

AN ANALYSIS OF 380 V DC TOPOLOGIES IN MOBILE TELECOM APPLICATIONS

by

Augustin Crémer

B.S. in Electrical Engineering, ESIGELEC, 2013

Submitted to the Graduate Faculty of
The Swanson School of Engineering in partial fulfillment
of the requirements for the degree of
Master of Science

University of Pittsburgh

2015

UNIVERSITY OF PITTSBURGH
SWANSON SCHOOL OF ENGINEERING

This thesis was presented

by

Augustin Crémer

It was defended on

March 26, 2015

and approved by

Gregory F. Reed, Ph.D, Professor, Department of Electrical and Computer Engineering

Zhi-Hong Mao, Ph.D, Associate Professor, Department of Electrical and Computer
Engineering

Tom E. McDermott, Ph.D, Associate Professor, Department of Electrical and Computer
Engineering

Thesis Advisor: Gregory F. Reed, Ph.D, Professor, Department of Electrical and Computer
Engineering

Copyright © by Augustin Crémer

2015

AN ANALYSIS OF 380 V DC TOPOLOGIES FOR MOBILE TELECOM APPLICATIONS

Augustin Crémer, M.S.

University of Pittsburgh, 2015

The mobile telecom industry is expected to undergo substantial growth in the next five years. Cell towers represent close to 80% of the power consumption of a mobile network operator. In developing countries, most sites run on diesel due to a weak or non-existing power grid. Growing concern regarding CO₂ emissions, and increasing copper costs over the past 15 years make the efficiency of cell sites with respect to energy and materials an interesting issue to explore.

Similar concerns have led the datacenter industry to adopt a more energy efficient topology through the use of 380 V DC. Cell sites and data centers are very different from a mechanical standpoint. However, from an electrical perspective, these two types of facilities are very similar.

This thesis presents a quantitative analysis of the benefits of a 380 V DC topology, compared to the current 48 V DC topology. This analysis is based on the simulation of typical telecom distribution configurations, taking into account regulations and best practices currently in use in the telecom industry. A sensitivity study is conducted to assess the strengths and weaknesses of different configurations for varying tower loads and heights. Conclusions about these topologies are finally discussed based on economical and efficiency characteristics.

TABLE OF CONTENTS

PREFACE.....	X
LAYOUT	1
1.0 INTRODUCTION.....	2
1.1 BACKGROUND	3
1.2 PROSPECTS OF THE MOBILE TELECOM MARKET	4
1.3 ENERGY AND ENVIRONMENTAL CONSIDERATIONS.....	6
2.0 TRADITIONAL CELL TOWER DESIGN	10
2.1 RADIO FREQUENCY EQUIPMENT	12
2.1.1 The Base Transceiver Station	12
2.1.2 The Remote Radio Head	13
2.1.3 The Antennas.....	15
2.2 SUPPORT EQUIPMENT.....	15
2.2.1 Rectifier.....	15
2.2.2 Battery Systems.....	16
2.2.3 Cabling.....	17
2.2.4 Cell Site router	17
2.2.5 Remote monitoring	18
2.2.6 Air conditioning system.....	18

3.0	PROBLEM FORMULATION.....	19
3.1	THE 48 V DC LEGACY	19
3.2	POWER SAVING STRATEGIES	19
3.3	LESSONS FROM THE DATA CENTER INDUSTRY.....	20
3.3.1	Background	20
3.3.2	AC and DC topology comparison.....	21
3.3.3	Witnessed benefits of the 380 V DC topology in data centers.....	23
	3.3.3.1 Capital expenditure	23
	3.3.3.2 Operational expenditure	24
	3.3.3.3 Power quality improvements.....	24
3.4	ANTICIPATED BENEFITS OF USING 380 V DC IN CELL TOWERS... 25	
3.5	POSSIBLE DRAWBACKS OF USING 380 V DC IN CELL TOWERS 25	
4.0	SYSTEM SIMULATIONS.....	27
4.1	SIMULATION PARAMETERS	27
4.2	COMMON COMPONENTS	28
4.2.1	Voltage source	28
4.2.2	Cabling modeling	29
4.2.3	Load modeling.....	29
4.2.4	Control	30
4.3	LEGACY 48 V DC SYSTEM.....	30
4.4	380 V DC SYSTEM.....	31

4.5	HYBRID 380/48 V DC SYSTEM	32
4.6	DISCUSSION	34
5.0	SENSITIVITY STUDY	35
5.1	PROBLEM VARIABLES	35
5.1.1	Evaluated parameters	36
5.1.2	Evaluated systems	36
5.1.3	Evaluated scenarios	37
5.2	RESULTS	38
5.2.1	Varying tower loads	39
5.2.2	Varying tower heights	40
5.3	CONCLUSIONS	42
6.0	SUMMARY AND FUTURE WORK	44
	APPENDIX A	46
	APPENDIX B	46
	BIBLIOGRAPHY	48

LIST OF TABLES

Table 1: Different technologies and usages	4
Table 2: Availability of natural resources [8]	8
Table 3: Different types of cell sites to address different demands [10]	10
Table 4: Simulation results for varying tower loads	46
Table 5: Simulation results for varying tower heights.....	47

LIST OF FIGURES

Figure 1: Global mobile data traffic by region and by device [2]	5
Figure 2: Telecom towers grid access segmentation [6].....	6
Figure 3: Telecom towers unreliable grid connected sites segmentation [6].....	7
Figure 4: Off grid telecom tower segmentation based on power source [6].....	7
Figure 5: Copper price fluctuations in USD/MT (2000-2015) [9]	9
Figure 6: Cell tower / Cell on wheels	11
Figure 7: Ericsson Remote Radio Heads on a cell tower.....	13
Figure 8: Legacy topology - With Remote Radio Head	14
Figure 9: Resonant rectifier	16
Figure 10: DC datacenter topology comparison (a) AC topology (b) 380 V DC topology[19]...	21
Figure 11: Voltage levels in a datacenter for AC and DC topologies [19].....	22
Figure 12: Relation between voltage and wire size for a given amount of power [19].....	24
Figure 13: 48 V DC system	31
Figure 14: 380 V DC system	32
Figure 15: Hybrid 380/48 V DC system.....	33
Figure 16: Cost and efficiency comparison for varying tower loads.....	39
Figure 17: Cost and Efficiency comparison for varying tower heights	41

PREFACE

Prior to this Master's thesis, I would like to acknowledge every person who gave me the chance to conduct it.

My family for their continuous support for the last 23 years.

The ESIGELEC and Dr. El-Nokali for giving me the great opportunity of coming to study here in the United States.

My thesis advisor, Dr. Reed, for allowing me to pursue this advanced degree within his research group, and his guidance in the personal, academic and sporting aspects of my graduate student life.

Dr. Mao for his always-interesting control classes and his guidance in my pursuit of this advanced degree.

Dr. McDermott and for his guidance in the completion of this thesis.

The faculty of the Swanson School of Engineering, for all the things that I've learned here.

My fellow graduate student peers, for the good moments and the help they provided over the course of the past twenty months. This journey would not have been the same without you.

LAYOUT

This thesis is subdivided into 6 parts.

1.0 provides some insight into the current state of the mobile telecom market, its prospects, and some energy and environmental considerations associated with these prospects.

2.0 details the current trends in cell site design, gives some information on the different components of the system, and outlines the part they play in the system.

3.0 covers the key parameters that make this study relevant and the lessons learned from the datacenter industry, its witnessed benefits, and how those would apply to a mobile telecom site.

4.0 addresses the choices made for the simulation of the mobile telecom sites and the results that were derived from the simulations of the three systems.

5.0 provides a sensitivity study in order to identify the factors that could lead to the choice of one solution over another.

Finally, 6.0 presents a discussion of conclusions and future work identified through completion of this thesis.

1.0 INTRODUCTION

The last decade has seen our reliance on mobile telecommunication systems explode. Nowadays we are able to do much more in the palm of our hand than we were a decade ago with a desktop computer. The face of the mobile phone business has completely changed as well; yet our telecom infrastructure has stayed pretty much the same over the same time period.

The telecom industry has relied on -48 V DC since its origin, mostly for safety reasons. As the years went by, this voltage was kept for its reliability. With an increase of the power loads on top of cell towers, currents within the system rise, bringing the efficiency of the system down.

At a time when we become increasingly aware of the value of energy, efficiency is a key metric that needs to be accounted for in order to support always-increasing user demand.

The data center industry has started transitioning from a legacy AC system to a more energy-efficient topology based on the use of 380 V DC. This topology is based on the removal of multiple conversion steps inside the facility and an increase in operational voltage. Literature has shown several benefits, including increased efficiency, increased reliability, reduced capital and operational costs, and reduced footprint.

Such improvements could be highly beneficial to cell towers. Increased efficiency of the system would allow using reduced amounts of renewable energy generation and the use of smaller battery banks, lowering the total cost of ownership of cell sites as well as open the way to islanded cell sites in remote locations.

Also, the switch to higher voltage levels would reduce current in the facility, thus leading to the use of smaller cables leading to reduced wiring costs.

This thesis aims at exploring the benefits of applying such topology to mobile telecom base stations. This will be done by comparing a full DC 380 V and a hybrid DC 380V/48V topology to a legacy 48V DC installation. A sensitivity study is then conducted to assess the advantages and possible drawbacks of each topology under different scenarios.

1.1 BACKGROUND

The early 2000s was the time of the emergence of the Internet as we know it today. Online services brought great improvements in productivity allowing companies to outsource and automate actions and increase overall productivity. The only limit to this productivity increase was that devices had to somehow access the Internet, and their range was limited to home or office space.

With the arrival of the smartphone and cloud services, things have changed. Consumers as well as professionals can now access “relevant” information on the go, thanks to the data network of cellular service providers.

The data services have seen steady progress over the past decade, and data service usage has evolved as well.

Table 1 lists the different network technologies, along with the speeds associated with them. We can notice that, as the throughput of the network increases, the usage that is made of it changes.

Table 1: Different technologies and usages

	Peak Network Downlink Speed	Average User Throughput	Usage
GPRS	115 kbps	30-40 kbps	Microbrowsing Multimedia messaging
EDGE	473 kbps	100-130 kbps	Video calling General browsing Email
UMTS (3G)	14 Mbps	550-1100 kbps	Video and Audio streaming

In order to meet the customers' needs, mobile networks are in constant evolution to keep up with the ever-changing needs of their customer base. This is done through constant improvement of the transmission equipment.

