tested:

- Same Channel (Worst case): In this case, the same group of sub-channels from the palette of available ones is given to all the macrocells and femtocells (i.e. the same 4 sub-channels are taken from the 16 available ones for each cell).
- Random allocation: The sub-channels of all the macrocells and femtocells are randomly chosen from the palette of available sub-channels. (i.e. 4 random sub-channels are taken from the 16 available ones).
- FRS 1X1X3: The palette of available sub-channels is divided in three sub-groups. Afterwards, each femtocell gets sub-channels only from its given sub-group. Neighbouring femtocells are assigned to different sub-groups to reduce interference probability (i.e. the 16 available sub-channels are divided in 3 sub-groups, then each sub-group is assigned to one femtocell).
- Femtocell Optimization: A Simulated Annealing optimization algorithm is used to allocate the sub-channels. In this case, only the sub-channels of the femtocells are planned together.
- Femtocell and Macrocell Optimization (Best Case): Same as previous strategy, however, not only the sub-channels of the femtocells are planned together here, but also the macrocell.

The results are given in Table 10.7, where the number of successful users, the total throughput and a cost function (representing the amount of interference) are given. It is verified that optimization methods provide very good results compared to the use of standard methods such as FRS 1X1X3. Moreover, it was also demonstrated that, when both the macrocells and the femtocells are optimised, the performance is higher, that is why it may be useful in the future to implement Self Organization (SON) not only in the macrocells, but also in the femtocells, so that all the cells can automatically choose their optimal parameters, see also section 11.3.

Best deployment strategies

To deploy a WiMAX network, both approaches have advantages and drawbacks. Field trials are more accurate but they are time consuming and expensive. The use of planning tools suffer a lower precision since it is based on models, but it is helpful to test dense and complex scenarios. That is why it

Table 10.7: System level simulation results with a scenario made of 63 WiMAX mobile users served by 1 macrocell and 30 femtocells

Method	Successful users	Total Throughput	Cost function
Same Channel	3	3168.0	2256.0
Random	46	4752.0	607.9
FRS 1X1X3	56	5913.6	143.5
Femtocell Optim	60	6336.0	22.5
Femto/Macro Optim	63	6652.8	12.5

is recommended, since all the scenarios are different, to plan the network by combining measurements and simulations. Moreover, as verified in the previous paragraph, it is verified that the use of optimization methods performs well and is necessary in order to reach high performance.

10.3.2 IEEE 802.11 WLAN

The main goal of radio network planning is to provide widely available wireless service of high quality at a reasonable price. In IEEE 802.11 WLAN, decisions on access point (AP) placement and channel assignment are traditionally taken sequentially. AP placement is often modelled as a facility location problem while channel assignment is represented as an (extended) graph coloring problem. As treating these key decisions separately may lead to suboptimal designs, the authors from [AES07a], [AES07b], [AEn08] proposed an integrated model that addresses both aspects whilst considering the Media Access Control (MAC) layer issues and maximizing the throughput. The interaction between the physical and the MAC layer in IEEE 802.11e was addressed in [OC07], [OC08], [OC09]. The achieved performance was analyzed via simulation in the presence of acknowledgements and block acknowledgements, and a weighted scheduling algorithm was proposed. In [MBR09], the influence of the propagation phenomena on the performance of wireless mesh networks is analysed.

Mesh networks are emerging as a wireless networking solution to provide coverage in areas where it has previously either been prohibitively expensive or not feasible. Traditional wireless network solutions require that each Access Point (AP) has a fixed connection to a backhaul network; this means that deploying a wireless network over large geographical areas normally requires the installation of expensive cabling. Wireless Mesh Networks provide a solution to this problem by greatly reducing the number of nodes and APs which require a wired connection to a backhaul network. For Wireless Mesh Networks to achieve similar levels of performance as traditional wired networks, multiple radios are required in each device. Unfortunately, the co-location of multiple radios in a single device causes a number of interference problems; these must be solved before Wireless Mesh Networks have any chance of being deployed by network operators. In [SRM10], the impact of non-overlapping channel interference in IEEE 802.11a based multi-radio nodes is investigated. The primary contribution is the discovery of a channel interference effect which is present over the entire 802.11a frequency space. This interference appears if two radios are located less than 50 cm from each other while both are behaving independently without any coordination.

The authors from [PSaN09], considered system capacity aspects as well as economic aspects. A simple WLAN planning tool was used to optimize the position and number of APs that considers the cost of the required equipment. Propagation measurements were considered and a comparison with the Dominant Path (DP), modified Friis and COST 231 models was performed. An algorithmic approach is addressed which considers the mixture of applications and the resulting system capacity in the optimization proccess.

