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Wireless communication system for land seismic operations: A feasibility study

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Problem Description

Wireless communication system for land seismic operations: A feasibility study.

The thesis related to this activity consists of:
1. Study of the available wireless technologies suitable for this aplication.
2. Generation of a report including:
   a) Comparison of different technologies based on criteria such as complexity, price, logistics, maturity etc.
   b) Suggesting the best solution, and presenting the suggested solution in detail.

Assignment given: 18. February 2008
Supervisor: Bjørn B. Larsen, IET

Abstract

Wireless data networks have seen rapid growth and deployment in the recent years, replacing traditional wired data networks.

WesternGeco is currently using a traditional wired data network in the land seismic operations to connect the Head Vibrator with the Recording Truck.

The thesis provides a survey of the most important wireless data network technologies available. A comparison between them is done in order to determine the best suited for WesternGeco's communication mechanism. The study has lead to the conclusion that IEEE 802.11g is the most suited technology. Through the use of high gain antennas, modification of MAC layer parameters and the proper channel allocation, the suggested solution is capable of responding what WesternGeco needs.

Preface

First of all I would like to apologize for all the mistakes and errors this thesis may contain. I have put all my effort in order to correct them but I am sure that more than one are still there.

My mother tongue is Spanish and, although I can express myself quite accurately, my knowledge of English is far away from being perfect. Therefore some written expressions in this thesis may sound strange. They are the consequence of thinking in Spanish and, afterwards, translating into English.

I would like to thank Bjørn B. Larsen my friend and supervisor at NTNU for his support, and Daniel Golparian my supervisor at WesternGeco for his guidance and patience. I would especially like to thank Amrei Binzer for her outstanding assistance in linguistic matters. I would also like to thank all the people I have come to meet here in Trondheim for making this semester one of the most enjoyable of my life.

Trondheim, July 19th,2008

Ander Ramos Gana

Abbreviations

AAA	Adaptive Antenna Array
ACK	Acknowledgement
ADSL	Asymmetric Digital Subscriber Line
AP	Access Point
BBM	Break Before Make
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
BS	Base Station
BSS	Basic Service Set
CCK	Complementary Code Keying
CI	Channel Identifier
CP	Cyclic Prefix
CPE	Customer Premises Equipment
CSIRO	Commonwealth Scientific and Industrial Research Organization of Australia
CSMA/CA	Carrier Sense Multiple Access/Collision Avoidance
CTS	Clear To Send
DCF	Distributed Coordination Function
DIFS	DCF Inter Frame Spacing
DL	Down Link
DSSS	Direct Sequence Spread Spectrum
EIRP	Equivalent Isotropically Radiated Power
ESS	Extended Service Set
ETSI	European Telecommunications Standards Institute
FBSS	Fast Base Station Switching
FDD	Frequency Division Duplex
FEC	Forward Error Correction
FHSS	Frequency Hopping Spread Spectrum
FFT	Fast Fourier Transform
FT	Fourier Transform
GI	Guard Interval
HCF	Hybrid Coordination Function
HC-SDMA	High Capacity Spatial Division Multiple Access
HHO	Hard HandOff
HV	Head Vibrator
IEEE	Institute of Electrical and Electronics Engineers
IFFT	Inverse Fast Fourier Transform
IFT	Inverse Fourier Transform
IMT	International Mobile Telecommunications
IP	Internet Protocol
IR	InfraRed
ISI	Inter Symbol Interference
ISM	Industrial Scientific and Medical
LOS	Line Of Sight
LTE	Long Term Evolution
MAC	Medium Access Control
MBB	Make Before Break
MBWA	Mobile Broadband Wireless Access

MDHO	Macro Diversity HandOver
MIMO	Multiple Input Multiple Output
MSDU	Mac Service Data Unit
NF	Noise Figure
NLOS	Non Line Of Sight
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
PCF	Point Coordination Function
PDP	Power Delay Profile
PHY	Physical
PIFS	PCF Inter Frame Spacing
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RF	Radio Frequency
RT	Recording Truck
RTS	Request To Send
SCFDMA	Single Carrier Frequency Division Multiple Access
SDMA	Spatial Division Multiple Access
SIFS	Short Inter Frame Spacing
SNR	Signal to Noise Rate
SOFDMA	Scalable Orthogonal Frequency Division Multiple Access
SS	Subscriber Station
TCP	Transmission Control Protocol
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
TG	Task Group
UL	Up Link
UMTS	Universal Mobile Telecommunications System
VG	Vibrator Group
VoIP	Voice over Internet Protocol
Wi-Fi	Wireless Fidelity

Table of contents

1. Introduction

Before going any further we are going to make a first approach to what our working scheme should be.

1.1 The problem

We want to enable the communication between a Recording Truck (RT) and a given number of Vibrator Groups (VG) while they are moving at a certain speed within an area.

1.2 The scenario

In each Vibrator Group there is one Vibrator that acts as the head and is responsible for gathering the information from the other Vibrators in its group and sending it to the Recording Truck. For this first approach we are going to consider just four Vibrator Groups. The uplink bandwidth needed for the Head Vibrator (HV) to send the data is approximately 1 Mbps and the downlink bandwidth needed is about 100 Kbps.

