

## RESEARCH ARTICLE

## WiMAX Based Monitoring Network for a Utility Company: a case study

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### ABSTRACT

As the network of a power distribution company can be very large, maintaining such a network is not only very time-consuming but also very costly, especially when failures occur. A huge amount of effort could be saved by monitoring the substations remotely which allows, amongst others, to trace failures more efficiently. In this study, such a monitoring network is designed based on WiMAX. To the best of the authors' knowledge, this study differs from previous studies by combining both coverage and cost calculations. Firstly, the number of base stations needed to cover the considered area is determined. Therefore, link budget calculations are performed to obtain the ranges of the base stations. Secondly, the cost to install and maintain the network is determined using the results of the first step.

A cost of approximately 6.5 EUR was found per km<sup>2</sup> that needs to be covered. This result is very sensitive to possible changes of the technical parameters, which can lead to cost fluctuations between 33.5% and 3007%. Changes in the cost parameters have, however, less impact on the total cost than the technical parameters.

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### 1. INTRODUCTION

Power distribution companies typically have a large network with a hierarchical structure of different types of substations, even to the farthest corners of the country. The architecture of such a network is shown in Fig. 1. An important element in this network is the substation. A substation transforms power from one voltage level to another (lower) level. Two types of substations can be identified: transformer and distribution substations. The "large" transformer substations (typically 50x50 m<sup>2</sup>) transform voltages of 150 and 36 kV to 11 kV and deliver the power to the distribution substations [1]. The distribution substations transform the voltage level then from 11 kV to 220 or 230 V and deliver the electricity to a number of houses or buildings [2]. The distribution substations can thus be found in almost every street, resulting in a total of 40,000 substations to provide electricity for a region in Flanders (ca. 10,000 km<sup>2</sup> with ca. 4.8 million inhabitants). Maintaining such a network of substations is not only time-consuming but also very costly, especially when failures occur. A huge amount of effort could be saved by monitoring the substations remotely. In this way, failures could be traced more

efficiently and faster, instead of waiting until a technician has established which substation has failed by going on the spot. As the failure can be traced more quickly, the time to solve the problem is reduced, which keeps the customers satisfied and reduces the operational costs.

In this paper, a monitoring network for a power distribution company is designed based on WiMAX (Worldwide Interoperability for Microwave Access) [3]. WiMAX is introduced as a wireless technology for broadband connection and thus a perfect wireless alternative for the wired last mile connection. Companies around the world provide commercial networks based on WiMAX, not only to cities, but also to the far-away areas which were never reached by wired lines [4]. Although some operators in Russia and Malaysia intend to switch their networks from WiMAX to LTE (Long Term Evolution) as the latter allows to achieve a higher throughput [5, 6, 7], there are also cases where WiMAX is successful such as in the city of Houston, USA, which decided to deploy a municipal wireless network based on WiMAX for their city services [8]. This network allows to control traffic signals and school zone flashers remotely, to monitor water meters, to replace expensive wired lines, to make excess bandwidth available to enable

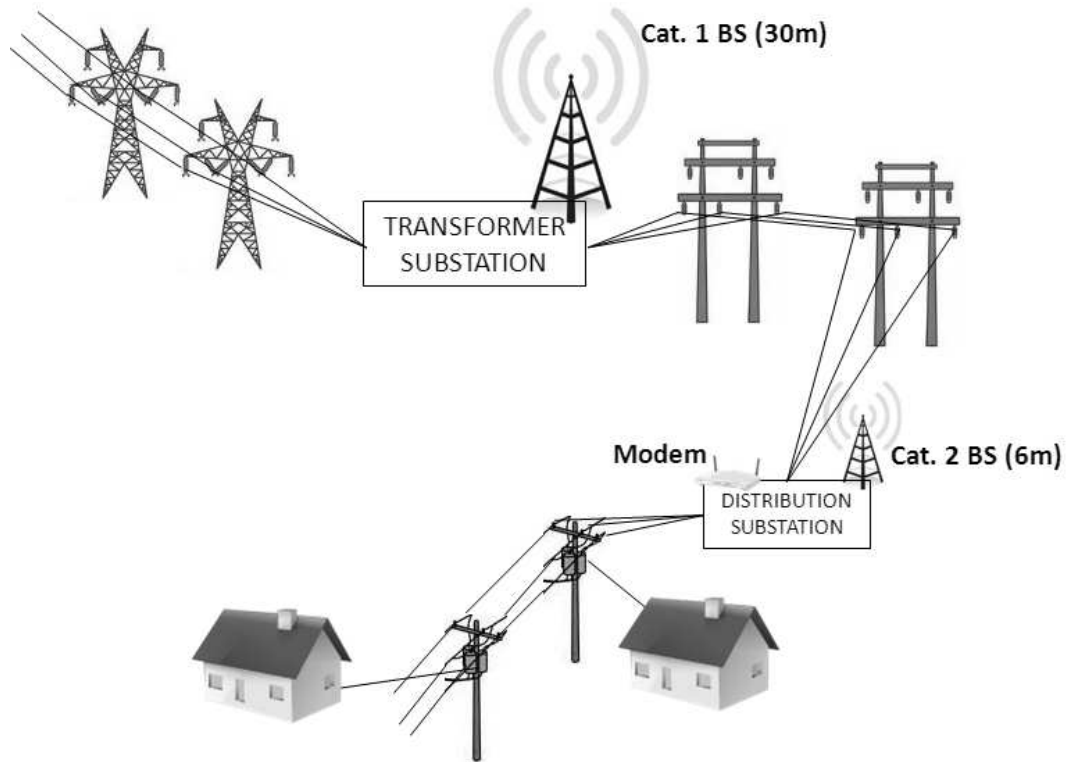


Figure 1. Architecture of a power distribution network.

free Internet services for the city residents in underserved and underprivileged communities (i.e., public computer centers for children), etc. The reason why Houston selected WiMAX as technology is that WiMAX allows huge savings on infrastructure expenses, while it can be easily and remotely managed to reduce the operational costs. As an extra, it permits to provide wireless access to the residents as well. Therefore, it might be interesting to investigate if WiMAX is a suitable technology for the monitoring network of a power distribution company as most monitoring networks are based on GPRS (General Packet Radio Services) [9, 10]. In [11] and [12], WiMAX is used as an alternative for GPRS, however, no cost calculation was made. Only range and coverage were calculated in [11, 12]. As both the cost and the coverage are never been investigated at the same time, according to the authors knowledge, it is interesting to investigate the consequences of choosing WiMAX as wireless technology for the monitoring network. Here, it is determined how many WiMAX base stations (BSs) are needed by calculating the coverage of each WiMAX base station. Also the cost to install and maintain the monitoring network is determined. Finally, it is investigated how sensitive the results are to changes in both the technical and cost parameters. Note that in this study a power distribution company is considered, but the results can also be applied to any other utility company as their networks are built similarly to that of a power distribution company.