1.2 PROSPECTS OF THE MOBILE TELECOM MARKET

Mobile telecom companies are well placed to undergo substantial growth in the near future, with an expanding smartphone user base, as well as an always-increasing amount of connected devices

arriving to the market. According to a Cisco report [1], a growth of up to 57% annually is forecasted until at least 2019. Figure 1 shows two charts detailing the forecasted demand for

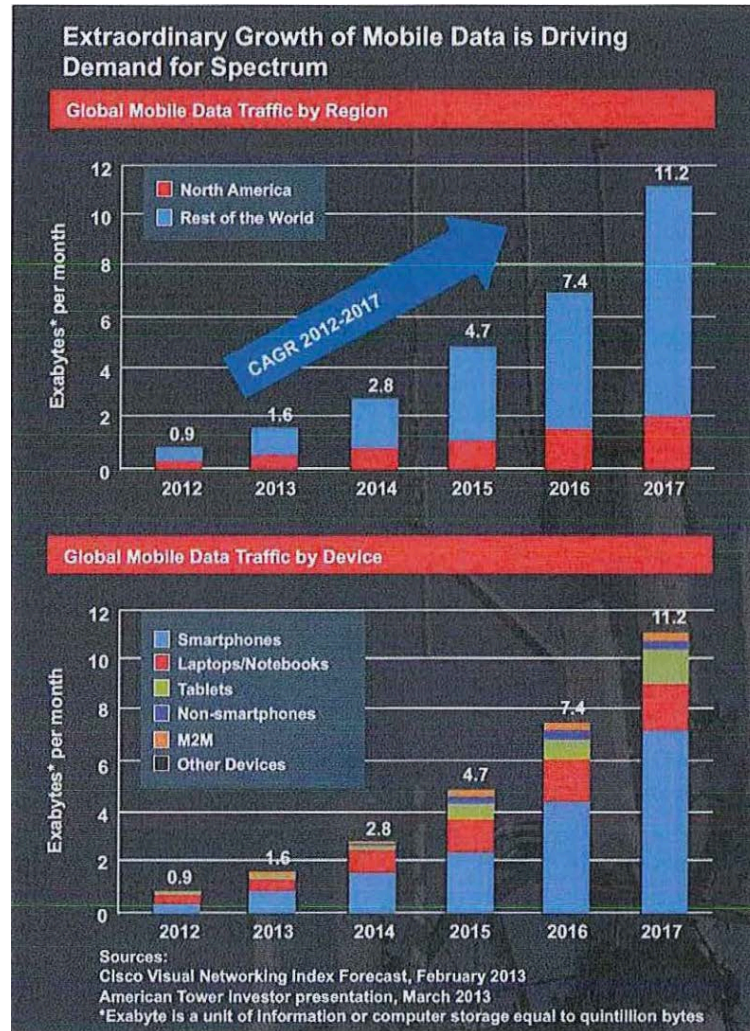


Figure 1: Global mobile data traffic by region and by device [2]

cellular data by region and by device.

With a younger generation that has no problem going all wireless (36% of today's households are already all-wireless [3]), the amount of cell sites is expected to explode in the next few years. Along with this massive increase in the cell tower realm, the energy question will become prevalent.

1.3 ENERGY AND ENVIRONMENTAL CONSIDERATIONS

Approximately 600 TWh (around 3% of the world’s energy consumption) are consumed by ICT facilities every year. This number is expected to increase to up to 1700 TWh by 2030 [4].

It has also been shown that cell sites represent up to 80% of the power consumption of a cell service provider [5].

Finally, diesel is used extensively in developing countries, where the grid is either weak or non-existent. The example of India speaks for itself. A report from the GSMA [6] took a look at the Indian cell site landscape, based on numbers from 2011. The results are detailed in Figures 2-4 below. Figure 2 shows that more than half of the Indian cell sites are either off grid or connected to an unreliable grid.

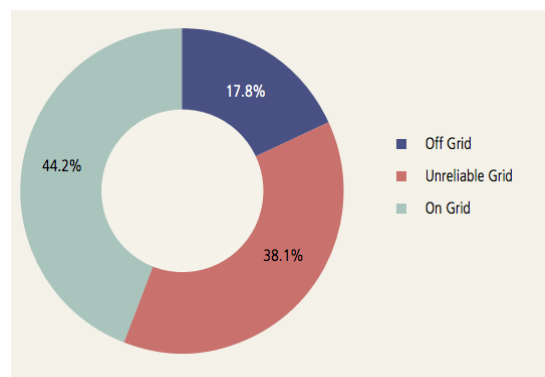


Figure 2: Telecom towers grid access segmentation [6]

Figure 3 shows that sites connected to an unreliable grid usually see at least six hours of daily electrical outages, and more than 40 % of these sites have more than 16 hours of daily outages.

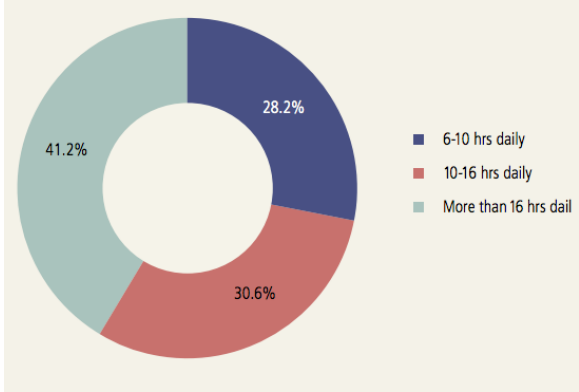


Figure 3: Telecom towers unreliable grid connected sites segmentation [6]

Local telecom service providers reach their Quality of Service (QoS) requirements by using local generation. Figure 4 shows the distribution of different power sources used to do so.

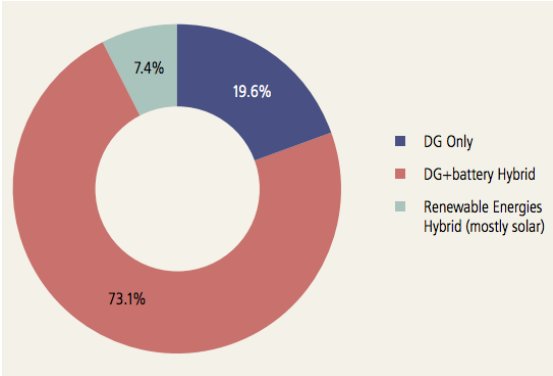


Figure 4: Off grid telecom tower segmentation based on power source [6]

The telecom industry in India consumed approximately 850 million gallons of diesel in the year 2011 alone. This is only economically viable because the local government highly subsidizes diesel. With both economical and environmental concern growing, the Indian government wants 50% of its 400,000 rural base stations to run off renewable energy [7].

The deployment of renewable-energy-powered cell sites would highly benefit from an increase in efficiency at the base station level, allowing to reduce necessary amounts of renewable generation, use of battery banks, and enable better deployment in developing countries.

Finally, the supply chain for one important component of cell towers, copper, is also a reason for concern.

Table 2 shows the available resources for different commodities, and Figure 5 shows the price progression of copper over the past 15 years.

Table 2: Availability of natural resources [8]

Resource	reserves/production ratio (years)
Iron	63
Aluminum	149
Silver	15
Copper	34
Oil	46
Coal	118
Natural gas	58
Uranium	100>



Figure 5: Copper price fluctuations in USD/MT (2000-2015) [9]

As we can see, the availability of copper is not only limited, but its prices have been multiplied by 3 in the past fifteen years, and are expected to keep rising as the supply becomes more scarce.

The growth figures in the mobile telecom industry, the growing concern about CO₂ emissions, and the future supply of copper make the material and electrical efficiency of mobile telecom installations an interesting question to explore.

2.0 TRADITIONAL CELL TOWER DESIGN

A cell site is where antennas and telecom equipment are located, in order to provide mobile telecom service to a defined area in a network. The area covered by this service is called a "cell". The locations of cells are carefully chosen to prevent both "holes" in the coverage and unnecessary overlap.

Cells towers come in different sizes, in order to address different types of demand, as it is showed in Table 3.

Table 3: Different types of cell sites to address different demands [10]

Tower type	Range	Description
Macro-cell	10 miles or more	Standalone or structure attached
Micro-cell	1 mile radius	Urban and suburban
Pico-cell	Several hundred yards	Airports, Campuses
Femto-cell	Limited to a building	Personal devices for home/office usage

Cell sites can also take many forms, being located on top of buildings, on a mast, or even on wheels, when support of sudden surges in load is required at certain locations (Music festivals are a good example.)



Figure 6: Cell tower / Cell on wheels

Cell towers are the most common form in which cell sites are found. The height provided by the mast allows for an increase in the coverage area (line of sight propagation) of the radio equipment on top it.

The equipment of the base station can be divided in two categories: (1) the radio frequency equipment, and (2) the support equipment, usually found in a confined space, at the bottom of the cell tower.

2.1 RADIO FREQUENCY EQUIPMENT

The transmission equipment is there to make the link between the user equipment (UE) and the network. It consists of three main components, which are the Base Transceiver Station (BTS), an optional Remote Radio Head (RRH), and the actual antennas mounted on the mast.

2.1.1 The Base Transceiver Station

The Base Transceiver Station (BTS) makes the connection between the wired telecom network and the user's device.

The BTS can be viewed as an ensemble of components that makes the telecom transmission possible. It is traditionally made of the following pieces of hardware:

- The transceiver handles the reception and emission of radio signals through the antennas.
- The power amplifier amplifies the signal from the transceiver in order for it to be sent to the antenna. The process is quite energy-hungry. The transmission is then done through coaxial cables up the tower to feed the antennas.
- The converger merges the feeds of different transceivers in order for them to be sent through a single antenna.
- The duplexer is the counterpart of the converger. It separates inbound and outbound signals arriving from the antenna.

2.1.2 The Remote Radio Head

Traditionally, power amplifiers were located on the ground, as an integral part of the Base Transceiver Station. The signals are amplified in order to be transmitted. Losses in the coaxial feeders up the tower make this already power-hungry process inefficient.

A solution to improve the energy efficiency is to keep the some of the function of BTS on the ground, and move the power amplification and RF functions to the top of the tower in a closed container called Remote Radio Head (RRH). Figure 7 shows multiple RRHs on top of a cell site.