The distance that each link can reach is about 10 km and the speed we are going to consider for each Vibrator Group is the human walking speed (in average 6 kmph). Despite the fact that the Vibrator Groups are going to be moving we are going to consider that the Recording Truck will stand still in the same place while the communication lasts. There is the possibility that also the Recording Truck is moving while sending or receiving data from the Vibrator Groups but we are not considering it.

Since the main terrain is going to be the desert it is expected to face very high temperatures during the day time and low temperatures during the night time.

There also can be some Radio Frequency (RF) obstacles in the communication path, depending on the geographical location of the operation.

1.3 Organization of the thesis

The thesis is divided in two parts:

- The first part focuses on the available wireless technologies and compares them in order to find the most suited for the thesis purpose. It goes from chapters 2 to 7. Each chapter of this part is dedicated to a different technology except from the last one which consists of the comparison and conclusions.
- The second part goes further in the study of the chosen technology in order to make it meet the communication mechanism requirements and presents the suggested solution in detail. It goes from chapters 8 to 13. Chapters 8, 9, 10 and 11 are dedicated to different aspects of the technology that must be revised such as the physical layer, the medium access control layer or the channel. Chapter 12 presents the architecture of the system and chapter 13 the conclusions.

1.4 Special considerations

Most of the references in the bottom of the pages of this thesis contain a hyperlink to the Internet. Since most of them are product Internet pages I thought it would be helpful to add a link directly in the thesis, for the readers of the digital version to be able to go directly to the mentioned page.

I would also like to specify that the equations that are not numbered it is because I have not used them to make any specific calculation and thus they can be consider as a plain text.

2 IEEE 802.11

2.1 Introduction

It was 1985 when the Federal Communications Commission of the United States authorized the Industrial, Scientific and Medical frequency bands (ISM). Until then, the wireless technologies were immature and scarcely interesting.
In 1989, the 802.11 Working Group began elaborating the draft that, later on, in 1997 was ratified; it is known today as the 802.11 Legacy standard. Since then a large list of amendments to the standard has followed, with the commercial success of 802.11b/g amendments.
The scope of 802.11 family is to deliver wireless connectivity as does the 802.3 (Ethernet) standard.

2.2 Standards and amendments

Most important released standards and amendments:

Legacy Standard (802.11-1997):
The original wireless Lan standard, was released in 1997 and then clarified in 1999. It specifies two different radio frequency (RF) physical layers operating at the 2.4 GHz ISM band, Direct Sequence Spread Spectrum (DSSS) and Frequency Hopping Spread Spectrum (FHSS). It also specified an Infrared (IR) physical layer although most vendors prefer to implement the RF solutions.
The bandwidth for every layer is typically 1 Mbps, with the possibility of 2 Mbps in clean environments.
At the same time the standard was clarified, the amendments 802.11a and 802.11b were released.
Recently, due to the complexity of combining the previous standard (802.11-1999) and the recent amendments, a new revision of the standard was done to help clarifying it. As a result the current version of the standard is called 802.11-2007.

802.11a amendment:
This amendment although using the same core protocol works in the band of the 5 GHz, uses Orthogonal Frequency Division Multiplexing (OFDM) and allows a maximum of 54 Mbps bandwidth[1]. It is compatible neither with 802.11 Legacy nor with 802.11b due to the different Spectrum used. It was released in 1999.

802.11b amendment:
This amendment works in the same band as the original standard and it is backwards compatible with it. Grants a maximum of 11 Mbps bandwidth and uses Complementary Code Keying (CCK). Because of its increased bandwidth and the use of the ISM band it has been worldwide accepted, and through the Wi-Fi Alliance vendors provide the market with products which interoperability is granted. It was released in 1999.

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[1] Notice that when talking about maximum bandwidth it is referred to a raw bandwidth. Headers of the Mac, Ip and Tcp frame for example are to be taking in account.

802.11g amendment:
Released in June 2003, this amendment goes a step further in the raw bandwidth it can supply, reaching the 54 Mbps of bandwidth. It uses OFDM, it works in the 2.4 GHz frequency band and is fully backwards compatible with 802.11b hardware.

Most important standards and amendments to come:

802.11mb revision of the standard:
It is expected that by March 2011 a new revision of the 802.11 standard is being released. This amendment will collect the latest information learned from the usage of the base standard and the development of other amendments.

802.11n amendment:
This amendment will provide a theoretically maximum bandwidth of 600 Mbps twice the range[3] 802.11a/b/g is able to provide. This will be possible due to the introduction of a new air interface technique called multiple-input multiple-output (MIMO). It will also work in the 2.4 GHz and 5 GHz frequency bands and will be backwards compatible with 802.11a/b/g legacy devices. The amendment is expected to be released by June 2009 and its current version is Draft 3.0[2]. Currently the Wi-Fi Alliance is certifying products that comply with the Draft 2.0 of the 802.11n amendment to the standard.

Table 1 compares the main 802.11 specifications.