The outline of this paper is as follows. In Section 2, a technical overview of WiMAX is given. Section 3 discusses the assumptions made and the proposed scenario. In Section 4, it is studied how many WiMAX base stations are needed for the monitoring network and how sensitive the results are for changes in the technical parameters. In Section 5, the costs for the monitoring network are determined based on the results of Section 4. Furthermore, it is investigated how sensitive the results are to changes in the cost parameters. Finally, Section 6 gives the conclusions of this study.

## 2. TECHNICAL OVERVIEW OF WIMAX

WiMAX is a wireless technology for broadband communication, mainly based on the IEEE 802.16 standard. Technology details and product certification are specified by the WiMAX Forum to support interoperability between different vendors.

Two important system profiles can be distinguished: Fixed WiMAX [13] and Mobile WiMAX [3], both trademarks of the WiMAX Forum. Fixed WiMAX supports fixed, nomadic, and portable services, while Mobile WiMAX is developed for mobile wireless applications and adds mobility to WiMAX. Currently, Mobile WiMAX has the most commercial interest and is being actively developed and deployed.

Mobile WiMAX (Release 1.5) is used in this study, as most of the current WiMAX products are supporting this standard [14]. Of course, this does not imply that the client nodes need to be "mobile" or on the move. In fact, in this case, all client nodes will remain in their place and the antennas are not moving.

### 3. ASSUMPTIONS AND SCENARIO

In this section, the area to be covered and the network architecture are presented. Furthermore, the determination of the number of base stations needed and the bit rate requirement are discussed.

#### 3.1. Area to be covered

The area to be covered is situated in Flanders, Belgium and has a surface of ca. 10,000 km<sup>2</sup> counting ca. 4.8 million inhabitants [15]. For simplicity, this area will be called "Flanders".

Within this area, two region types can be defined from a propagation based point of view: suburban regions (cities in "Flanders" such as Antwerp, Ghent, etc.) and rural areas. The surface of the suburban area is about 10% (ca. 1,000 km<sup>2</sup>) of the surface of "Flanders", and counts 28% of the population (ca. 1.4 million inhabitants). Note that examples of urban areas are New York, Tokyo, Los Angeles, etc.; and that Belgian cities thus not belong to that category. The remaining area of "Flanders" can be considered as rural. This distinction between suburban and rural areas is important for the range and coverage calculations of Section 4.

#### 3.2. Network architecture

As mentioned above, 40,000 distribution substations are needed to provide "Flanders" with electricity from which 10,000 are situated in the suburban area and 30,000 in the rural area. To deliver electricity to the distribution substations at the correct power level, 600 transformer substations are also needed, from which 150 are situated in the suburban area and 450 in the rural area. As all of the distribution substations need to be monitored, base stations have to be installed through "Flanders". The base station will be attached to the existing (transformer and distribution) substations of the power network.

If necessary, a transformer substation can be extended with a Category 1 (Cat. 1) base station which has an antenna height of 30 m as shown in Fig. 1. A 30 m pylon is thus required for these base stations. Furthermore, it is assumed that all of the transformer substations are equipped with a fibre for the backhaul connection. Analogously, if necessary, a distribution substation can be extended with a Category 2 (Cat. 2) base station also shown in Fig. 1. The antenna of a Cat. 2 BS will be positioned on the roof of the substation with a height of 6 m. This height is necessary to cover the distance between the distribution

substations as discussed in Section 4.2.1. The Cat. 2 BSs will be either directly connected to a Cat. 1 BS, equipped with a backhaul connection, or indirectly by intermediate Cat. 2 BSs as shown in Fig. 2. The full grey line in Fig. 2 indicates the physical (i.e. area where utility station delivers electricity) range of the substation, while the grey dotted line indicates the wireless range of the Cat. 1 BS installed on this substation. As shown in Fig. 2, the Cat. 2 BSs will need to hop to each other until they reach a Cat. 2 BS that is directly connected to a Cat. 1 BS because the Cat. 1 BSs are the only BSs that have a connection with the backhaul network as discussed above. For the hopping, the Cat. 2 BS behaves as a relay station (RS) and in this way a mesh network will be formed. Note that the mesh/relay technology is only supported from Mobile WiMAX release 2.0.

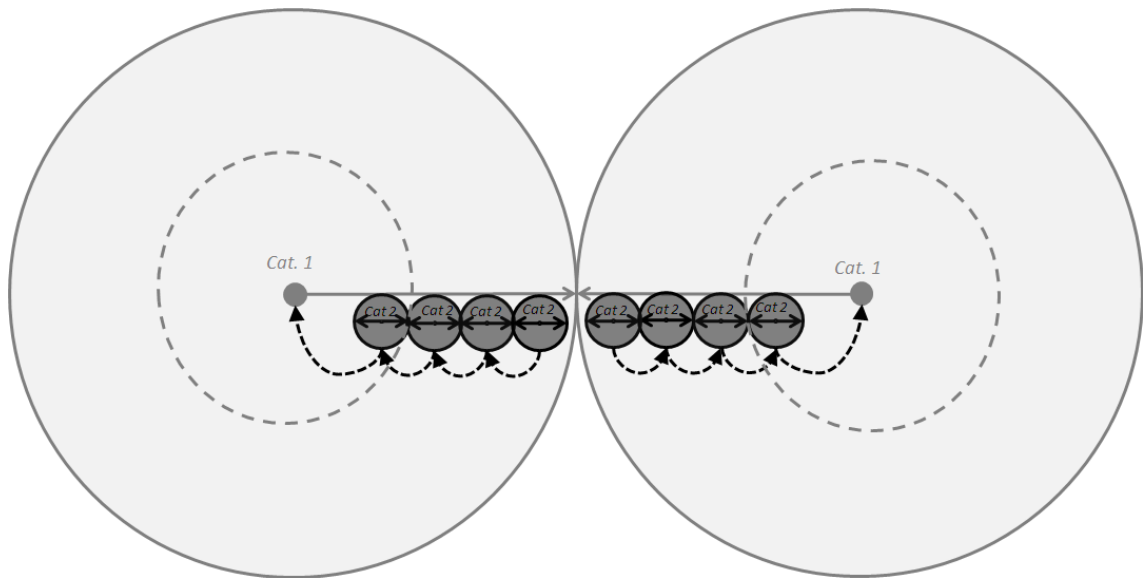
An overview of the two categories of base stations is given in Table I. Note that the only difference between the Cat. 1 and Cat. 2 base stations is the antenna height and the backhaul connection. A base station typically consists of the following equipment: the transceiver, the power amplifier, the digital signal processing, the rectifier, and the air conditioning [16].