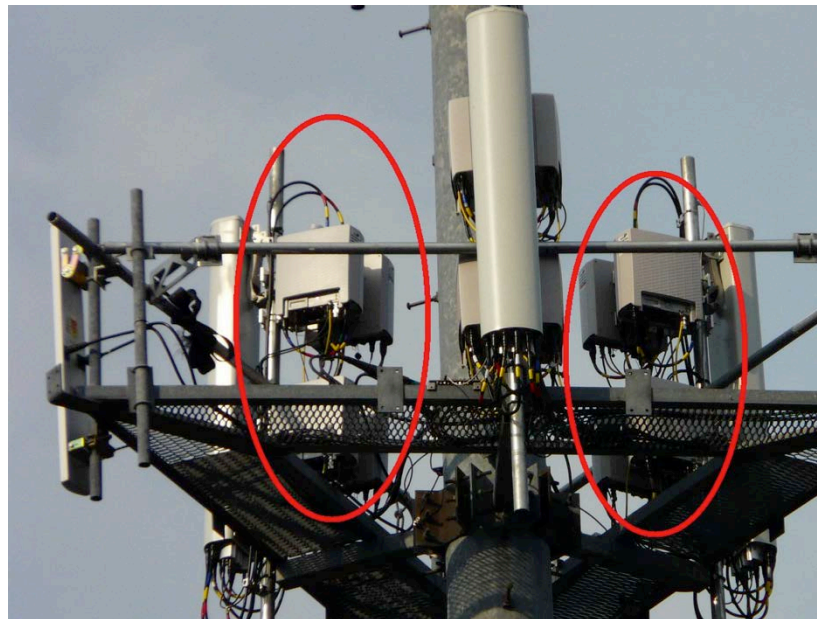


Figure 7: Ericsson Remote Radio Heads on a cell tower

The RRH is powered through the use of a DC bus going up the tower. The communication with the ground is ensured through the use of optical fiber. The benefits of using a RRH include power consumption reductions due to lower losses in the feeders, and also reduced cooling needs, since one of the processes that produces the most heat in the shelter has now been moved outside. Figure 8 offers a good overview of both types of setup.

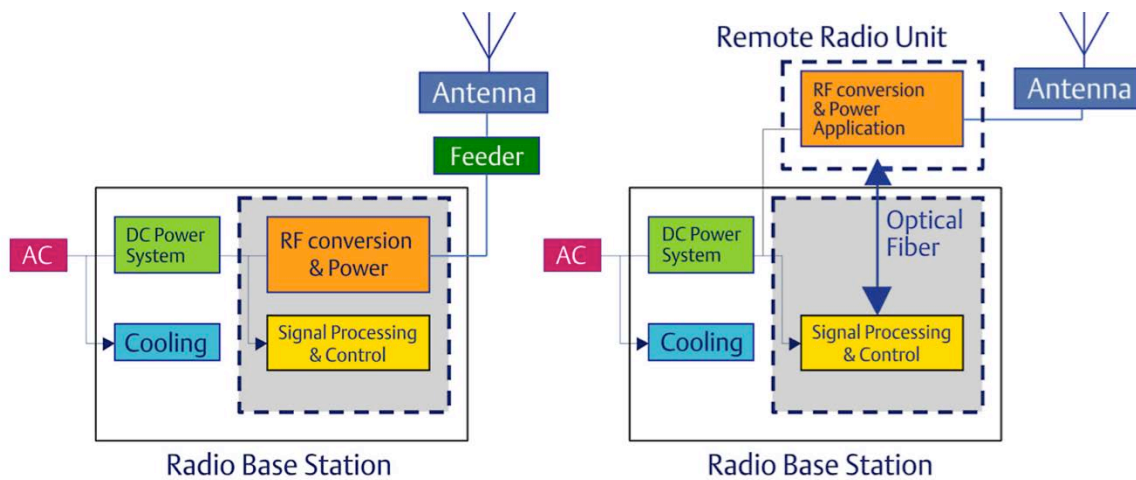


Figure 8: Legacy topology - With Remote Radio Head

While there are some great benefits associated with the use of RRH units, there are some drawbacks associated with their use as well.

A legacy topology would only run coaxial cables up the tower to feed the antennas. A DC bus, as mentioned before, feeds the RRH. Cell sites are located on top of high metallic structures in flat areas or on top of elevated structures in order to ensure maximum coverage. This makes them perfect targets for lightning strikes.

The presence of this DC bus feeding the RRH poses a threat to the sheltered equipment of the cell site in case of lightning strikes. The DC bus can conduct surges back into the equipment room, which potentially presents a risk for the telecom equipment, rectifiers or other equipment present at the site.

Appropriate grounding and surge protection methods have to be applied in order to prevent damage to the equipment [11].

2.1.3 The Antennas

At the end of the chain, the antennas send and receive the signals. They are usually distributed by sector, commonly covering a radius of 120°. Their size is directly related to the frequency of spectrum covered by the antenna. Given that wireless service providers use multiple frequency spectrums, it is not uncommon to see cell sites with antennas of different sizes.

2.2 SUPPORT EQUIPMENT

Support equipment is defined as the equipment that is here to support the functionality of the radiofrequency equipment. This part of the equipment has a relatively low share of the site's energy consumption.

2.2.1 Rectifier

The rectifier takes in the single phase AC power that feeds the base station, and rectifies it to power the DC equipment.

The common topology in the telecom industry is a resonant rectifier, which handles multiple functions, as it will be explained later. The topology of the rectifier can be found in Figure 9.

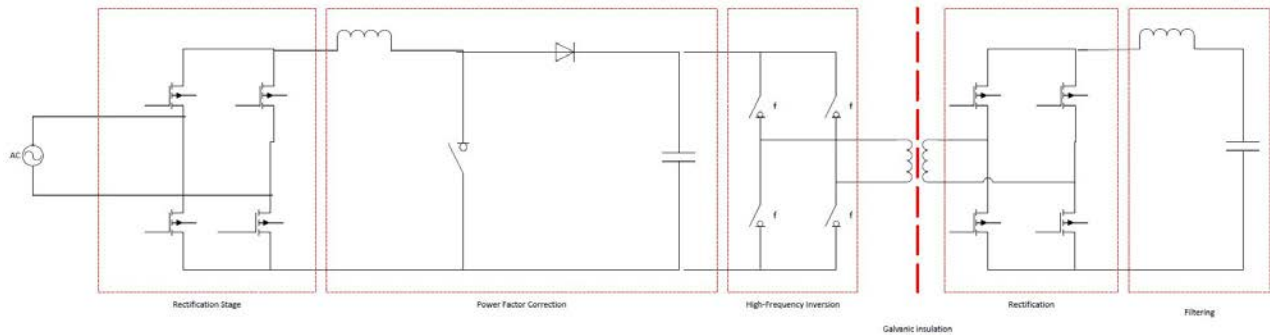


Figure 9: Resonant rectifier

The first portion of the resonant rectifier is a full bridge rectifier, which provides a full-wave rectification. The incoming voltage then goes through a power factor correction stage thanks to a boost converter before reaching a high frequency inverter. The use of a high frequency waveform enables the use of a smaller and cheaper transformer in order to provide galvanic isolation to the system. Finally, the outcoming voltage is rectified again before entering the system at the desired voltage.

The rectifier has been a critical piece of telecom power systems for a long time, and has reached very good levels of efficiency through the use of complex control strategies.

2.2.2 Battery Systems

Most of the cell sites have battery banks attached to them in order to ensure that QoS is maintained in case of a power outage.

Nickel-Cadmium (Ni-Cd) and Lithium (Li) batteries are the most common in the industry. They may be sized either to ensure service for a defined amount or time (usually from 1 to 8 hours), or just until a generator set has started. They are usually arranged in strings of 12 V batteries in order to reach the operating voltage of the site. In the case of a 48 V DC site, that would be four

12 V batteries connected in series, and variable amounts of strings connected in parallel in order to reach the desired capacity.

It is also noteworthy that 380 V battery cells are starting to enter the market as well, making the use of strings composed of several tens of batteries to reach the desired voltage no longer necessary.

2.2.3 Cabling.

Cabling is a key component of the telecom system, and there are several regulations associated with its selection in order to ensure maximum reliability for telecom installations. There are also some necessary considerations to take into account since some of the wiring will be located outdoors.

The ETSI standard states that the voltage drop in the entire 48 V DC loop has to be limited to 1V[12]. This leads to oversized cables, especially on long distances in order to meet requirements.

It is also necessary to make sure that the tensile strength is high enough to ensure that it will withstand the varying temperatures and the exposure to the sun, and the ability to support its own weight going up a tower with minimal support.

2.2.4 Cell Site router

This component makes the connection between the cell site and the central mobile switch, which then connects the site to the outside world. It is usually manufactured by IT and telecom companies such as Cisco, Alcatel-Lucent or Juniper.

2.2.5 Remote monitoring

Most cell sites are located in remote locations. The remote monitoring unit is there to report alarms to the network operating center if something were to go wrong.

2.2.6 Air conditioning system

The air conditioning system is there to ensure the sensitive equipment in the shelter is kept at appropriate temperatures. Some pieces of equipment in the shelter, such as power supplies or power amplifiers, can release considerable amounts of heat, while the IT equipment requires a precise temperature range to function properly. Some interesting topologies have been explored in literature to reduce the impact this unit has on the power consumption on the cell site [13].

3.0 PROBLEM FORMULATION

3.1 THE 48 V DC LEGACY

At its origin, the telecom industry relied on 48 V DC technology, for safety reasons in wireline communication networks. As the years went by, this voltage was kept because of the large installed base, which led to lower equipment cost. Also, years of use of the technology made it very reliable. The increase of technologies to support (GPRS, EDGE, 3G and now 4G) led to an increase in the amount of equipment on top of cell sites, leading inevitably to increased loads. Increased power consumption means higher currents, which leads to thicker and more expensive cables and reduced efficiency.

3.2 POWER SAVING STRATEGIES

Several power saving strategies are explored in the literature. Most of them take place at the network level, in situations of low load [14].

The first approach to reduce the network energy consumption is to turn off entirely some sites in densely populated areas. In this situation, surrounding Base Stations take over the load of the cell that was turned off [15].

Another network-wide way to reduce energy consumption without turning off entire base stations is to turn off certain frequencies (or channels) or services at times where the demand is low [16].