	Legacy	**802.11a**	**802.11b**	**802.11g**	**802.11n**
Release Date	1997	1999	1999	2003	Not yet released
Modulation	DSSS or FHSS	OFDM	DSSS or CCK	DSSS or CCK or OFDM	DSSS or CCK or OFDM
Maximum Achievable Bandwidth	2 Mbps	54 Mbps	11 Mbps	54 Mbps	600 Mbps
Frequency Band	2.4 GHz	5 GHz	2.4 GHz	2.4 GHz	2.4 GHz or 5 GHz
Outdoor Range	100 m	120 m	140 m	140 m	250 m

Table 1: Main 802.11 Specifications.

2.3 Which Flavor

It has been more than ten years since the release of Legacy, and since 1999 the Wi-Fi Alliance has been working in order to provide the customers with reliable and compatible hardware. This sets the basis for further improvement on the standard via amendments and has brought us to the current scheme. Nowadays we can find four major versions of the wireless networking technology (Wi-Fi) being certified: a, b, g and n.

[2] According to the *IEEE 802.11 Official Timelines* LINK

Figure 1: Wi-Fi Certified logo [3].

While 802.11a/b/g have been ratified and widely proven 802.11n is still in the draft phase. The main reason behind this fact is that, apparently, the Commonwealth Scientific and Industrial Research Organization of Australia (CSIRO) owns some patents that are used in the 802.11n amendment[3] and is not willing to issue a Letter of Assurance any time soon. This implies that any vendor who implements 802.11n hardware is at risk of being sued by the CSIRO.

Then, which amendment should be best suited for implementing a solution to deploy in desert areas? Probably the wisest choice would be 802.11g in the short term. The following table shows some of the relevant features of both amendments.

	802.11g	**802.11n**
Released Date	2003	Expected June 2009
Maximum Bandwidth	54 Mbps	600 Mbps. Achievable using MIMO with 40 MHz channel, guard interval of 400 ns and 4 data streams
MIMO	No	Yes. MIMO technology requires multipath propagation, likely to happen in indoor scenarios but unlikely in desert areas
Price	Lower	Higher
Interference	They work in the ISM band, which is affected by interference caused by microwave ovens, Bluetooth devices and other wireless devices working in the same band. It is expected that this kind of interference would be minimal in the desert areas.	
Number of Certified hardware products	2597	240

Table 2: Comparison of relevant features.

[3] According to Bill Ray, September 2007, *Next generation Wi-Fi mired in patent fears* LINK

The issue regarding the patents that the CSIRO owns and are being used in 802.11n is a serious matter and has some immediate consequences:

- The amendment has suffered several delays in its date of release.
- Some vendors may not want to develop 802.11n hardware or they will delay the development of new hardware based on it.
- There are not so many available 802.11n hardware and more expensive than 802.11g.

Although the maximum bandwidth rate achievable with 802.11n (600 Mbps) seems impressive, it is quite unlikely to happen in our scenario. One of the key features of 802.11n is that uses MIMO technology, which allows 802.11n to use spatial multiplexing –sending multiple data streams in the same channel– but it needs a short multipath scenario, where there is slightly difference between the arrival times of the streams. This is more suitable for indoor and urban scenarios and less suited for wide open areas such as a desert. Besides, to achieve such a data rate will imply the use of sophisticated emitters and receivers because 4 data streams on a 40 MHz channel are needed. The current devices being certified support up to 2 data streams on 40 MHz channel meaning that the maximum data bandwidth reachable is 300 Mbps.
In the end we can expect that the maximum data bandwidth is 130 Mbps using 2 streams on 20 MHz channel or 65 Mbps using 1 stream on 20 MHz, because:

- The guard interval should remain at 800 ns as the standard 802.11a/b/g. Lowering it will decrease the protection against multipath propagation.
- It is better to use 20 MHz. Using 40 MHz channels imply that we are spreading our signal energy in a wider band shorting the effective range.

802.11a is not an option because it has the same features as 802.11g but works in a higher frequency band (5 GHz). Working in a higher frequency band implies that the waves would be absorbed easier by the obstacles found in the way, shorting the effective range of the link.

Considering all the factors stated above probably the best option is a solution based on 802.11g hardware in the short term.

2.4 Spectrum and potency

Tables 3 and 4 summarize the potency and spectrum used in 802.11g devices:

Data Rate	Maximum EIRP	
	mW	dBm
6 Mbps	50	17
9 Mbps	50	17
12 Mbps	50	17
18 Mbps	50	17
24 Mbps	50	17
36 Mbps	40	16
48 Mbps	31.6	15
54 Mbps	20	13

Table 3: Maximum EIRP for IEEE 802.11g[4].

The equivalent isotropically radiated power (EIRP) is the amount of power that a theoretically isotropic antenna would need to emit in order to produce the peak power density observed in the direction of maximum antenna gain.

Channel identifier	Frequency (MHz)	Regulatory Domains			
		Americas	EMEA	Japan	Rest of World
1	2412	X	X	X	X
2	2417	X	X	X	X
3	2422	X	X	X	X
4	2427	X	X	X	X
5	2432	X	X	X	X
6	2437	X	X	X	X
7	2442	X	X	X	X
8	2447	X	X	X	X
9	2452	X	X	X	X
10	2457	X	X	X	X
11	2462	X	X	X	X
12	2467	-	X	X	X
13	2472	-	X	X	X
14	2484	-	-	X	-

Table 4: Channels IEEE 802.11b/g[4].