Furthermore, the distribution of the different substations (i.e., how the different substations are spread over the suburban and rural area of "Flanders") approaches a uniform distribution. This is evident because such a distribution is the most convenient approach of the network for a utility company. In this way, they can cover "Flanders" with a minimal number of substations and thus with a minimal cost. For estimating the WiMAX coverage, an important input parameter is the distance between the different base station locations. To calculate this average distance, the rural area and the suburban area are divided by the number of transformer (resp. distribution) substations. This gives us the surface  $S$  ( $= A/N$  with  $A$  the surface of the area and  $N$  the number of substations) of the coverage of one distribution (resp. transformer) substation in the rural and suburban area. Assuming that  $S$  corresponds with a circle, the radius  $R$  ( $= \pi \cdot (S/2)^2$ ) of the circle can be determined. This radius corresponds with the average distance between two transformer (resp. distribution) substations. The average distance between two transformer substations amounts to 2.9 km in suburban area and to 5.0 km in rural area. For the distribution substations, an average distance of 356.8 m and 618.0 m is found in, respectively, the suburban and the rural area.

Finally, each distribution substation is equipped with a WiMAX modem to transfer the monitoring data from these substations (Fig. 1). The antenna of these modems is placed at a height of 2.5 m.

#### 3.3. Coverage requirement

In a first step, it is determined how much Cat. 1 BSs are needed to cover the rural (resp. suburban) area of "Flanders". The number of base stations  $\#BS$  needed to



**Figure 2.** Architecture of the WiMAX network. The grey full line shows that the physical (not wireless) range of the Cat. 1 BS, while the grey dotted line shows the wireless range of the Cat. 1 BS.

	Cat. 1 BS	Cat. 2 BS
<b>No. of possible rural locations</b>	450	30,000
<b>No. of possible suburban locations</b>	150	10,000
<b>Antenna height</b>	30 m	6 m
<b>Connection backhaul</b>	Fibre	(i) Directly to Cat. 1 BS (ii) Indirectly by intermediate Cat. 2 BS

**Table 1.** Characteristics of the two categories of base stations.

cover an area with surface  $S$  (in  $\text{km}^2$ ) is then:

$$\#BS = \lceil \frac{S}{\pi \cdot R^2} \rceil \quad (1)$$

with  $R$  the range of the base station (in km) and  $\lceil \cdot \rceil$  the ceil function. How to determine  $R$  is discussed in Section 4.

If the number of Cat. 1 BSs needed is lower or equal than the number of transformer substations, the calculation is stopped as the solution is found. Otherwise, all the available transformer substations will be equipped with a Cat. 1 BS and it is determined how large the part of the rural (resp. suburban) area is that is not yet covered by Cat. 1 BS. It is then determined how much Cat. 2 BSs are needed to cover the resulting part of the area.

Note that in this study the actual position of the substations and the topology of these positions are not yet taken into account. The purpose of this study is to make an estimation of the order of magnitude for the cost of the network. Based on this estimation, it can then be decided if WiMAX is suitable for the problem considered, and a more in-depth analysis can then be done. Moreover as "Flanders" is very flat, this approach is accurate for a cost estimation [17, 18]. Furthermore, as discussed in Section 3.2, the substations are uniformly

distributed over the suburban and rural area of "Flanders". The above described area based algorithm also assumes a uniform distribution as the area considered is divided by the area covered by one base station to calculate the required number of base stations. In this way, it is possible to map a base stations location to a substation site as there can be maximum the same amount of base stations as substations in the area. However, for a more in-depth analysis, a more complex network planning algorithm has to be used such as for e.g. GRAND (Green Radio Access Network Design) [16].

### 3.4. Bit rate requirement

For the monitored data, the collaboration with the power distribution company illustrates that a physical uplink throughput of 64 kbps per substation is sufficient. The lowest modulation scheme (i.e., 1/2 QPSK) supported by WiMAX corresponds with 3.5 Mbps downlink and 2.64 Mbps uplink which is thus sufficient for this case. The physical bit rate is the total number of physically transferred bits per second including useful data as well as the protocol overhead. An uplink of 2.64 Mbps allows 41 modems (= 2.64 Mbps/64 kbps) per sector to send their

data simultaneously to the nearest base station. As a base station typically has three sectors, this results in a total of 123 modems that can be served simultaneously by one base station. Even if a higher amount of modems needs to be connected to one base station, an uplink of 2.64 Mbps will be sufficient as it is not necessary that all modems send their data simultaneously but rather on a timely basis (for e.g., every 10 minutes, quarter or even half hour). A suitable transmission scheme can thus be developed for the modems connected to a base station. The development of such a transmission scheme is however beyond the scope of this study.

Using a higher modulation scheme (resulting thus in a higher offered bit rate which is actually not necessary as described above) is not interesting, because this can lead to a decrease of the signal's robustness and thus to a lower coverage.

In the scenario considered, the Cat. 1 and Cat. 2 BSs are used to cover "Flanders" for 90% which is a typical value when deploying networks. This means that 10% of the distribution substations will not be covered by the developed network and thus needs to be connected in a different way. This is however beyond the scope of this study.

## 4. RANGE AND COVERAGE

In this section, it is discussed how a base station's range is determined. Furthermore, it is calculated how much base stations are needed to cover "Flanders". The sensitivity of these results is also investigated.

### 4.1. Determination of a base station's range

To determine the coverage of a base station, a link budget has to be calculated. A link budget takes into account all of the gains and the losses that occur from the transmitter, through the medium, to the receiver [16]. Table II gives an overview of the most important parameters [16, 19]. More information about these parameters can be found in [16]. Note that it is assumed that the input power of both the base stations and the modem is 35 dBm. In this way, our coverage investigation is representative for both downlink and uplink. Furthermore, it is assumed that the antennas are placed outdoor (building penetration loss = 0 dB).