Access Point Placement and Channel Assignment

One common, but major drawback of the heuristic approaches available in the literature is their inability to provide information on how much better an alternative design might be. In [AES07a], [AES07b], the following optimization models were applied. For positioning APs, coverage planning models are fairly effective and can often be solved to optimality. Frequency assignment has been studied extensively, for example, in the context of GSM network planning [KAS03]. The channel assignment problem belongs to the hardest problems in wireless network design. But due to a small number of available channels in IEEE 802.11 technology, the problem is still within reach of integer programming techniques. IEEE 802.11g networks operating in the infrastructure mode at 2.4 GHz were considered, a typical configuration in office environments.

The authors from [AES07a] show how the individual models can be merged into a complete optimization model for WLAN planning. This model allows to optimize the trade-off between high throughput and little cell overlap. In a case study based on realistic data for an indoor office environment, optimal network designs are computed with respect to the integrated model, where the MAC contention is considered. It was demonstrated how emphasis on maximizing throughput or on avoiding overlap changes the structure of the resulting solution. The different optimization objectives and their trade-off are taken into consideration simultaneously. Computational results from [AES07a] show that indeed the integrated approach is superior to the sequential one.

In [AEn08], the automated planning of IEEE 802.11 was also addressed, as an extension of the work from [AES07a]. As the main network performance criterion, the net throughput (or goodput) that the WLAN delivers to the network layer and to the user application was considered. The candidate AP locations for an office scenario are the ones from [AEn08].

A new method for dealing with the complex WLAN planning problem was proposed. To reduce complexity, two simplified evaluation schemes were employed for the preferred planning solution: throughput and overlap. Using multi-criterial optimization methods, several network configurations were generated that represent different trade-offs between overlap reduction and throughput maximization. To pick the best configuration, a new detailed analysis was conducted by simulation. Because only a few candidate configurations are left, this is computationally feasible. The first step consists of trading-off throughput and overlap and has already been tried in computational experiments, as shown in Figure 10.9, while the second one (detailed simulation) is work in progress.

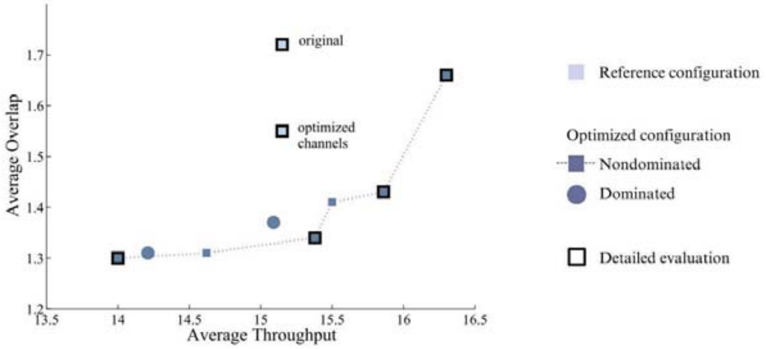

Figure 10.9: Trade-off between throughput and overlap.

Simulation results will enable to decide for a preferred configuration, validate the success of simulation, and better understand the relation of our simplified measures to realistic network behavior.

Impact of Propagation Issues on Wireless Mesh Networks Performance

The effect of dominant propagation contributions in wireless mesh network (WMN) throughput and delay has been investigated in [MBR09], considering different path loss exponent values, varying from 2, in free space, to 5, in severe Non Line-of-Sight (NLoS) conditions. While in scenarios A only the effect of traffic interference is considered, in scenario B both fading and noise are introduced. Strategy 1 from [MBR09] corresponds to no variation of the average number of neighbouring nodes, N, and a variation of the transmission power, P_t. Strategy 2 corresponds to a case where P_t is kept constant and the total number of nodes, n, varies.

In Figure 10.10, the total network throughput of Scenario A and Scenario B was compared for both strategies (strategy 1: varying P_t; strategy 2: varying n and thus traffic density).

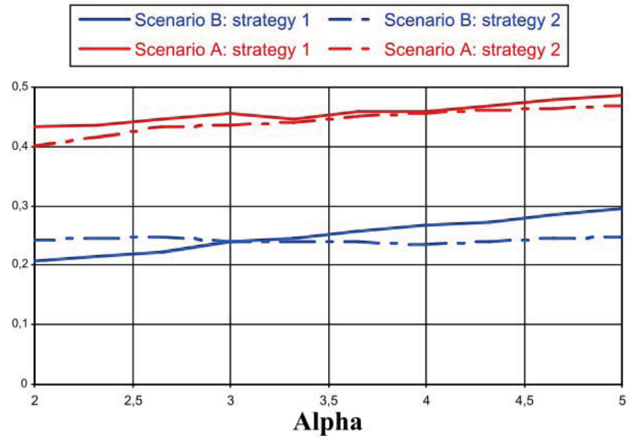

Figure 10.10: Network throughput distribution: comparison between Scenario A and Scenario B for both strategies.