Table 3 refers to the maximum EIRP for pc-cardbus card with 0 dBi antenna gain and pci card with 1 dBi antenna gain.

2.5 Handoff

The IEEE 802.11 network MAC specification allows two operating modes namely, the ad hoc and the infrastructure mode:

- o Ad hoc: Peer to peer communication between two wireless stations without any infrastructure.
- o Infrastructure: In this mode there is a fixed entity called access point (AP) that bridges all data between the wireless stations associated to it, creating a Basic Service Set (BSS). A collection of AP's can extend a BSS into an Extended Service Set (ESS) as show in figure 2.

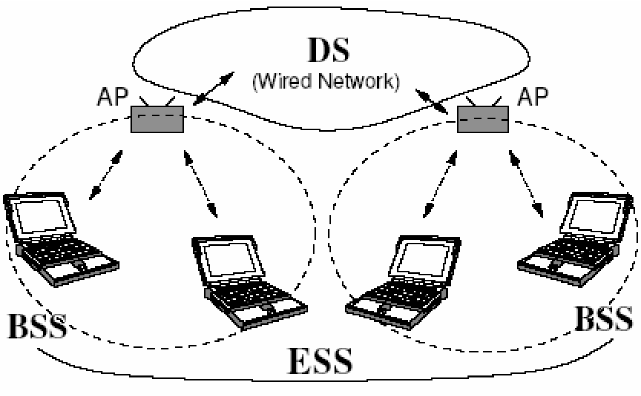

Figure 2: The IEEE 802.11 Extended Service Set [2].

A handoff occurs when a mobile station moves beyond the radio range of one AP, and enters another BSS, leaving the former BSS and associating to the new one. This is achieved through the exchange of management frames between the entities involved. Consequently, there is latency involved in the process during which the mobile station can not send or receive data.

We can divide the handoff process into two distinct logical steps:

1. Discovery: The signal strength and the signal-to-noise ratio (SNR) of the signal from a station's current AP might degrade and cause it to begin to loose connectivity and to initiate a handoff. Then the mobile station begins to scan for beacon messages sent out periodically by other APs at the default rate of 10 ms. Thus the mobile station creates a candidate set of APs prioritized by the received signal strength.
2. Reauthentication: The station attempts to reauthenticate to an AP according to the priority list. Typically implies an authentication and a reassociation to the new AP. Involves the transfer of credentials and other state information from the former AP to the new one.