Based on this link budget, the maximum allowable path loss  $PL_{max}$  to which a transmitted signal can be subjected while still being detectable at the receiver is calculated [16]. The path loss is the ratio of the transmitted power to the received power of the signal and includes all of the possible elements of loss associated with interactions between the propagating wave and any objects between the transmitter and the receiver. Based on  $PL_{max}$ , the range of the base station can be calculated by using a propagation model. As "Flanders" is mainly flat, the Erceg C model is used in this study [19, 20]. For this model, appropriate parameters are defined, which take

Parameter	Value
Frequency	3.5 GHz
Input power of the BS	35 dBm
Input power of the modem	35 dBm
Antenna gain BS	18 dBi
Antenna gain modem	8 dBi
Feeder loss BS	0.5 dB
Feeder loss modem	0 dB
Fade margin	10 dB
Yearly availability	99.995%
Interference margin	0 dB
Bandwidth	5 MHz
Physical bit rate	3.5 Mbps
Receiver SNR	6 dB
Noise figure of modem	4.6 dB
Implementation loss modem	0 dB
Building penetration loss	0 dB

Table II. Characteristics of the WiMAX system considered.

account for the suburban and rural character of areas. So the Erceg C model can be used for both the suburban and the rural area.

### 4.2. Results

It is now investigated what the range of the different categories of base stations is. Based on these results, it is determined how much base stations of each category are needed to cover "Flanders". Furthermore, it is studied how sensitivity these results are for changes in the technical parameters.

#### 4.2.1. Range for the different categories of base stations

In this section, the range for each category of base station is determined by following the procedure described above. Table III lists the ranges for the Cat. 1 and Cat. 2 BS in the suburban and rural area.

As shown in Table III, the range is higher in the rural area than in the suburban area. This is due to the fact that in the suburban area more objects are present on the line between the transmitter and the receiver. These objects can disturb the quality of the signal resulting in a lower range.

Furthermore, the wireless ranges of Table III are higher than the average distances between two distribution substations, namely 0.36 m (< 0.56 m) in the suburban area and 0.62 m (< 0.67 m) in the rural area and it is possible for the Cat. 2 BSs to hop to each other.

#### 4.2.2. Coverage of "Flanders"

The number of Cat. 1 and Cat. 2 BSs used to cover "Flanders" for 90% is shown in Table IV. The suburban area can be covered by using 87 Cat. 1 BSs, no Cat. 2 BSs are needed here (no hopping model required). The rural area is covered by using 444 Cat. 1 BSs. Again, no Cat. 2

Cat. BS	Transmitter height [m]	Receiver height [m]	Range [km]	
			Suburban	Rural
Cat. 1 BS	30	2.5	1.82	2.41
Cat. 2 BS	6	2.5	0.56	0.67

Table III. Range of Cat. 1 and Cat. 2 base stations for the different areas.

BSs are needed. In total, 531 Cat. 1 BSs and 0 Cat. 2 BSs are needed to cover "Flanders" for 90%.

Cat. BS	Suburban	Rural	Total
Cat. 1 BS	87	444	531
Cat. 2 BS	0	0	0

Table IV. Number of Cat. 1 and Cat. BSs used to cover "Flanders" for 90%.

### 4.3. Sensitivity of the results

In this section, it is investigated how sensitive the results are for changes in maximum allowable path loss  $PL_{max}$ . Section 5.4 will investigate the sensitivity of the cost parameters. The fluctuations in  $PL_{max}$  can be caused by differences between the assumed parameter values of Table II and the actual values. For example, an antenna gain which is  $x$  ( $x \in \mathbb{R}^+$ ) dBi lower, resp. higher, than the antenna gain assumed lowers, resp. increases,  $PL_{max}$  with  $x$  dB. Analogously, when the actual input power of the BS or modem is  $x$  dB lower, resp. higher, than assumed,  $PL_{max}$  lowers, resp. increases, with  $x$  dB. Also the height of the BS or modem has an influence on the path loss.

Here,  $PL_{max}$  is increased and decreased by 5 and 10 dB, which is a realistic variation for the cumulative differences in antenna gain, input power, BS and modem heights, etc. The influence on the range and thus the number of base stations needed to cover "Flanders" is studied. Fig. 3 shows the range of the Cat. 1 and Cat. 2 BSs when  $PL_{max}$  is increased and decreased with 5 dB and 10 dB. The ranges increase with 18% to 32%, resp. 39% to 75%, when the maximum allowable path loss  $PL_{max}$  is increased with 5 dB, resp. 10 dB and the ranges decrease with 14% to 24%, resp. 28% to 43% when  $PL_{max}$  is decreased with 10 dB.

Table V shows the influence of variations in  $PL_{max}$  on the number of Cat. 1 and Cat. 2 BSs to cover "Flanders" for 90%. When the maximum allowable  $PL_{max}$  is increased with 5 resp. 10 dB, the number of Cat. 1 BSs decreases with 43% resp. 67% and no Cat. 2 BSs are even needed. When  $PL_{max}$  is decreased with 5 resp. 10 dB, the number of Cat. 1 and Cat. 2 BSs is significantly higher (2628% resp. 5642% due to the high amount of Cat. 2 BSs) than needed in the reference scenario of Section 4.2.2. It is thus very important to make a good and realistic estimation of the parameter values of Table II as small differences in these values can lead to significantly different results.

Note that when the path loss is 5 or 10 dB lower than predicted, the number of Cat. 2 BS becomes extremely high. Therefore, in practice, the solution would be to increase the antenna height of the Cat. 2 BS. For example, when both the Cat. 1 and the Cat. 2 BS have an antenna height of 30 m, 1033 BSs will be needed in total to cover "Flanders" when  $PL_{max}$  is decreased with 5 dB and 1799 BSs in total when  $PL_{max}$  is decreased with 10 dB. Clearly, in this case, the only difference between the Cat. 1 and Cat. 2 BS is that the Cat. 1 BSs have backhaul connections.

## 5. COST CALCULATIONS

In this section, the deployment costs of the network are investigated. Many costs are involved when rolling out such a network. In this section, an overview is given of all these costs. Furthermore, the sensitivity of the total cost for changes in individual costs is investigated.