In certain heterogeneous network configurations, coverage requirements are usually achieved through the use of macro cell sites (cf. Table 2) and smaller cells are used for load support. In situations of low load, the smaller cells can be turned off [17].

Finally, adjusting the size of the area covered by a cell site is also a possibility, as is explained in [18].

On the site level, most of the power saving strategies have revolved around the use of remote radio heads to prevent losses in the feeders and a better climate control of the facility.

3.3 LESSONS FROM THE DATA CENTER INDUSTRY

3.3.1 Background

Since the early 2000s, and the rise of Internet-based services, the overall power consumption of ICT equipment has increased a lot. Back in 2006, a study conducted by the Environmental Protection Agency revealed that the power consumption of data centers represented 1.5% of the US energy consumption, which is equivalent to the power consumption of around 5.8 million American households [19]. This led the industry to search for a new way to power data centers in order to address the efficiency issues that the current topology had.

3.3.2 AC and DC topology comparison

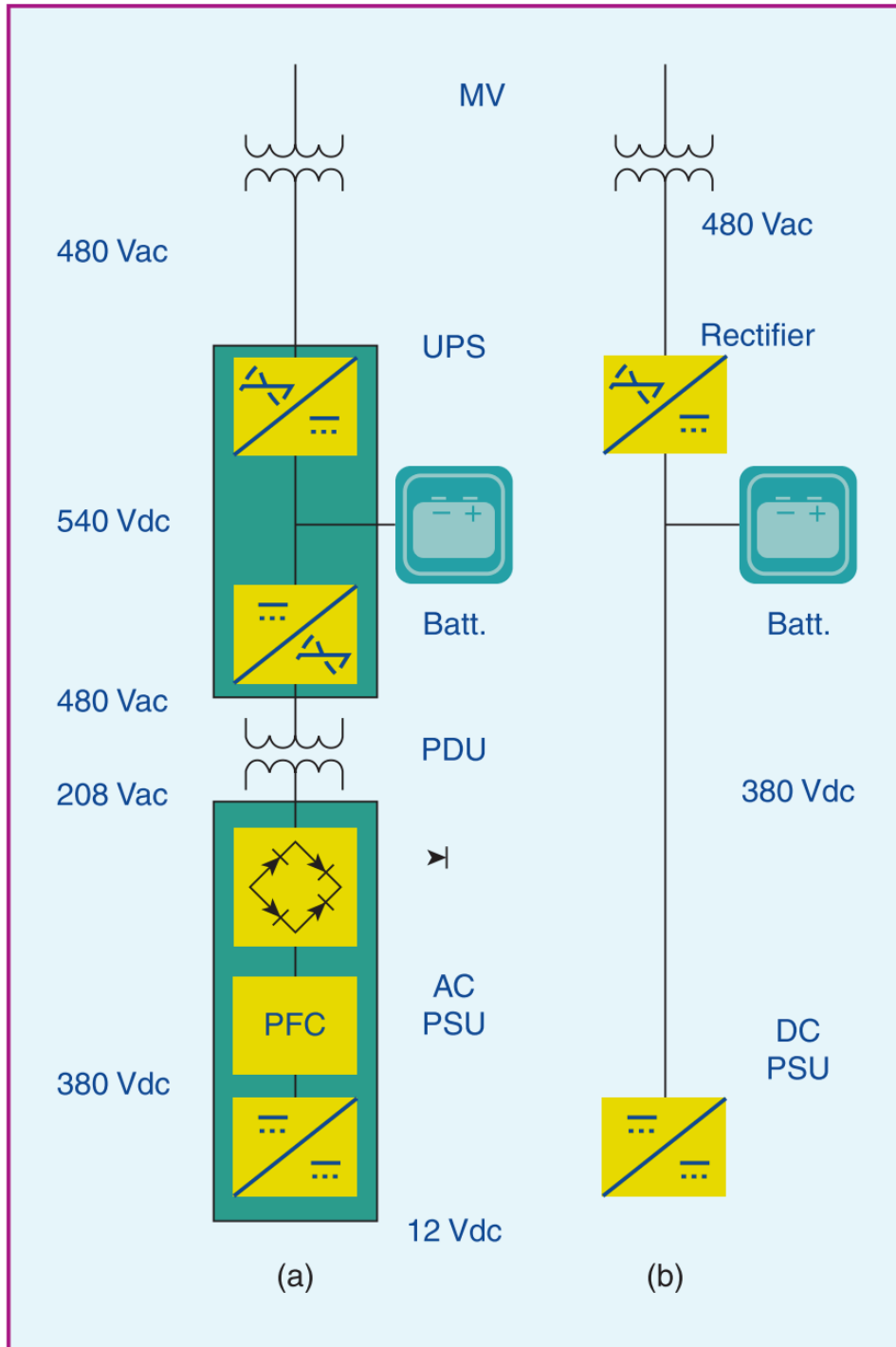


Figure 10: DC datacenter topology comparison (a) AC topology (b) 380 V DC topology[19].

Figure 10 compares the typical North American AC data center topology with the 380 V DC one. The power would get inside the facility at medium-voltage levels before being stepped down to 480 V AC (208 V AC topologies were also used), and then be rectified in order to eliminate disturbances and charge the batteries. The voltage would then be inverted back to AC, before reaching an AC power distribution unit (PDU) that would provide galvanic insulation to the servers and distribute the power. Finally, power was rectified again at the power supply level, to finally serve the computing load. This power feeding process features four conversion steps with varying levels of efficiency that, once combined, lead to poor facility efficiency.

The choice that was made to mitigate the losses in this very high power density environment was to increase the voltage, and reduce the amount of conversion steps (only two in the 380 V DC topology) in order to mitigate the conversion and conduction losses associated with the AC setup. Figure 11 provides a good overview of the two systems from the voltage side.

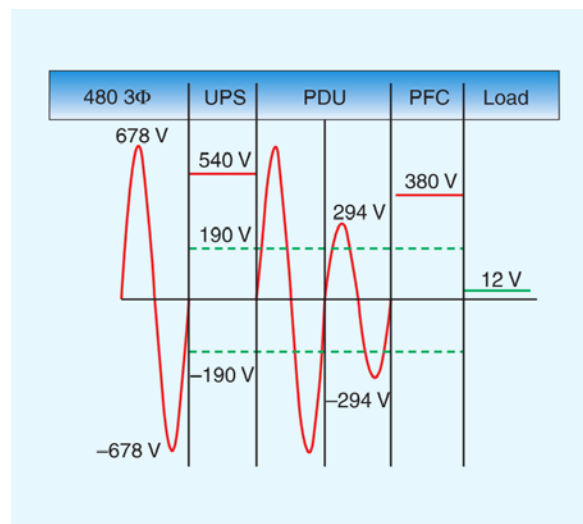


Figure 11: Voltage levels in a datacenter for AC and DC topologies [19]

The voltage was determined to be 380 V DC because it is a voltage that was already present in the power supply at the time, thus facilitating the deployment of the technology. 380 V DC is also considered a low voltage from a regulatory standpoint.

3.3.3 Witnessed benefits of the 380 V DC topology in data centers

The results that were witnessed showed great benefits on capital expenditure (CAPEX), operational expenditure (OPEX) and power quality.

3.3.3.1 Capital expenditure

Less conversion steps lead to a reduced amount of hardware. This has a double effect. First, capital cost of the facility can be reduced by up to 15%. Literature also shows a decrease of up to 25% of the footprint[20] for high power density facilities.

By choosing such topology, the amount of hardware is reduced, most notably the inverter at the exit of the UPS and the power factor correction, which results in lower capital cost.

Finally, going from a 3-phase AC to DC system leads to significant savings in copper: the AC system is composed of 4 wires (phase A, B, C and ground) whereas the DC system is only composed of 2 wires (+/-).

Also, even though all copper wires can carry either AC or DC, their ability to carry the power is not the same. Figure 12 shows the wire size depending on the voltage type and magnitude.

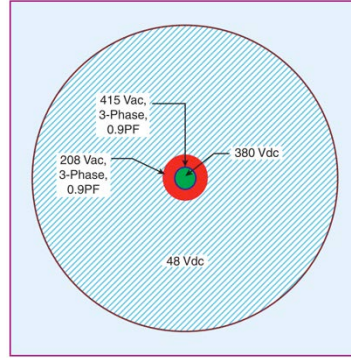


Figure 12: Relation between voltage and wire size for a given amount of power [19]

3.3.3.2 Operational expenditure

Increases in efficiency from 7 to 28% were seen in comparison to 415 and 208 Vac systems[21][22]. These improvements reduced cooling needs for the facility, since a watt not lost during a conversion step is one watt less to spend on cooling. This ensemble of measures yielded significant efficiency improvements over the entire facility, allowing to maximize the computing power for a given price point.

The reduced amount of hardware led to a decrease in the expenditure in maintenance and operation of up to 33% [22]. The reduced amount of hardware also led to increased reliability (between 200 and 1000%). The economic impact of this increase in reliability is hard to gauge since downtime costs vary largely from one industry to another. It remains a key metric for both datacenter and telecom industries.

3.3.3.3 Power quality improvements

Power quality improvements are difficult to quantify economically, and will have no relevance in our study of a cell site system, since such facilities are already running on DC power.

The 380 V DC topology got rid of all phase balancing issues, as well as harmonics present in the legacy AC system. Also, DC offers much better integration of renewable resources, such as PV panels, wind power and fuel cells, that are natively DC.

3.4 ANTICIPATED BENEFITS OF USING 380 V DC IN CELL TOWERS

Many of the improvements resulting from the use of 380 V DC in the data center industry can also be applied to a cell site facility.

From a capital expenditure standpoint, the switch to a 380 V DC topology should result in reduced amounts of copper in regard to a 48 V DC topology. The reduced wire size should allow reduced spending on installation costs [23].

On the side of operational expenses, the increase in voltage will provide a reduced amount of current going up the tower, which will result in reduced copper losses. The gains are expected not be as spectacular as they were going from an AC topology to a higher voltage DC topology in a high power density environment, but should be worth considering nonetheless.

3.5 POSSIBLE DRAWBACKS OF USING 380 V DC IN CELL TOWERS

Concern is often expressed about the reliability of new systems in regard to 48 V DC systems. It is difficult to compare the reliabilities of both systems because they come from different backgrounds. Most of the reliability comparisons for 380 V DC systems are made in regard to the previous AC topologies, whereas the 48 V DC topology is only compared to itself. It will be

necessary to wait for a bigger sample of 380 V DC facilities to give a definitive answer, however most of the datacenter facilities making use of this topology have praised its reliability.