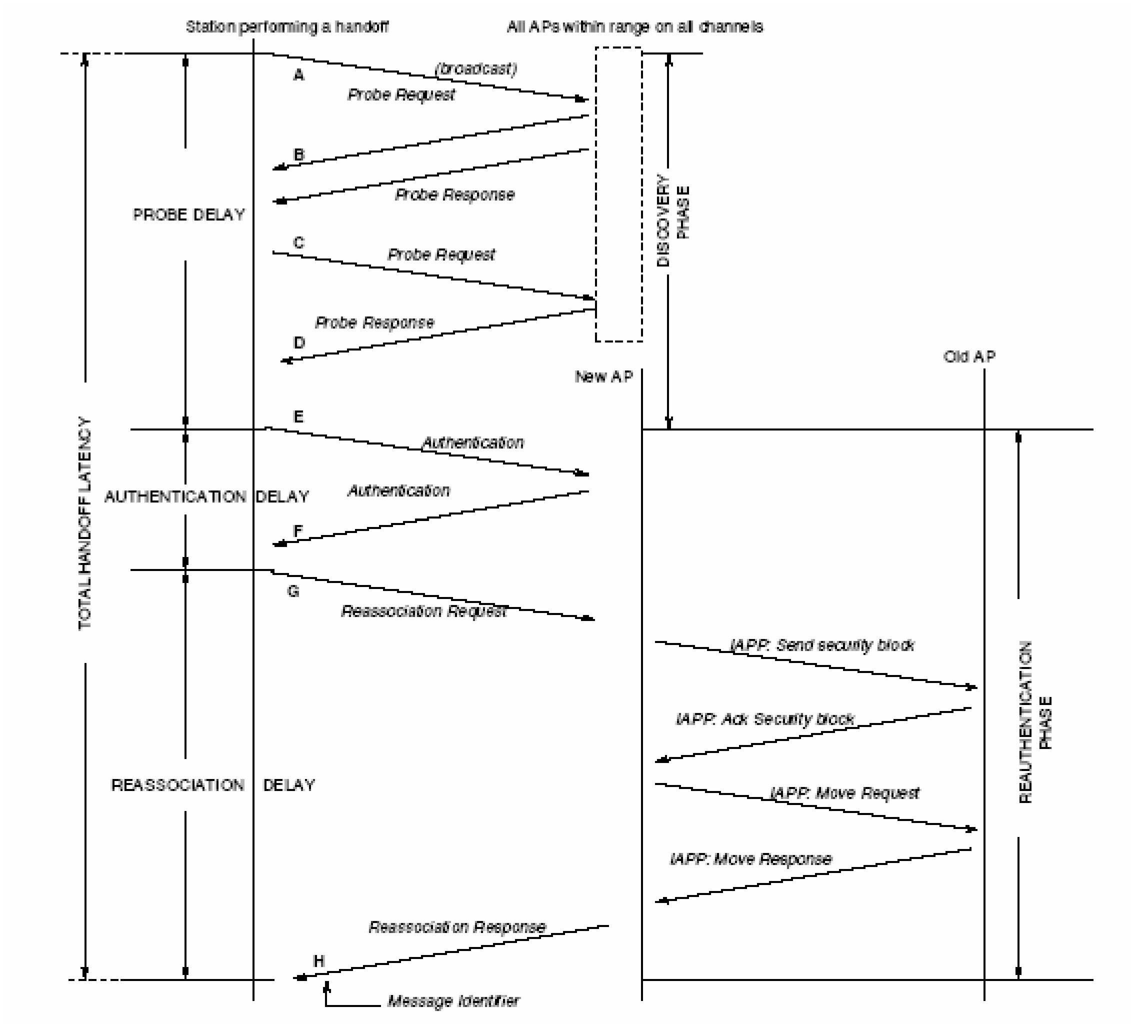

Figure 3: The IEEE 802.11 Handoff Procedure [2].

In figure 3 we can see the main procedure of the handoff process and the delays associated to each phase that are responsible of the total handoff latency.

Mishra et. al have done an empirical study[2] under controlled conditions of the latency of the IEEE 802.11 handoff process with different equipment. The results shown that the probe delay, the one responsible of discovering new APs, is the dominating component of the latency.

As for the latency value, it greatly varies from one vendor to another and the maximum value reaches the 420 ms of delay. Since the study is done under controlled conditions, the real latency delay is expected to be higher.

In a posterior work[1] Mishra et. al. suggest that Neighbor graphs can help reduce the handoff latency by proactively distributing necessary key material one hop ahead of the user.

2.6 Special Issues

Before suggesting a preliminary architecture of the solution, there are some issues regarding the scenario and the hardware that need to be mentioned:

1. Power Supply: If we are to place signal repeaters in places where no power supply is available we need to take care of it beforehand. Systems with built in / add on Solar cell power are best suited to solve the problem.

2. Since we are going to place equipment outdoor we need to make sure that this equipment is able to deal with the worst scenario possible. Protection against dust and water IP 65 and good temperature coefficient are to be taken into account.

3. Since the vibrators will be moving while sending data, handoffs and re-associations may occur. This will depend on the placement of repeaters, its range and the vehicular speed of the vibrators.

2.7 Preliminary architecture

If 802.11g technology is chosen to be the basis for the requested solution the following suggestion is one of multiple architectures possible and should be taken as a first approach.

If the group vibrators are to move in a given area we need to start defining that area. Figure 4 illustrates the suggested architecture.