### 5.1. Base station costs

In this section, the cost for the different categories of base stations is determined based on [21, 22, 23]. These values are updated based on private interviews with several equipment vendors and operators. Table VI shows the cost break-up for the two categories of base stations. First, the BS equipment needs to be purchased (Section 3.2). This results in a total cost of 24,000 EUR for both the Cat. 1 and Cat. 2 BSs. There is no difference in this cost between the two categories of base stations as it is assumed that their only difference is the antenna height and not their functionality. Note that the costs for the backhauling connection is not included as this connection will be provided by the utility company. The second cost that is taken into account is the cost for the antennas. A base station typically has three antennas i.e., one antenna per sector each covering 120° [16]. Assuming a cost of 1,000 EUR for one antenna results in a total cost of 3,000 EUR for both categories of base stations. Furthermore, a pole is needed for the installation of the antennas. For a Cat. 1 BS, a 30 m pole is needed with a cost of 16,000 EUR, while for the Cat. 2 BS, a 6 m pole is used with a lower cost of 4,000 EUR. For placing such poles, a building permission is obliged. Based on information about the license to build a windmill, a cost of 5,000 EUR was derived for the Cat. 1 BS and 500 EUR for the Cat. 2 BS. The cost of the license itself is very

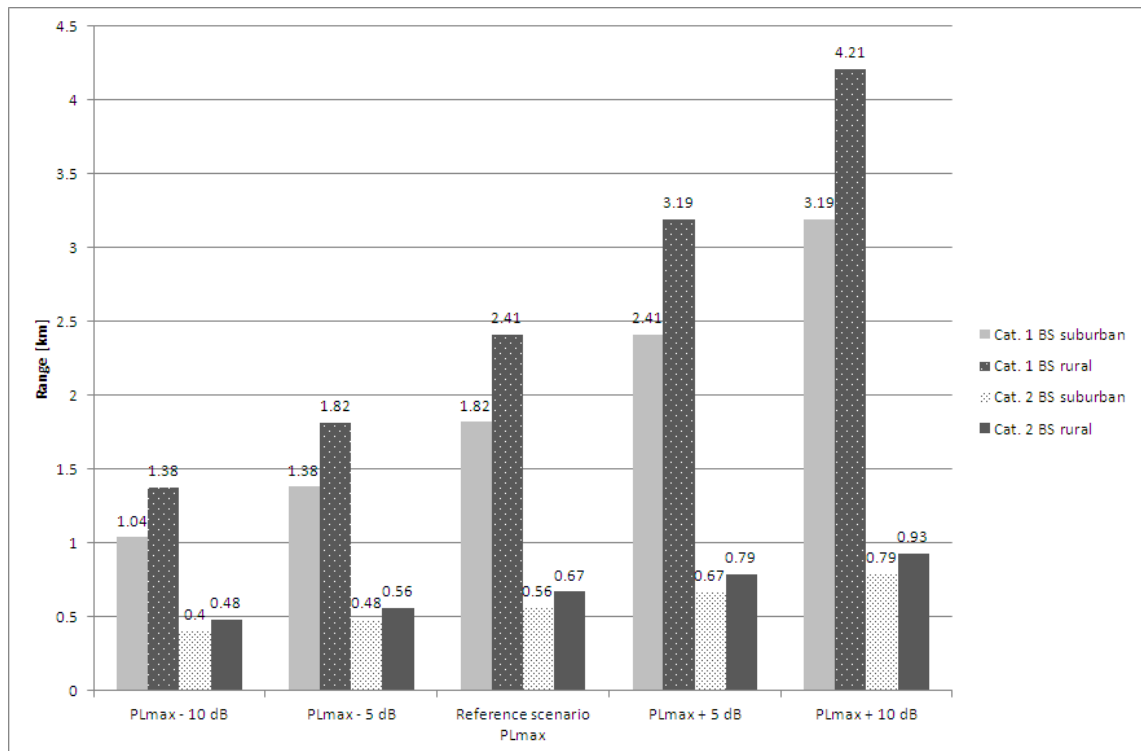


Figure 3. Range of the Cat. 1 and Cat. 2 BS when PL<sub>max</sub> is increased/decreased with 5 and 10 dB.

PL <sub>max</sub>	+5 dB	+10 dB	0 dB	-5 dB	-10 dB
Cat. 1 BS	304	175	531	600	600
Cat. 2 BS	0	0	0	13888	29820
Deviation	-43%	-67%	—	+2628%	+5642%

Table V. Total number of Cat. 1 and Cat. 2 BSs used to cover "Flanders" for 90% when PL<sub>max</sub> is increased and decreased with 5 and 10 dB and the deviation of #BS with respect to PL<sub>max</sub> + 0 dB.

limited (between 10 and 50 EUR), but the research into the suitability of each location is very time consuming. A 30 m pole is more drastic for the landscape view and therefore its cost is significantly higher than for a 6 m pole. Finally, the antennas and the pole need to be installed. A cost of 3,000 EUR for a Cat. 1 BS and 500 EUR for a Cat. 2 BS is considered. The antenna installation cost for a Cat. 1 BS is of course higher than for a Cat. 2 BS as it has a higher antenna height. A total of 51,000 EUR for a Cat. 1 BS and 30,000 EUR for a Cat. 2 BS is thus found for the CapEx (Capital Expenditures) costs.

Besides the initial CapEx costs, there is also the costs for yearly maintenance and licensing. The yearly maintenance cost is estimated at 10% of the initial cost. Also the license fee for the use of the WiMAX frequencies has to be paid yearly. As mentioned above, each base station supports three sectors which implies the use of 3 channels of 5 MHz bandwidth. Based on the costs that the WiMAX operator Clearwire has paid (i.e., 349 EUR/MHz/BS), a yearly cost of approximately 5,000 EUR for each base station

is estimated. The total OpEx (Operational Expenditures) amount thus to 10,100 EUR for a Cat. 1 BS and 8,000 EUR for a Cat. 2 BS.

Cost item	Cat. 1 BS	Cat. 2 BS
Equipment	24 kEUR	24 kEUR
Antenna (3)	3 kEUR	3 kEUR
Pole	16 kEUR	4 kEUR
Antenna installation	3 kEUR	0.5 kEUR
Building permission	5 kEUR	0.5 kEUR
<b>Total CapEx</b>	<b>51 kEUR</b>	<b>30 kEUR</b>
Maintenance	5.1 kEUR	3 kEUR
WiMAX license	5 kEUR	5 kEUR
<b>Total OpEx</b>	<b>10.1 kEUR</b>	<b>8 kEUR</b>

Table VI. Cost overview for Cat. 1 and Cat. 2 BS.