Another concern regarding this type of setup is the cost of protection associated with it. Literature suggests that the installation costs of a 48 V DC system outweigh the extra cost of protection for 380 V DC systems.

Finally, some concern is expressed regarding the stability of battery banks at this new voltage, which requires long strings of battery cells. As mentioned previously in 2.2.2, 380 V DC battery banks are entering the market, thus addressing this issue.

4.0 SYSTEM SIMULATIONS

In order to assess the benefits of a 380 V DC topology, simulations were conducted using the PSCAD software package. We will here first have a look at the design parameters of the simulated system, and then look at the results from every one of the simulated systems.

4.1 SIMULATION PARAMETERS

A typical cell site is modeled as 1 kW permanent load, accompanied with an extra 1 kW of load running 25% of the time.

The 1 kW permanent load represents the RF equipment as well as the support equipment.

The permanent load will be distributed as follows: 667 W at the top of the mast (representing the load of a Remote Radio Head), and 333 W of support equipment (Signal processing and control).

The extra 1 kW of load represents the air conditioning unit. Considering that most AC units on the market are connected on the AC side, they have no relevance in our topology comparison and will thus be ignored in the following analysis. The lighting load was also not addressed because it is only active for maintenance operations.

4.2 COMMON COMPONENTS

4.2.1 Voltage source

A single-phase 120 V AC voltage feeds the system. The choice of this voltage was motivated by the fact that the loads to power were small, and thus did not require the extra equipment that would have been necessary to deal with 3-phase power.

Rectifiers have attained great levels of efficiency in both telecom and ICT applications (their efficiencies reach around 96.5% for both voltage levels) through the use of complex controls that are not within the scope of this study. Given our goal to compare different topologies, and the difficulty to improve in any way the rectification process, it was decided to replace the AC feed and the rectifier by a 169 V DC source in order to model a rectified 120 V AC feed. Thus our assessment will be based solely on what happens after the rectification stage. The efficiencies mentioned further below assess the efficiency of the topology post-rectification stage and not the overall efficiency of the site.

Boost and buck converters were added to the system in order to reach the desired voltages for each one of the systems. Switching frequency was set at 10 kHz to ensure proper efficiency and reduced capacitor and inductor sizes.

The filter inductor and capacitor were sized in order to ensure acceptable amounts of ripple in steady state.

4.2.2 Cabling modeling

Cabling was selected following the principles of the ETSI EN 300 132-2 for the 48 V DC system (less than 1 V of voltage drop in the entire loop).

The regulations for a 380 V system were unclear up to two years ago. The Japanese Electric code states that the voltage drop rate has to be 1.5% or less for a branch circuit, or 2.5% or less including the main line. These specifications are defined for facilities carrying sensitive ICT equipment, which fits the description for cell sites, and was the generally accepted reference for the industry [23], [24], until two years ago, when both the European Telecommunications Standards Institute and the International Telecom Union released their standards for datacom facilities running at voltages up to 400 V [25], [26].

Following these design principles, and based on the load distribution on the site, AWG 5 wire was selected for the 48 V DC system. AWG 14 wire was selected for the 380 V DC system. This is a very conservative choice from a voltage drop standpoint, but smaller cables would not have been suitable on the tensile strength side to ensure proper use outdoors. Assuming that most of the power is lost on the way up the tower, particular attention was paid to the modeling of this part of the system. The cabling was modeled as a PI-Section, using common values of resistivity, inductance and capacitance for the chosen size of wire.

4.2.3 Load modeling

The load is maintained constant, since literature shows that variations in user demand only marginally affect the energy consumption of the site [14]. The model uses purely resistive loads for the equipment, as is usually the case for IT equipment.

4.2.4 Control

Duty cycles within the system were controlled through the use of feed-forward control. Manual adjustments were made to the duty cycle values in order to reach the desired amount of voltage at the output of the converters.

4.3 LEGACY 48 V DC SYSTEM

This simulation will be used as a baseline for comparison to the other systems. The 48 V DC system is fed by a 169 V DC source, simulating the output of the rectifier. The voltage was then stepped down to the desired value of 48 V DC, before being served to the loads.

The AWG 5 cabling going up the tower was modeled as a PI-section of 0.0625 ohms, self inductance of 62.8 uH and a parallel capacitance of 295 pF.

Figure 13 shows the simulated system.

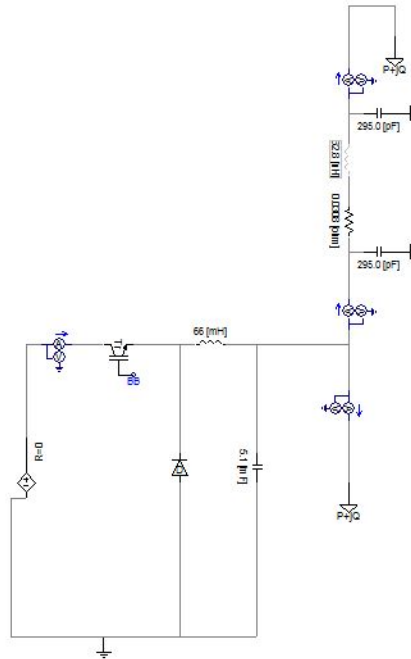


Figure 13: 48 V DC system

The simulation yielded an overall consumption of 1019 W to power 1000 W of load, a number that is in accordance with what would have been expected from such system. The 1 V voltage drop gives the loop an efficiency of around 98%, verified through simulation.

4.4 380 V DC SYSTEM

The 380 V DC topology is the more extreme approach from an efficiency standpoint. This topology is based on the assumption that 380 V DC equipment will become available in the future.

Here, the power is provided by a 169 V DC source, and then boosted to 380 V to feed the loads at the bottom of the tower and on top of the mast.

The AWG 14 cable used in the simulation was modeled as a PI-section of 0.5039 ohms, self-inductance of 69.7 uH and a parallel capacitance of 183.5 pF.

Figure 14 shows the simulated system

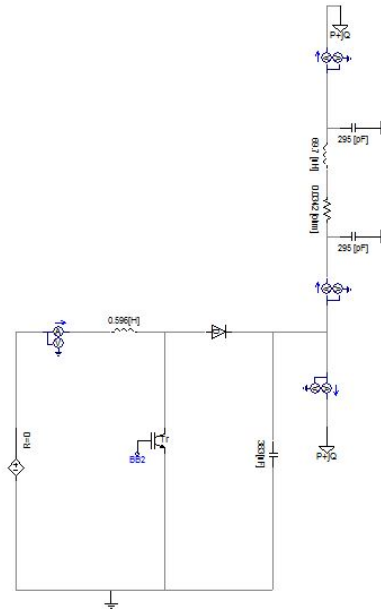


Figure 14: 380 V DC system

The simulation for the 380 V DC system yielded an overall consumption of 1008 W for a load of 1000W. This number is also in accordance of what was expected of such a system.

4.5 HYBRID 380/48 V DC SYSTEM

This topology provides a "middle-ground" solution between the legacy topology and the full 380 V DC topology. The datacenter experience has shown that even though the 380 V DC topology started being adopted 8 years ago, lots of product lines have still not been updated to embrace this

new voltage level. A similar situation is expected for the telecom industry. The hybrid topology provides a good interim step until equipment is released to accommodate this new voltage level.

The voltage originates from the DC source at 169 V DC, before being boosted to a voltage of 380 V DC. This voltage is subsequently bucked to a voltage of 48 V DC to feed the loads at the top of the tower and in the shelter. Particular attention was given to the modeling of the converters, to ensure that their efficiency matches the current state of the art, whose efficiency is around 98.2% [27].

Figure 15 shows the setup for the hybrid topology.

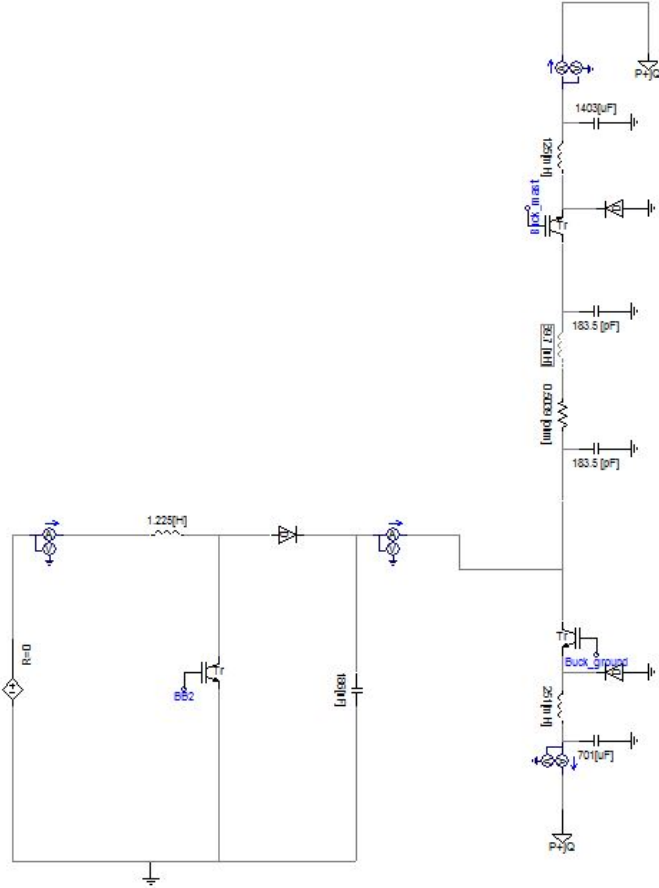


Figure 15: Hybrid 380/48 V DC system

The simulation yielded an overall consumption of 1025 W to power 1000 W of load.

This result is in accordance with our expectations, given the addition of two converters whose efficiency figures have an obvious impact on the consumption of the site.

4.6 DISCUSSION

As we would have expected, the 380 V DC system is more energy efficient than the 48 V DC system. The hybrid topology is the least efficient of the three systems, a result that is not surprising considering the addition of two DC/DC converters. The simulations show marginal gains when switching to a 380 V DC topology, unlike what was witnessed in the data center industry. This can be explained by the use of smaller cables, whose higher levels of resistivity have a significant impact on the losses up the tower. It remains important to note that the AWG 5 wire used in the 48 V DC system represents eight times more copper than the AWG 14 wire used in the 380 V DC system to power a similar load. This highlights the fact that it is possible to reach a better efficiency in telecom systems while still reducing capital costs.