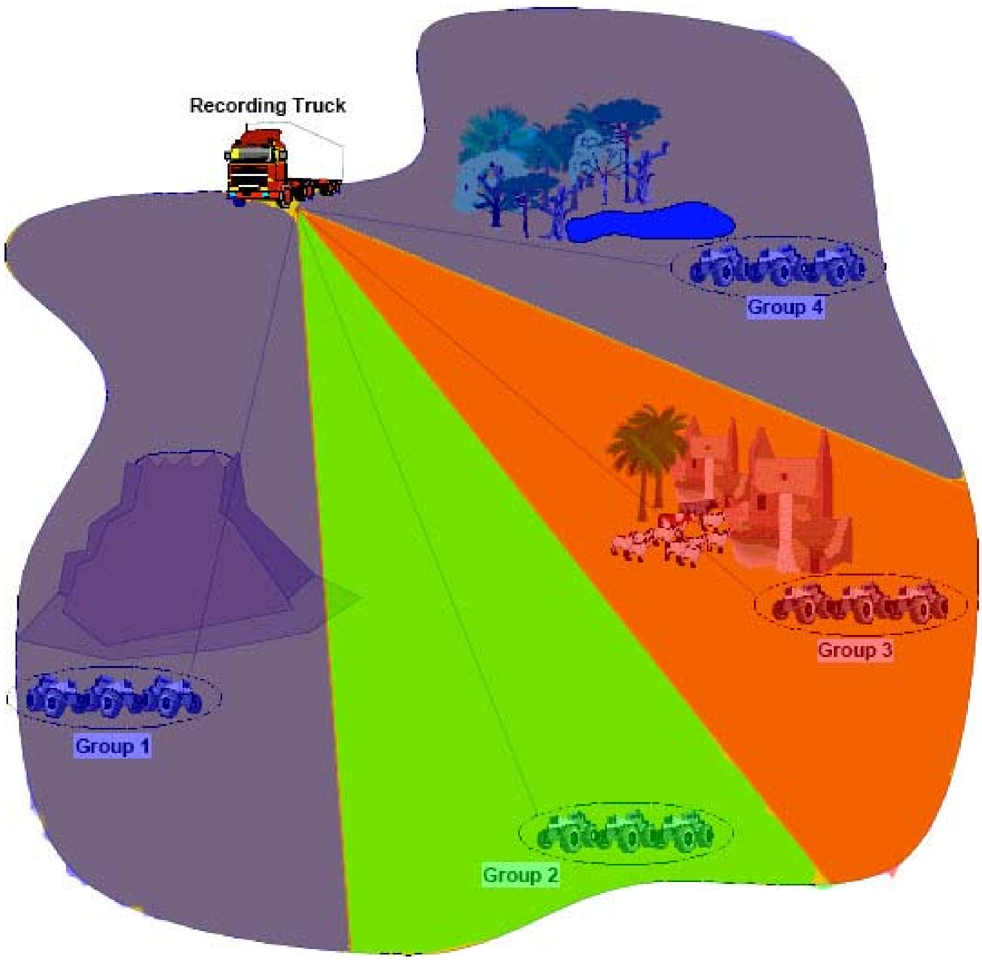

Figure 4: Area Division.

The main idea behind this division is to set a different Wi-Fi channel to each sub-area. There can be up to three channels coexisting in the same area to avoid power overlapping. There are some papers claiming that up to four channels can be used with some energy overlapping, but as shown by Cisco Systems in this paper[13] it should be avoided at all costs.

The first blue area where Group 1 is located is going to have Channel Identifier (CI) 1 assigned, the green area is going to have CI 7, the red area is going to have CI 13 and finally the second blue area where Group 4 is located is going to have CI 1 again. In this way, there will not be power overlapping between areas and the blue areas are not neighbor areas so they will not be interfering with each other.

The reason having different areas with different channels is that in this way we can have just one Channel per Vibrator Group. If we were to have just one Channel for the whole area there is the possibility that two Vibrator Groups who are linked to the same node have to share its bandwidth (we are forcing a communication path).

The Recording Truck will be equipped with four Wi-Fi CPE plugged with high-gain omni-directional antennas, one per channel. Afterwards we are going to place several Wi-Fi repeaters also plugged with high-gain omni-directional antennas to cover the sub-area and make a Mesh Network per channel.

Another issue that has to be taken into account is that each hop (repeater) will divide the bandwidth by two, in that way two hops means that the total bandwidth will be divided by four. This is reasonable since the repeater will be half of the time receiving and half of the time repeating, delaying the transmission, or, in other words, halving the bandwidth.

2.8 Equipment and prices

The resulting architecture displayed in Figure 2 consists of four Mesh Networks (one per each sub-area). In a Mesh Network each node is not just repeating but it is constantly checking each route to know beforehand where it has to send the data.

For this purpose we could use several units of the following equipment:

1. Meraki Outdoor[4]: as our main Mesh repeater equipment. Main features:
    a. Typical Coverage Radius: Outdoor with high-gain antenna: 0.6-5mi (1-8km)
    b. Operating Temperature: 14°F - 122°F (-10°C – 50°C)
    c. IP-65 Environmental rating
    d. Mesh Technology
    e. Price: 199 $.

2. Meraki High-Gain Omni-Directional Antenna[5]: this antenna is to be plugged in the Meraki Outdoor to extend its effective range. Price: 19 $.

3. Meraki Panel Antenna[6]: this antenna is to be plugged in the Meraki Outdoor to extend its effective range in a given direction. Price: 49 $.

4. Meraki Solar[7]: Solar panel and battery to be attached to a Meraki Outdoor, with approximately 20 minutes of autonomy. It has not been released yet, but it is coming soon. Its price will be around 100 $.

These serve us as an example of equipment and prices that we are likely to use if we want to make Wi-Fi our solution.

[4] Meraki Outdoor specifications LINK
[5] Meraki High-Gain Omni-Directional Antenna specifications LINK
[6] Meraki Panel Antenna specifications LINK
[7] Meraki Solar Picture LINK

3 IEEE 802.16 / WiMAX

3.1 Introduction

In 1999 the IEEE Standards Board established the IEEE 802.16 Working Group aimed to prepare the formal specifications for the global deployment of broadband Wireless Metropolitan Area Networks. In 2001 the first standard was released, the IEEE 802.16. In the same year the WiMAX Forum was created to promote conformance and interoperability of the standard. Since the IEEE 802.16 standard only defines layers 1 (Physical) and 2 (Medium Access Control) to support higher networks, the WiMAX Forum used the IEEE 802.16 to create WiMAX: a standards-based technology enabling the delivery of last mile wireless broadband access as an alternative to cable and DSL.

3.2 Standards and amendments

Most important standards and amendments:

802.16 standard:
It was released in 2001 and could only deliver point to multipoint wireless transmission in the band of 10-66 GHz with line of sight (LOS). It is also called 802.16-2001.

802.16a amendment:
It was the first amendment to the 802.16 standard and was ratified in 2003. It added point to multipoint wireless transmission in the band of 2-11 GHz and non line of sight (NLOS) capability. The Physical layer was improved by adding OFDM and OFDMA capability.

802.16-2004 standard:
It was released by the TGd of the IEEE 802.16 although the name of the standard is 802.16-2004. It combined the previous standard plus a/b/c amendments and also aligned the standard with aspects of the ETSI HiperMAN standard. It gives wireless connectivity in LOS and NLOS environments with OFDM and OFDMA capability to fixed stations. The frequency band is 2-11 GHz.