## 5.2. Modem costs

As mentioned above, each transformer substation will be equipped with a modem. Therefore, a total of 40,000 modems needs to be installed across "Flanders". In [21], the modem was considered as user equipment. However, in this case, the modems will be deployed by the utility company and thus an in-depth investigation of its cost is necessary. Table VII shows the cost break-up for the modem. The functionality of these modems is very standard and the cost of one modem is thus estimated at 200 EUR. This amount is based on the price of the modems of different vendors currently found on the market. 200 EUR may appear rather high, but a high quality modem is needed to avoid costly and lengthy repair and replacement procedures. For the installation of the modem, dedicated personnel is used which are working from a central point in "Flanders". Furthermore, it is assumed that substations which are physically close together are equipped with a modem on the same day. Therefore, a round-trip of on average 120 km (which is approximately the distance from the central point in "Flanders" to any other region in "Flanders") is assumed. When considering a tariff of 0.3 EUR/km, the transportation cost per day amounts to 36 EUR. This round-trip takes close to two hours. Assuming a 8 hour work day and an hourly wage of 30 EUR per person, this leads to a daily cost of 240 EUR per installer. In the remaining 6 hours, it is estimated that 4 different modems can be installed. The average cost  $C_{mi}$  per modem installation (in EUR) can thus be calculated as follows:

$$C_{mi} = (D_{pd} \cdot K_{mc} + H_{pd} \cdot W_{ph}) / M_{pd} \quad (2)$$

with  $D_{pd}$  the average distance per day per installer (in km),  $K_{mc}$  the tariff per km (in EUR/km),  $H_{pd}$  the hours worked per day by the installer (in hours),  $W_{ph}$  the wage per hour of the installer (in EUR/hour), and  $M_{pd}$  the number of modems installed per day by one installer. This leads to an average cost of 69 EUR per installed modem.

Cost item	Modem
Equipment	200 EUR
Installation	70 EUR
<b>Total CapEx</b>	<b>270 EUR</b>
Cost per failure	224 EUR

Table VII. Cost overview for the modem.

For the maintenance costs of the modem, the same two components are considered i.e., the transportation and the personnel cost. However, in this case, the transportation has to be made for each modem separately. Moreover, in 50% of the failures, it is assumed that it is better to completely replace the modem instead of repairing it. In general, the MTBF (Mean Time Between Failures) for routers and modems is in the order of 200,000 hours, or thus an average failure rate of 4%. This only contains hardware failures, so here a failure rate of 8% (50% of

these failures are hardware failures) is considered. Non-hardware failures could be e.g. related to software bugs. This leads to an average cost of 224 EUR per failure calculated by the following formula:

$$C_{mf} = D_{pf} \cdot K_{mc} + H_{pf} \cdot W_{ph} + P_{hw} \cdot C_m \quad (3)$$

with  $C_{mf}$  the average cost per modem failure (in EUR),  $D_{pf}$  the average distance per failure,  $K_{mc}$  the tariff per km,  $H_{pf}$  the hours worked per failure by the installer (including transport),  $W_{ph}$  the wage per hour of the installer (in EUR/hour),  $P_{hw}$  the probability of a hardware failure (in %), and  $C_m$  the cost of a modem.

## 5.3. Results

In this section, the cost for the complete network is determined based on the input of the above sections. The cost here considered is the Net Present Cost (NPC) of the project over 5 years, with a discount rate of 5.5% and represents the total current cost based on all expected future costs during the project life-span. The results of Section 4.2.2 are here used as input.

Fig. 4 shows the cost break-up and evolution of the reference scenario, discussed in Section 4.2.2. Year 0 is the time of roll-out and includes the initial CapEx investments. The following years include the OpEx costs. Summing up all the costs leads to a NPC of 63.8 million EUR (over 5 years). Note that the poles still have a value after 5 years, which is however hard to estimate. Applying the accounting rule of writing off the value linearly according to the useful life (estimated at 20 years), a residual value of about 6 MEUR is to be expected.

## 5.4. Sensitivity of the results

In this section, it is investigated how changes in the technical and cost parameters influence the cost calculations. First, it is studied how the technical parameters influence the cost calculations. Second, the influence of the cost parameters on the total cost is studied.

### 5.4.1. Influence of the technical parameters

For this study, the results from Section 4.3 are used as input. Fig. 5 shows the NPC of the project over 5 years with a discount rate of 5.5% when the maximum allowable path loss  $PL_{max}$  is increased and decreased with 5 and 10 dB. When  $PL_{max}$  is increased with 5 dB, resp. 10 dB, the total cost decreases with 33.5%, resp. 52.5% due to the lower number of Cat. 1 BS needed for these scenarios (Section 4.3). The total cost is thus non-linearly impacted by changes in the  $PL_{max}$ . When  $PL_{max}$  is decreased with 5 dB, resp. 10 dB, the cost increases with 1405.9%, resp. 3007.0% due to the very high number of Cat. 2 BS that need to be used to cover the area.

For comparison, the cost is also compared to the situation where the antenna height of the Cat. 2 BS is raised to 30 m (i.e., there is no difference any more between the Cat. 1 and Cat. 2 BS, see Section 4.3). In this case, the total



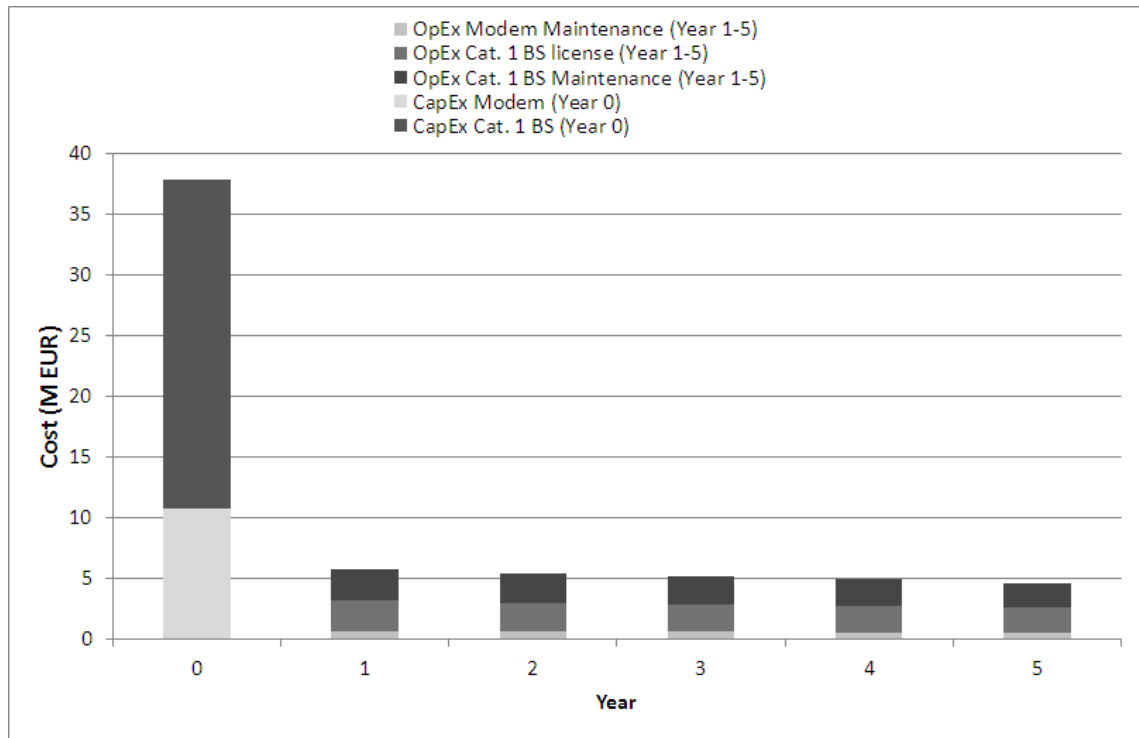


Figure 4. Cost break-up and evolution of reference scenario.