It is also noteworthy that the simulations were conducted on a rather small cell tower with 1 kW of load and a height of 100 feet. It is not uncommon to see service providers share sites, and thus have much higher amounts of power up the towers. As the load or the height of the tower increases, there is more of an incentive to switch to either the 380 V DC or the hybrid topology. This is what we are going to explore in the following sensitivity study.

5.0 SENSITIVITY STUDY

The ETSI EN 300 132-2 makes a 48 V DC loop energy efficient at the expense of great amounts of copper.

The 380 V DC system is energy efficient and costs less; its only drawback at the moment is that there is no telecom equipment available at this level of voltage.

Finally, the hybrid topology addresses both issues exposed above, with the addition of two buck converters in order to supply the appropriate voltage to the loads.

This makes what originally was supposed to be an efficiency problem an economics problem. There might be situations in which some solutions are better than others, for varying amounts of mast power consumption and tower heights. This is the question the following sensitivity study will try to address.

5.1 PROBLEM VARIABLES

In the following sensitivity study we are going to reuse the models of the previous study, taking into account parameters such as wiring costs, power electronics cost, overall efficiency and mast losses. These parameters will be evaluated in different setups (varying amounts of load and tower heights), and with different types of topologies, all of which are detailed below.

5.1.1 Evaluated parameters

Several parameters will be evaluated in this sensitivity study.

The first and obvious one is the cost of wiring, since it is one of the key differentiating elements between the systems. The pricing of the cables was determined based on the customary prices of several wire manufacturers in the United States.

Another cost to account for is the power electronics, which consist of two converters for the hybrid topologies. Pricing was evaluated at around \$500 per converter.

Finally, the consumption of the site and the losses up the tower will be evaluated for each scenario, in order to reach final conclusions on both the cost and efficiency metrics for every one of the systems.

5.1.2 Evaluated systems

The first system is the legacy 48 V DC topology. The wiring will be selected so as to satisfy the requirements of ETSI EN-300 132-2, and the power electronics cost will be kept at zero given the current availability of 48 V DC telecom equipment.

The second system is the 380 V DC topology. The wiring will be selected so as to satisfy the requirements of the Japan Electric Code, but also taking into account the tensile strength of the wiring. For that purpose, a minimal wire size of AWG 14 was selected. The power electronics cost is kept at zero, since this topology is made under the assumption that 380 V DC will become available in the future.

The third system is the hybrid 380/48 V DC topology. Wiring will be selected under the same standard as the 380 V DC system. The power electronics cost will have to take into account the addition of two buck converters in order to supply the loads with the appropriate voltage.

The last two topologies are based on a "retrofit" approach. Given the large installed base of cell sites, the change of voltage levels could be an interesting option to reduce operational expenses in cell sites, or add additional RF equipment on top of cell towers.

Thus, the fourth topology will be a 380 V DC topology making use of the already existing wires of a 48 V DC cell tower for a given load.

Finally, the fifth topology is a hybrid 380/48 V DC topology making use of existing 48 V DC cables. This setup acknowledges both the existing infrastructure and the current unavailability of 380 V DC equipment. The initial hybrid setup (380 V DC backbone and two buck converters to deliver 48 V DC to the loads) was modified to include one buck converter and one boost converter, respectively at the bottom and the top of the tower, in order to accommodate the existing 48 V DC backbone (rectifier, battery banks, signal processing and control equipment).

For both the fourth and the fifth topology, the wiring cost will be assumed to be zero, since those two systems make use of wiring already present at the telecom site.

5.1.3 Evaluated scenarios

The system will be evaluated for varying levels of power on top of the tower, whose height will be maintained at 100 feet. For simplicity purposes, the load at the bottom of the tower will remain at 333 W. The suggested power levels to be explored are successively 667 W, 1.33 kW, 2 kW, 2.67 kW, 3.33 kW and 4 kW.

Varying heights will also be evaluated for a given load, selected to be 1333 W, since higher towers tend to carry more RF power. The suggested heights to be explored are 100, 150, 200, 250, 300 and 350 feet, covering a wide range of cell tower heights.

These two different scenarios will provide a better understanding of the situations that could take most advantage of a specific topology.

5.2 RESULTS

Simulations were run multiple times for the three topologies, adjusting for the different parameters that were mentioned previously. The results were plotted for both types of scenarios. Before getting into any type of analysis of results, it seems important to put some of the numbers in perspective. A study from 2013 put the average price of a cell tower at around \$150,000 [28]. Installation costs are impacted by wire size as well. As shown in [23], labor costs for a 380 V DC system can be up to 78% lower than an equivalent system running 48 V DC.

Power consumption varies from about 1kW to 4kW of DC load, with higher figures when multiple service providers share the site. The extra 1 kW of load running 25% of the time also needs to be taken into account.

With that in mind, we can now look at the results of the sensitivity study, and see how loads and tower heights can affect the choice of one solution over the other.

The results of the sensitivity study are shown in graphical form hereafter (Retrofit topologies not displayed in the cost comparison). The totality of the results can be found in the 46 section of the document.

5.2.1 Varying tower loads

The results for varying amounts of load on top of a 100-foot cell tower are shown below.

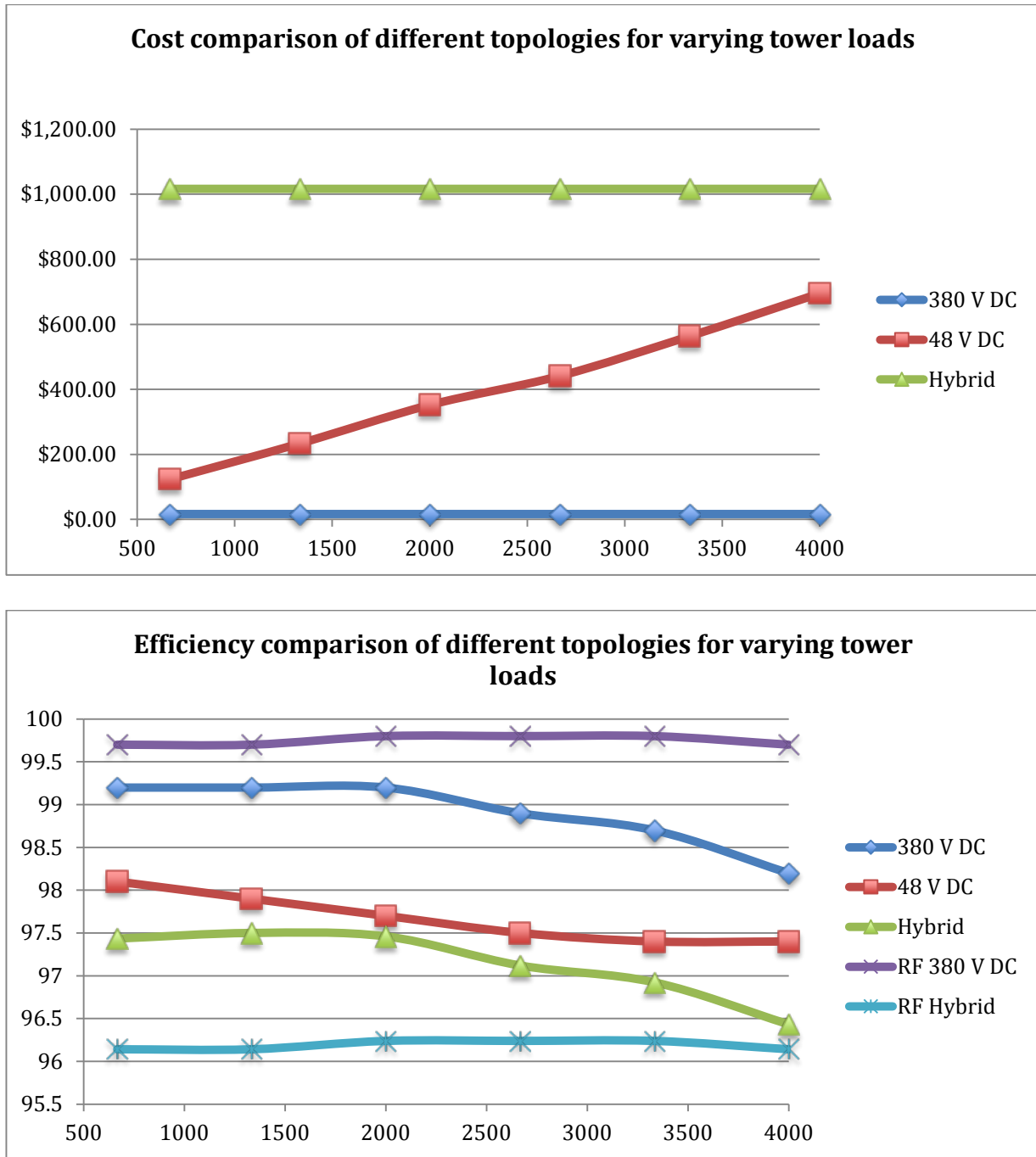


Figure 16: Cost and efficiency comparison for varying tower loads

From an efficiency and economical standpoint, the 380 V DC topology has the advantage. Wiring costs are dramatically reduced for a wide spectrum of loads, with competitive levels of efficiency through the entire range. The decrease in efficiency can be explained by the use of only one type of cable through the entire load range, because the voltage drop remained well within the guidelines defined by the Japanese Electric Code.

The 48 V DC topology sees its price steadily increase as the load gets higher, and cables get thicker to stay within acceptable limits of voltage drop. It is a solution that is both more expensive and less efficient.

For the hybrid 380/48 V DC topology, the cost of the converters and their impact on the efficiency of the system do not currently justify the use of this solution on a 100-foot cell site from either an economical or efficiency standpoint.

The 380 V DC retrofit topology offers outstanding levels of efficiency due to the use of existing 48 V DC cabling, and the absence of conversion steps to feed the loads.

The hybrid retrofit topology suffers from reduced efficiency due to the use of two cascading converters at the bottom and on top of the tower.

5.2.2 Varying tower heights

Displayed below in graphical form are the results for a load of 1333 W on top of a cell site, with varying tower heights.