802.16e amendment:
It was released in 2005 and is an amendment to the 802.16-2004 standard. It included enhancements such as better Quality of Service, support for MIMO Antennas, the use of Scalable OFDMA and it provides wireless mobility within LOS and NLOS environments. It is also known as 802.16e-2005.

Based on the 802.16-2004 standard, 802.16e amendment and the ETSI HiperMAN, the WiMAX Forum has released two major versions of WiMAX:

- 802.16-2004 WiMAX or Fixed WiMAX: Aimed to provide fixed and nomadic access in LOS and NLOS environments using OFDM / OFDMA. The first WiMAX Forum Certified products use the OFDM profile defined in the IEEE standard.

- 802.16e-2005 WiMAX or Mobile WiMAX: It provides portability and full mobility in LOS and NLOS environments using SOFDMA. Currently there are eight Mobile WiMAX Certified products, four Base Stations and four Subscriber Stations working in the 2.3 GHz frequency band[8]. They will reach the market later in 2008.

Table 5 shows the definitions for each type of access.

Access definition	Locations	Speed	Handoffs	WiMAX version
Fixed	Single	Stationary	No	802.16-2004
Nomadic	Multiple	Stationary	No	802.16-2004
Portable	Multiple	Walking speed	Hard handoffs	802.16e-2005
Mobile	Multiple	Low vehicular speed	Hard handoffs	802.16e-2005
Full Mobile	Multiple	High vehicular speed	Soft handoffs	802.16e-2005

Table 5: Access types[18].

3.3 Which Flavor

It has been almost 7 years since the release of the first 802.16 standard but just two years since the first WiMAX Forum Certified products appeared in the market. Today we can only find 802.16-2004 WiMAX Certified products in the market, but that does not mean that there are not 802.16e-2005 WiMAX products available. Most of them are Mobile WiMAX compliant products that is to say that the vendor has followed the WiMAX Forum recommendations and it is waiting to be Certified, yet the interoperability is not guaranteed. This is not a major issue if we define our solution with equipment from the same vendor.

It is clear that if the Vibrator Groups will be moving we have to choose the mobile version of WiMAX since we need portable access and onwards.

3.4 Main Features of Mobile WiMAX

The IEEE 802.16 defines the PHY and MAC layers. Afterwards the WiMAX Forum has to implement the network architecture necessary to make the end-to-end Mobile WiMAX link possible. In that way the WiMAX Forum chooses the more suitable profiles for each implementation; i.e. the first Mobile WiMAX Certified products will be working in the 2.3 GHz and 2.5 GHz frequency bands.

That is why there are many compulsory and optional features that the WiMAX Forum defines and the vendors implement as it is illustrated in figure 5.

[8] *WiMAX Forum® Announces First Mobile WiMAX Certified Products at WiMAX Forum Congress Asia 2008* LINK

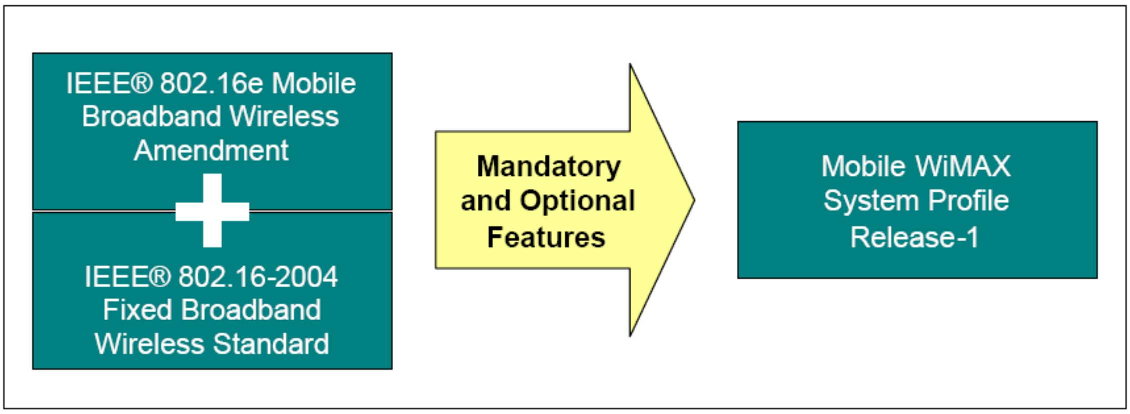

Figure 5: Mobile WiMAX System Profile[17].

Some of the salient features supported by Mobile WiMAX are:

- High Data Rates: Using MIMO antennae techniques along with flexible sub-channelization schemes, Advanced Coding and Modulation all enable Mobile WiMAX to support peak Down-Link bandwidth up to 63.36 Mbps and peak Up-Link bandwidth up to 28.22 Mbps in a 10 MHz channel.
- Quality of Service (QoS): The fundamental premise of the IEEE 802.16 MAC architecture. QoS in 802.16e is supported by allocating each connection between the Subscriber Station and the Base Station (called a service flow in 802.16 terminology) to a specific QoS *class*.
- Scalability: Mobile WiMAX is designed to enable scalability to work in different channelizations from 1.25 to 20 MHz to comply with varied worldwide requirements.
- Mobility: Mobile WiMAX supports optimized handover schemes with latencies lower than 50 milliseconds to ensure real-time applications such as VoIP perform without service degradation.