cost increases with only 74.0% when  $PL_{max}$  is decreased with 5 dB and with 187.0% when  $PL_{max}$  is decreased with 10 dB. However, note that acquiring building permits for 30 m BSs can be time-consuming or the request may be denied, in which case there is no other option but to use BSs at 6 m.

#### 5.4.2. Influence of the cost parameters

In this section, the influence of the cost parameters on the NPC is studied. Again, it is assumed that the project runs over 5 years with a discount rate of 5.5%. Three parameters are investigated: the price of the WiMAX license, the CapEx of the modem, and the CapEx of the Cat. 1 BS. The costs of the first two parameters are changed with -50% and +50%, while the cost of the latter is changed with -20% and +20%. This lower fluctuation represents a lower degree of uncertainty about the actual value of the parameter. Fig. 6 shows the total cost for each case.

Changing the WiMAX license cost with +50%, resp. -50%, results in a change of -8.9%, resp. +8.9%, for the total project cost. Analogously, changing the modem CapEx with 50% results in a change of 8.5% for the total project cost. Finally, when the CapEx of the Cat. 1 BS is increased, resp. decreased, with 20%, the total cost increases, resp. decreases, with 12.1%. Although the change of the parameter is lower than for the other two parameters considered, it still results in a higher change of the total cost. This is due to the fact that the CapEx of the

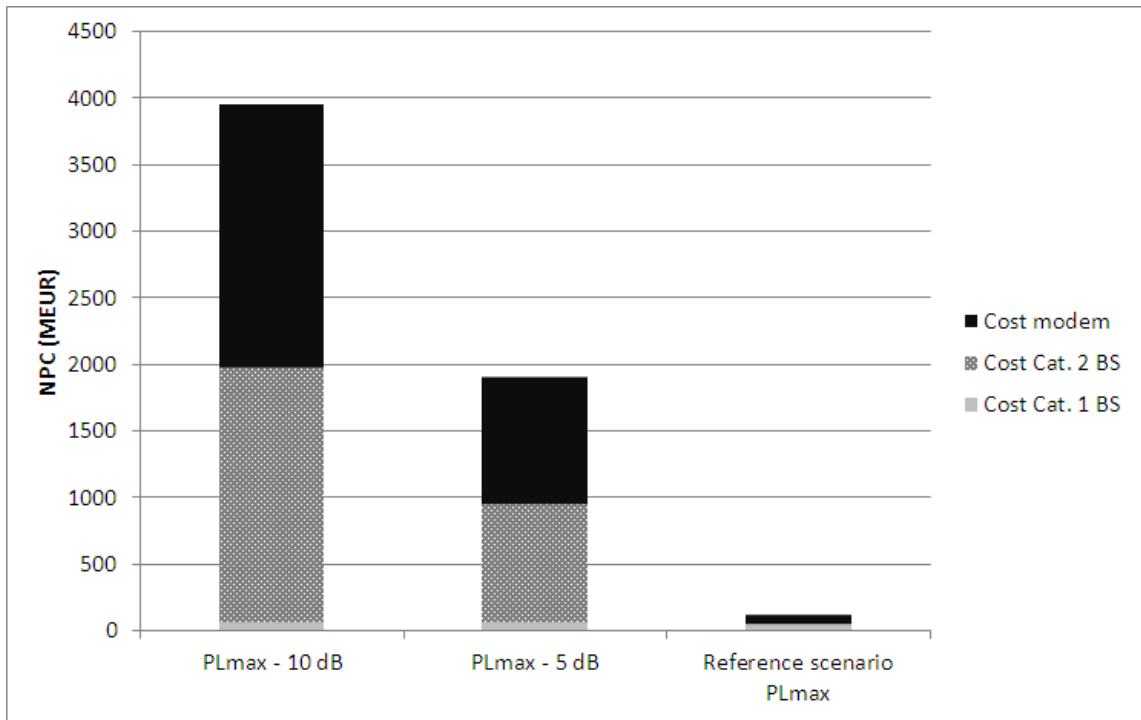
Cat. 1 BS is responsible for a big part of the total cost as shown in Fig. 4.