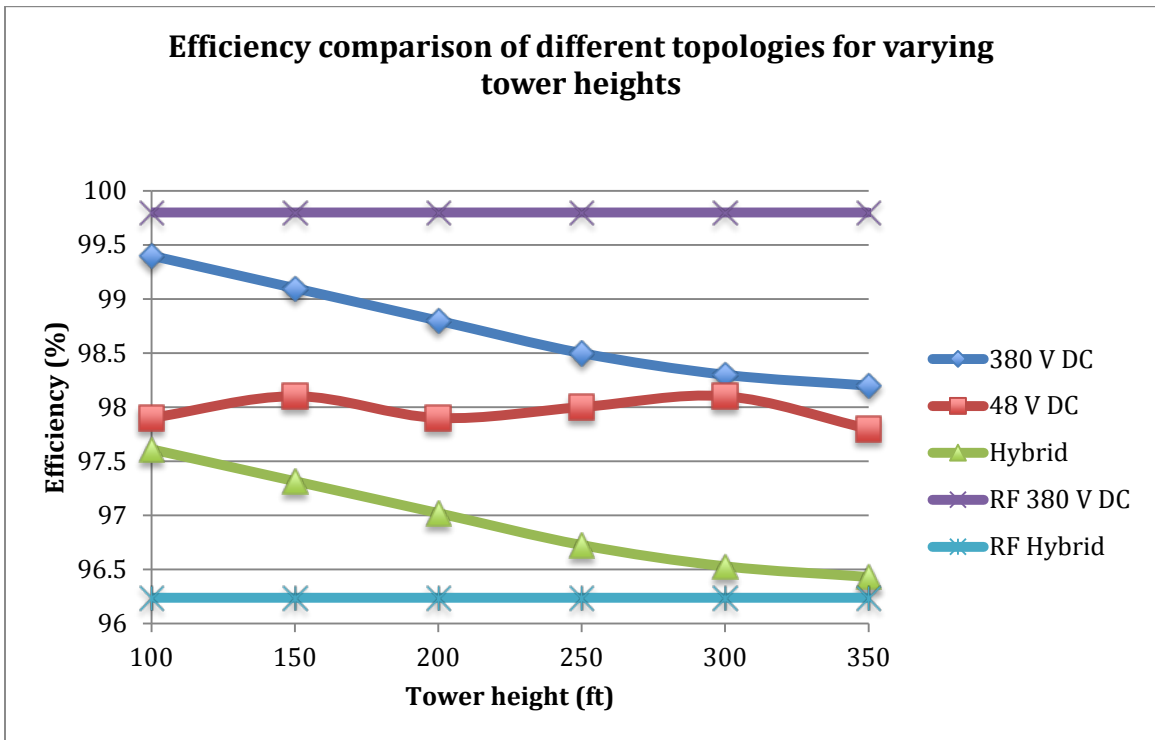
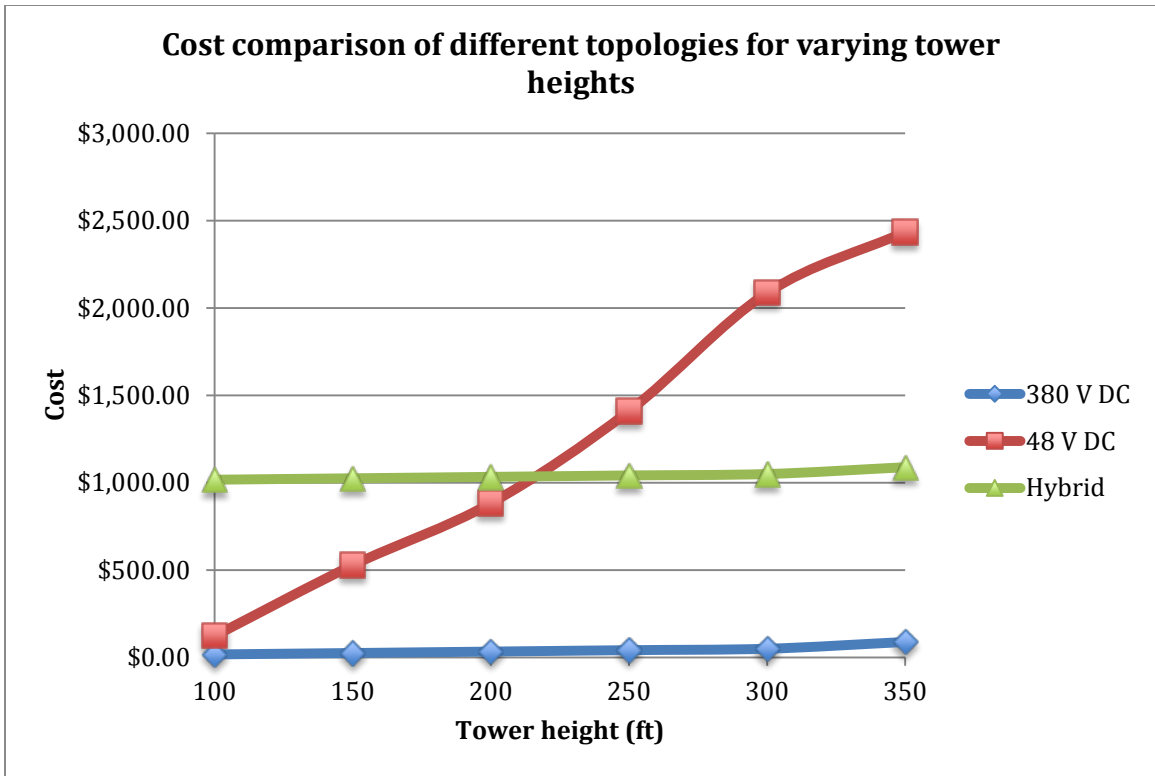


Figure 17: Cost and Efficiency comparison for varying tower heights

For varying tower heights as well, the 380 V DC topology remains both cheaper and more efficient.

Increasing the tower height has a double effect on the economical competitiveness of the 48 V DC topology. Not only does an increase in tower height call for thicker cabling in order to contain voltage drop, the necessary amount of cabling also increases. This leads to a significant difference in cost as compared to other topologies, and an efficiency that remains constant around 98%.

The hybrid 380 V DC topology appears to offer a credible economical alternative for towers above 225 feet. Its efficiency, however, remains below the 48 and 380 V DC systems.

Again, the 380 V DC retrofit topology offers outstanding levels of efficiency, while the hybrid retrofit topology offers reduced efficiency because of the cascading converters.

5.3 CONCLUSIONS

The 380 V DC topology offers a credible alternative from both economical and efficiency points of view. It is a solution that is significantly cheaper than 48 V DC, while still yielding better efficiency for a wide array of loads and tower heights.

The drawbacks for this topology are multiple. First the lack of available telecom equipment at this voltage level makes this topology a "proof of concept" at this point in time. Secondly, the gains remain marginal. It is indeed not certain that a 1% energy efficiency improvement and savings in the order of \$700-\$2400 on an investment of around \$150,000 would economically justify any move in that direction from the telecom industry.

The additional cost for the converters for the hybrid 380/48 V DC and the reduced efficiency due to the use of two converters do not currently justify the use of this solution on a 100-foot cell site from either an economical or efficiency standpoint. This option remains less efficient than 48 V DC and its use can only be economically justified for towers above 225 feet.

The 380 V DC retrofit topology offers outstanding levels of efficiency at no cost given the reuse of existing cabling. At the present moment, it also remains a "proof of concept" given the lack of available 380 V DC telecom equipment.

The hybrid 380/48 V DC retrofit topology offers interesting opportunities when increasing amounts of RF load are necessary on top of cell towers and the existing 48 V DC wiring is approximating its power transfer limit.

6.0 SUMMARY AND FUTURE WORK

This study has shown that the question of 380 V DC or 48 V DC in mobile telecom systems goes further than just efficiency considerations.

The standards released by the ETSI make the 48 V DC system intrinsically efficient, at the expense of great amounts of copper, which give an explanation to the marginal gains observed in the simulations. The difference between these results and those observed in the datacenter industry can be explained by the low power density of a telecom site and the fact that we are just increasing the voltage of an already DC system. The transition to 380 V DC in the datacenter industry included the removal of several inefficient conversion steps along with an increase in voltage.

The 380 V DC topology has shown promising results, with increased overall efficiency and reduced capital cost for varying tower heights and loads. However, the marginal efficiency gains and capital savings in regard to total site consumption/cost might not justify a move in that direction from telecom equipment manufacturers at this point in time. An increase in copper price in the future is a parameter that might tip the scale in its favor.

Hybrid 380/48 V DC topologies can only make sense for high towers where they are economically justified although less efficient than their 48 V DC counterparts. The current state of the art in converters prevents this topology from being a viable option for low-rise sites, as it is both more expensive and less efficient than the current 48 V DC topology.

However, the same hybrid topologies offer an interesting opportunity for retrofits, when increased amounts of load are required atop a cell site, and the wiring is nearing the limits of its power capacity.

Future research on this subject could include the impact of fast-switching power electronics close to RF equipment operating in the 700-2500 MHz range. Future simulations could also include a more detailed electrical model of the base station, although the work done here under the assumption that most losses happen on the way up the tower gives a valid assessment of the strengths and weaknesses of the different topologies.

In conclusion, 380 V DC does not appear to be the solution to a faster deployment of greener mobile telecom sites for the reasons explained above. It does, however, open interesting opportunities for telecom network operators in some specific cases.

Finally, the continuous decrease in the cost of solar, the development of microgrids and the push in the development of batteries instigated by handheld electronic devices and electrical vehicle manufacturers might be the triggering factors that will favor the emergence of autonomous cell sites in the future.