As expected, due to the presence of multipath propagation phenomena, adding a Rayleigh fading and an AWGN noise to the model, the total throughput of the network decreases by about 30-50% (this specific value depends just on the assumed transmission power and propagation exponent). Signal fluctuations and noise cause a lower carrier-to-interference-plus-noise ratio, Carrier to Interference plus Noise Ratio (CINR) value and the loss of a higher number of packets. From Figure 10.10 it can be noted that beyond a propagation exponent 3 the first strategy provides a higher value of throughput. In fact, the throughput is strongly dependent on the number of hops to reach the destination: as the number of hops increases, the probability to lose a packet increases.

When the fall of connectivity is compensated by an increase of the transmitting power, the transmission range of each node is the same, and the number of hops to reach the destination remains constant as the propagation exponent increases. Otherwise when the fall of connectivity is compensated by an increase of number of nodes, the number of hops increases. Therefore, the higher becomes the number of hops, the lower is the probability that the packet can successfully reach the destination. This is justified by the fact that as the density of nodes increases, the number of hops increases, too. Consequently, also the packet loss probability increases. In turn, when the transmitting power is increased, the same node coverage is ensured and so the number of hops slightly differs.

Co-Channel Interference in IEEE802.11a Multi-Radio Mesh Networks

The co-channel interference results were obtained by conducting experiments in a well planned testbed to produce reliable and reproducible results. The presented results incorporate multiple parameters including transmission power, modulation coding scheme, channel separation and physical layer effects such as adjacent channel interference, carrier sensing, retransmissions and packet distortion.

The most important factor when planning the experimental testbed was to provide reliable and reproducible results with the least number of external dependencies as possible. To achieve this goal, the testbed was deployed as shown in Figure 10.11 whilst accounting for the Fresnel zone to design the radio links properly, and considering the configuration and scripts proposed in [SRM10]. The reliability was ensured by verifying the confidence intervals. In IEEE 802.11a, there is a trade-off between adjacent channel interference (ACI) and the separation between co-located antennas, which is limited to 50 or 60 cm maximum because of the dimensions of the node casing. A numerical example is given in [SRM10] for the MikroTik R52 802.11a/b/g card for the 5.2 GHz carrier with a 20 MHz bandwidth.

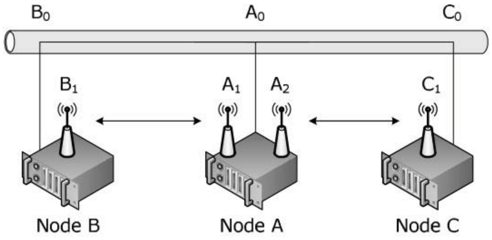

Figure 10.11: Multi-radio mesh network experimental setup.

The results show that by increasing the channel separation between co-located radios, the level of co-channel interference decreases. All presented results take the radio parameters TxPower, MCS, channel separation and physical layer effects into account to explain the performance degradation due to carrier sensing, packet distortion and backing-off. The results obtained will be used to develop an algorithm that takes the radio parameter settings, external dependencies and some prior knowledge as an input and provides the optimal global configuration of nodes in a WMN so that the co-channel interference will be minimised.

Planning: a Techno-economic Perspective

Presentation of the Wireless Planning Tool and Its Models

The Wireless Planning Tool (WPT) [PSaN09], [PSaR09] enables to optimise the number of the required access points (APs) or Base Stations (BSs) to be deployed, their positions, and the total cost of the equipment by considering the choice of the characteristics for different Wi-Fi technology suppliers. It supports the IEEE 802.11 a/b/g and WiMAX standards and it is able to estimate the Transition Region (TR) needed by the network, according to the capacity model. Items such as obstacles, APs characteristics and network card types can be directly updated into the software. Different propagation models can also be introduced and tested. The WPT helps in the process of making a complete plan for the coverage of a given area based solely on a digital format of the floor plan, obstacles, their materials and the locations for the wireless terminals. The program then generates an output with the layout, showing the received power/capacity and the positions for the APs. The optimum location for the APs, so as to minimize their number, was achieved using two methods. One method considers the received power in each position of the coverage area using empirical propagation models. The other one allows to choose the most probable position for each user and its capacity, according to the foreseen applications and the respective user's simultaneous factor (USF), via a specific algorithm. Details on the tool can be found in [PSaN09], [PSaR09], as well as a comparison with other tools for WLAN planning available in the market.