#### 5.4.3. Influence of the technical parameters versus influence of the cost parameters

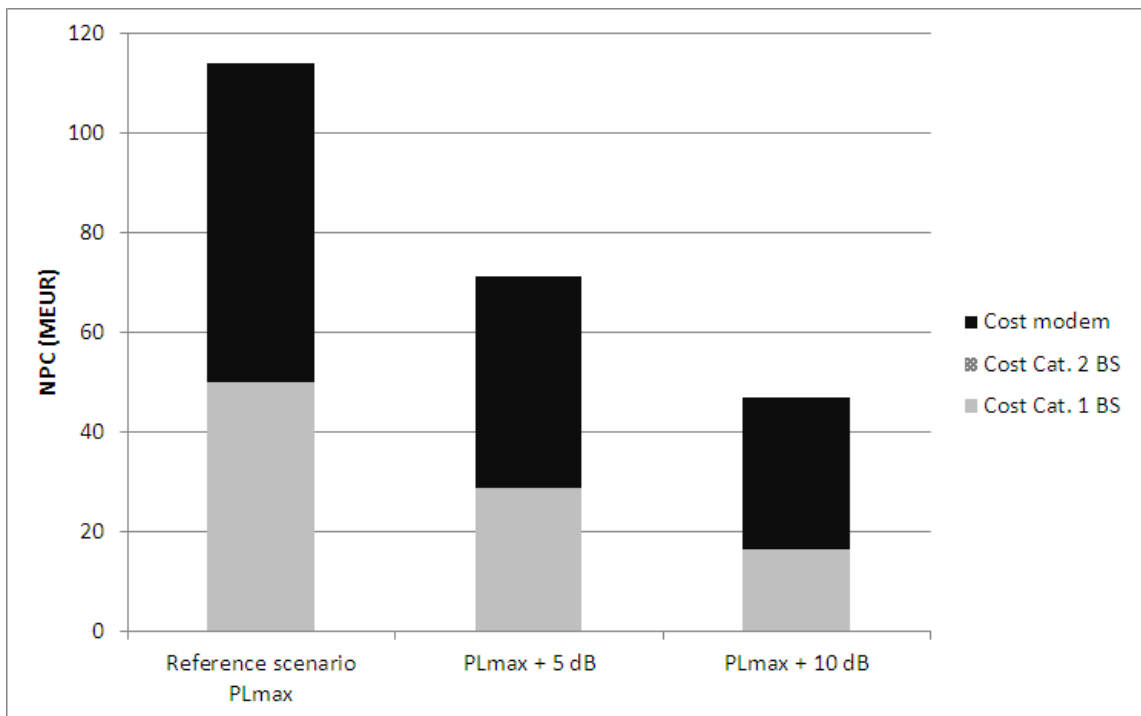
Comparing the influence of changes in the technical parameters (Section 5.4.1) and the influence of changes in the cost parameters (Section 5.4.2) on the total project cost, shows that the impact of changes in the cost parameters is considerably lower (8 to 12% versus 33% to 3007% for the technical parameters) than for the technical parameters as also concluded in [23]. Therefore, a reliable estimate of the path loss (possibly through actual measurements on the field) is thus a necessity to perform an accurate network dimensioning and cost calculation.

## 6. CONCLUSIONS

In this study, a monitoring network for the substations of a power distribution company is designed based on the wireless technology WiMAX. Furthermore, the cost to install and maintain the network is also determined. It was found that 531 WiMAX base stations are needed to cover the considered area "Flanders", Belgium, for 90%, leading to a cost of 63.8 MEUR (about 6,380 EUR per  $km^2$ ). These results are very sensitive to possible changes of the technical parameters, which lead to cost fluctuations of as much as 33.5% and 3007%. Therefore, a reliable



(a)



(b)

Figure 5. Influence of the technical parameters on the cost calculations.

estimate of the technical parameters (possibly through

actual measurements on the field) is a necessity to perform an accurate network dimensioning.

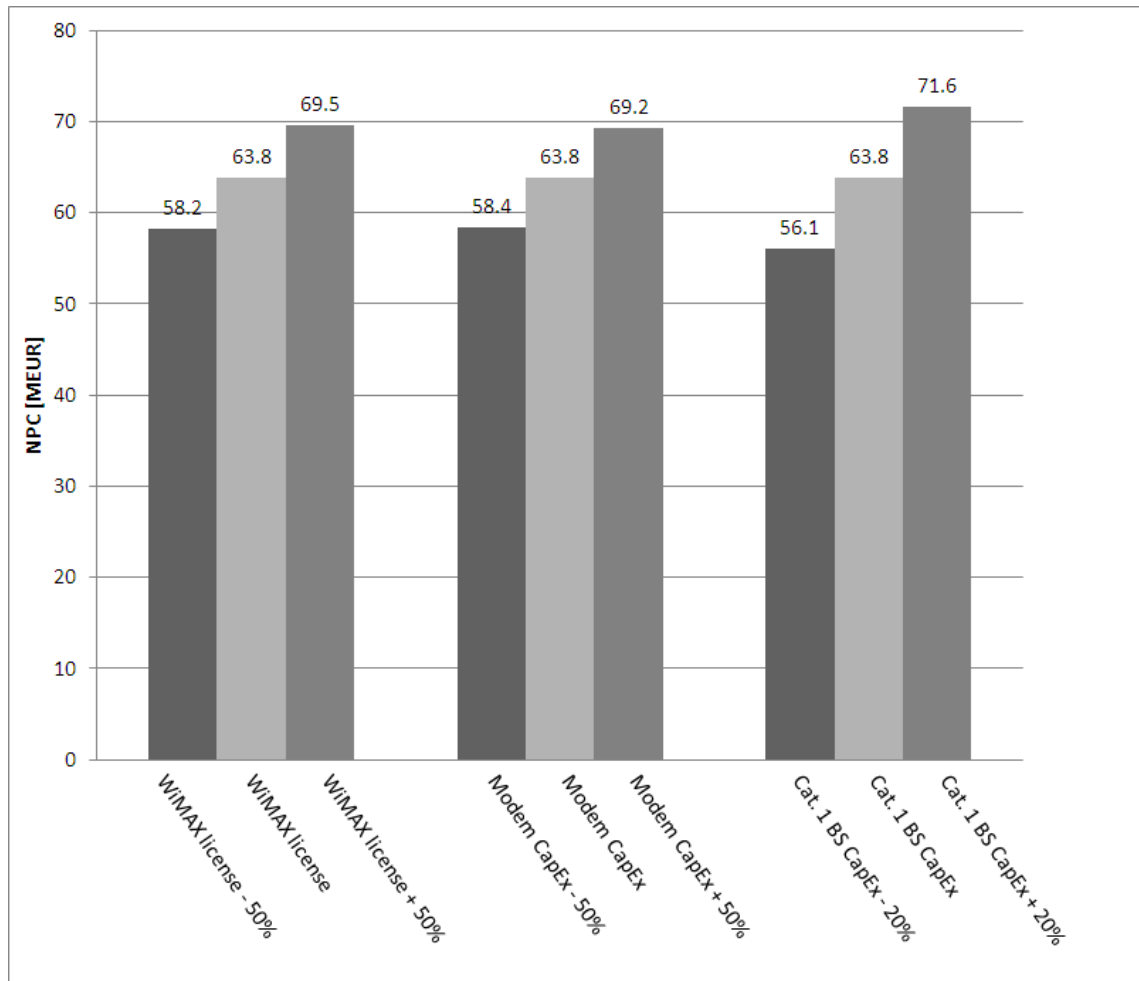


Figure 6. Influence of the cost parameters on the cost calculations.

Changes in the cost parameters have less impact on the total cost. Changes in the CapEx of the base stations have the highest influence on the total cost and leads to a limited fluctuation in the NPC (Net Present Cost) of only 12%.

Finally, using BSs with a height of 6 m is considerably less efficient than using poles of 30 m as both the number of BSs and the cost rise significantly. For low-bitrate WiMAX networks, it is better to use a low amount of BSs with an antenna height of approximately 30 m than BSs with an antenna height of approximately 6 m.

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