APPENDIX A

SENSITIVITY STUDY - TOWER LOAD VARIATION

Table 4: Simulation results for varying tower loads

Power Load (W, considering a 100 foot tower)		667	1333	2000	2667	3333	4000
380 V DC	Wire	AWG 14	AWG 14	AWG 14	AWG 14	AWG 14	AWG 14
	Cost	\$16.40	\$16.40	\$16.40	\$16.40	\$16.40	\$16.40
	Overall Consumption (W)	1008	1677	2351	3031	3714	4414
	Tower losses (W)	1.5	7.0	14.0	25.0	39.0	56.0
	Efficiency (%)	99.2	99.2	99.2	98.9	98.7	98.2
Hybrid 380 V DC	Wire	AWG 14	AWG 14	AWG 14	AWG 14	AWG 14	AWG 14
	Cost	\$1,016.40	\$1,016.40	\$1,016.40	\$1,016.40	\$1,016.40	\$1,016.40
	Overall Consumption (W)	1026	1710	2394	3089	3783	4493
	Tower losses (W)	1.6	7.0	14.5	26.0	40.0	58.0
	Efficiency (%)	97.4	97.5	97.5	97.1	96.9	96.4
48 V DC	Wire	AWG 5	AWG 2	AWG 1/0	AWG 2/0	AWG 3/0	AWG 4/0
	Cost	\$123.66	\$233.76	\$352.26	\$441.56	\$564.04	\$695.62
	Overall Consumption (W)	1019	1701	2389	3077	3763	4445
	Tower losses (W)	12.4	25	33	49	61	70
	Efficiency (%)	98.1	97.9	97.7	97.5	97.4	97.4
380 V DC Retrofit	Wire	AWG 5	AWG 2	AWG 1/0	AWG 2/0	AWG 3/0	AWG 4/0
	Cost	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00
	Overall Consumption (W)	1004	1670	2338	3006	3672	4344
	Tower losses (W)	<1	<1	<1	<1	<1	1
	Efficiency (%)	99.7	99.7	99.8	99.8	99.8	99.7
Hybrid 380 VDC Retrofit	Wire	AWG 5	AWG 2	AWG 1/0	AWG 2/0	AWG 3/0	AWG 4/0
	Cost	\$1,000.00	\$1,000.00	\$1,000.00	\$1,000.00	\$1,000.00	\$1,000.00
	Overall Consumption (W)	1040	1734	2424	3117	3810	4507
	Tower losses (W)	<1	<1	<1	<1	<1	1
	Efficiency (%)	96.1	96.1	96.2	96.2	96.2	96.1

APPENDIX B

SENSITIVITY STUDY - TOWER HEIGHT VARIATION

Table 5: Simulation results for varying tower heights

Tower Height (feet, considering 1333W mast load)	100	150	200	250	300	350	
380 V DC	Wire	AWG 14	AWG 14	AWG 14	AWG 14	AWG 14	AWG 14
	Cost	\$16.40	\$24.60	\$32.80	\$41.00	\$49.20	\$88.06
	Overall Consumption (W)	1676	1680	1686	1691	1694	1696
	Tower losses (W)	7	9	12	16	19	22
	Efficiency (%)	99.4	99.1	98.8	98.5	98.3	98.2
Hybrid 380 V DC	Wire	AWG 14	AWG 14	AWG 14	AWG 14	AWG 14	AWG 14
	Cost	\$1,016.40	\$1,024.60	\$1,032.80	\$1,041.00	\$1,049.20	\$1,088.06
	Overall Consumption (W)	1708	1713	1718	1723	1727	1729
	Tower losses (W)	7	9.6	12.8	16.1	19.3	22.5
	Efficiency (%)	97.6	97.3	97.0	96.7	96.5	96.4
48 V DC	Wire	AWG 5	AWG 1/0	AWG 2/0	AWG 3/0	AWG 4/0	AWG 4/0
	Cost	\$123.66	\$528.39	\$883.12	\$1,410.10	\$2,086.86	\$2,434.67
	Overall Consumption (W)	1701	1698	1701	1700	1698	1702
	Tower losses (W)	25	23	25	25	23	27
	Efficiency (%)	97.9	98.1	97.9	98	98.1	97.8
380 V DC Retrofit	Wire	AWG 5	AWG 1/0	AWG 2/0	AWG 3/0	AWG 4/0	AWG 4/0
	Cost	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00
	Overall Consumption (W)	1670	1670	1670	1670	1671	1671
	Tower losses (W)	<1	<1	<1	<1	<1	<1
	Efficiency (%)	99.8	99.8	99.8	99.8	99.8	99.8
Hybrid 380 VDC Retrofit	Wire	AWG 5	AWG 1/0	AWG 2/0	AWG 3/0	AWG 4/0	AWG 4/0
	Cost	\$1,000.00	\$1,000.00	\$1,000.00	\$1,000.00	\$1,000.00	\$1,000.00
	Overall Consumption (W)	1732	1732	1732	1732	1732	1734
	Tower losses (W)	<1	<1	<1	<1	<1	<1
	Efficiency (%)	96.2	96.2	96.2	96.2	96.2	96.2

BIBLIOGRAPHY

- [1] CISCO, “Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2014–2019,” 2014. [Online]. Available: http://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/white_paper_c11-520862.html. [Accessed: 27-Feb-2015].
- [2] C. Funk, J. Nicolay, and R. Carr, “Trends and Forecasts for the Wireless and Tower Industries,” *Above Ground Level*. [Online]. Available: <http://www.aaeonline.com/wp-content/uploads/2013/11/AGL-Trends-and-Forecasts-9-2013.pdf>. [Accessed: 03-Mar-2015].
- [3] S. Blumberg and J. Luke, “Wireless Substitution: Early Release of Estimates From the National Health Interview Survey.” [Online]. Available: <http://www.cdc.gov/nchs/data/nhis/earlyrelease/wireless201212.PDF>. [Accessed: 27-Feb-2015].
- [4] I. Humar, X. Ge, L. Xiang, M. Jo, M. Chen, and J. Zhang, “Rethinking Energy Efficiency Models of Cellular Networks with Embodied Energy,” *Network, IEEE (Volume:25 , Issue: 2)*, 2011. [Online]. Available: <http://mmlab.snu.ac.kr/publications/docs/Min-0-JNLb-2-8-IEEE-Networks2011.pdf>. [Accessed: 27-Feb-2015].
- [5] GSMA, “Mobile’s Green Manifesto,” 2012.
- [6] GSMA, “Energy for the Telecom Towers - India Market Sizing and Forecasting,” 2011. [Online]. Available: <http://www.gsma.com/connectedwomen/wp-content/uploads/2012/05/Energy-for-the-Telecom-Towers-India-Market-Sizing-and-Forecasting-September-2010.pdf>. [Accessed: 27-Feb-2015].
- [7] K. Tweed, “Why Cellular Towers in Developing Nations Are Making the Move to Solar Power,” *Sci. Am*.
- [8] D. Ginley and D. Cahen, “Fundamentals of Materials for Energy and Environmental sustainability,” 2011.
- [9] “tradingeconomics.com.”

- [10] R. Jain, S. Katiyar, and N. Agrawal, "Hierarchical Cellular Structures in High-Capacity Cellular Communication Systems," *International Journal of Advanced Computer Science and Applications*, 2011. [Online]. Available: <http://arxiv.org/pdf/1110.2627.pdf>. [Accessed: 10-Mar-2015].
- [11] R. P. Narayan, "DC SURGE PROTECTION OF REMOTE RADIO UNITS RRU or REMOTE RADIO HEAD RRH INTELEC ® 2014 Conference Proceedings," 2014.
- [12] ETSI, "ETSI EN 300 132-2 : Environmental Engineering (EE); Power supply interface at the input to telecommunications and datacom (ICT) equipment; Part 2: Operated by -48 V direct current (dc)."
- [13] A. Kwasinski, "Analysis of electric power architectures to improve availability and efficiency of air conditioning systems," *Telecommunications Energy Conference, 2008. INTELEC 2008. IEEE 30th International*. pp. 1–8, 2008.
- [14] J. Lorincz, T. Garma, and G. Petrovic, "Measurements and Modelling of Base Station Power Consumption under Real Traffic Loads," *Sensors*, vol. 12, no. 4, pp. 4281–4310, 2012.
- [15] L. Correia, O. Blume, D. Zeller, D. Ferling, Y. Jading, I. Godor, G. Auer, and L. Van der Perre, "Challenges and Enabling Technologies for Energy Aware Mobile Radio Networks," *Communications Magazine, IEEE (Volume:48 , Issue: 11)*, 2010. [Online]. Available: http://www.greentouch.org/uploads/documents/IEEECommMag_Earth.pdf. [Accessed: 26-Feb-2015].
- [16] D. Tipper, A. Rezgui, P. Krishnamurthy, and P. Pacharintanakul, "Dimming Cellular Networks," *Global Telecommunications Conference (GLOBECOM 2010), 2010 IEEE*, 2010. [Online]. Available: <http://d-scholarship.pitt.edu/5893/1/PID1050226.pdf>. [Accessed: 26-Feb-2015].
- [17] O. Blume, H. Eckhardt, S. Klein, E. Kuehn, and W. M. Wajda, "Energy Savings in Mobile Networks Based on Adaptation to Traffic Statistics," *Bell Labs Technical Journal (Volume:15 , Issue: 2)*, 2010. [Online]. Available: http://www.greentouch.org/uploads/documents/BLTJ_15-2%282010%2977-94_Energy Savings in Mobile Networks Based on Adaptation to Traffic Statistics.pdf. [Accessed: 26-Feb-2015].
- [18] Z. Niu, Y. Wu, J. Gong, and Z. Yang, "Cell zooming for cost-efficient green cellular networks," *IEEE Commun. Mag.*, vol. 48, no. November, pp. 74–79, 2010.
- [19] G. AlLee and W. Tschudi, "Edison Redux: 380 Vdc Brings Reliability and Efficiency to Sustainable Data Centers," *IEEE Power Energy Mag.*, vol. 10, no. 6, pp. 50–59, Nov. 2012.
- [20] G. AlLee, "DC – a technology whose time has come again," 2012.

- [21] A. Pratt, P. Kumar, and T. V Aldridge, “Evaluation of 400V DC distribution in telco and data centers to improve energy efficiency,” *Telecommunications Energy Conference, 2007. INTELEC 2007. 29th International*. pp. 32–39, 2007.
- [22] Intel, HP/EYP, and Emerson, “White paper,” 2009.
- [23] T. Tanaka, K. Hirose, D. Marquet, B. J. Sonnenberg, and M. Szpek, “Analysis of wiring design for 380-VDC power distribution system at telecommunication sites,” *INTELEC, Int. Telecommun. Energy Conf.*, pp. 1–5, 2012.
- [24] “Japan Electric Code.”
- [25] ETSI, “ETSI EN 300 132-3-1 Power supply interface at the input to telecommunications and datacom (ICT) equipment,” vol. 1, pp. 1–31, 2011.
- [26] ITU-T, “ITU-T L.1200 Direct current power feeding interface up to 400 V at the input to telecommunication and ICT equipment.”
- [27] Eltek, “Flatpack2 HVDC/DC Converter Datasheet.”
- [28] “steelintheair.com.”