Table 6 summarizes the main features regarding the first release of Mobile WiMAX.

Feature		**Mobile WiMAX Release-1**		
Frequency Bands		2.3 GHz & 2.5 GHz		
Channel Bandwidth		5 MHz, 7 MHz, 8.75 MHz, 10 MHz		
Physical Layer		Scalable OFDMA, Time Division Duplex		
Down-Link 10 MHz Channel BW	Modulations	QPSK	16 QAM	64 QAM
	Max. Data Rates	9.50 Mbps	19.01 Mbps	31.68 Mbps
Up-Link 10 MHz Channel BW	Modulations	QPSK	16 QAM	64 QAM
	Max. Data Rates	7.06 Mbps	14.11 Mbps	23.52 Mbps
Max. vehicular speed		120 kmph		
MAC Layer		QoS oriented: UGS, rtPS, ErtPS, nrtPS & BE		
Handoffs		Hard Handoff (HHO), FBSS & MDHO (Soft Handoff)		
Antenna Technologies supported		Beamforming, Space-Time Code (STC) & Spatial Multiplexing (SM) → MIMO		
Range		Up to 50 km		

Table 6: Mobile WiMAX Release-1 features. Highlighted Data Rates are optional[17].

Data rates showed in the table do not take into account MIMO technology. With MIMO (Spatial Multiplexing) data rates can be greatly increased.
Picture 6 shows the relation between achievable distance and the modulation used in the link. To maintain a constant bit error rate (BER) Mobile WiMAX switches automatically from one modulation to another.

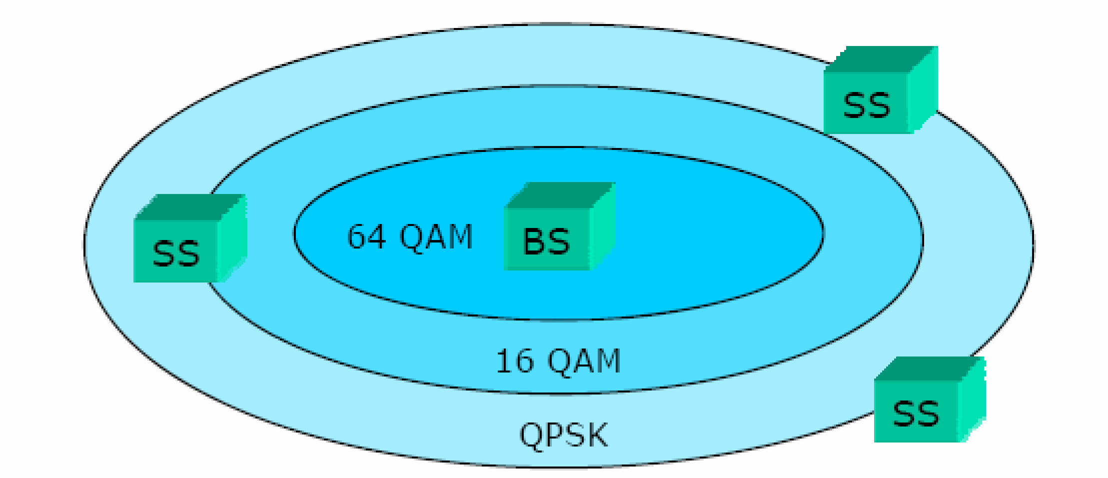

Figure 6: Distance vs Modulation.

The System Profile Release-1 or the first release of Mobile WiMAX Certified products are divided in two waves:

- First Wave: Focused on basic air protocol certification.
- Second Wave: Brings support for advanced features including MIMO and beamforming. Most of the vendors are targeting this second wave and claim that their products are already Wave 2 compliant.

3.5 Handoff

As seen in the Wi-Fi case, a handoff occurs when there is the need to change of Base Station to improve the signal strength.
There are three handoff methods supported within the 802.16e standard; Hard Handoff (HHO); Fast Base Station Switching (FBSS) and Macro Diversity Handover (MDHO). The first one is mandatory, while the other two are optional. The WiMAX Forum has optimized the HHO within the framework of the 802.16e standard to achieve MAC Layer handoff delays less than 50 ms.

Hard Handoff:
This type of handoff is defined as Break Before Make (BBM) because the communication with the target BS starts after a disconnection of service with the previous serving BS. To reduce the handoff delay a BS broadcasts Uplink Channel Descriptor (UCD) and Downlink Channel Descriptor (DCD) information of neighbor BSs. Then the SS uses this information to reduce the scanning time.

Basically, the SS uses the information of UCD and DCD of potential target BSs and requests a QoS level. The serving BS asks the target BSs and gets an estimated QoS level, recommending the potential BS to the SS. The SS confirms its intention of HO and proceeds to break the link with the serving BS and starts synchronizing with the target BS, as seen in figure 7.

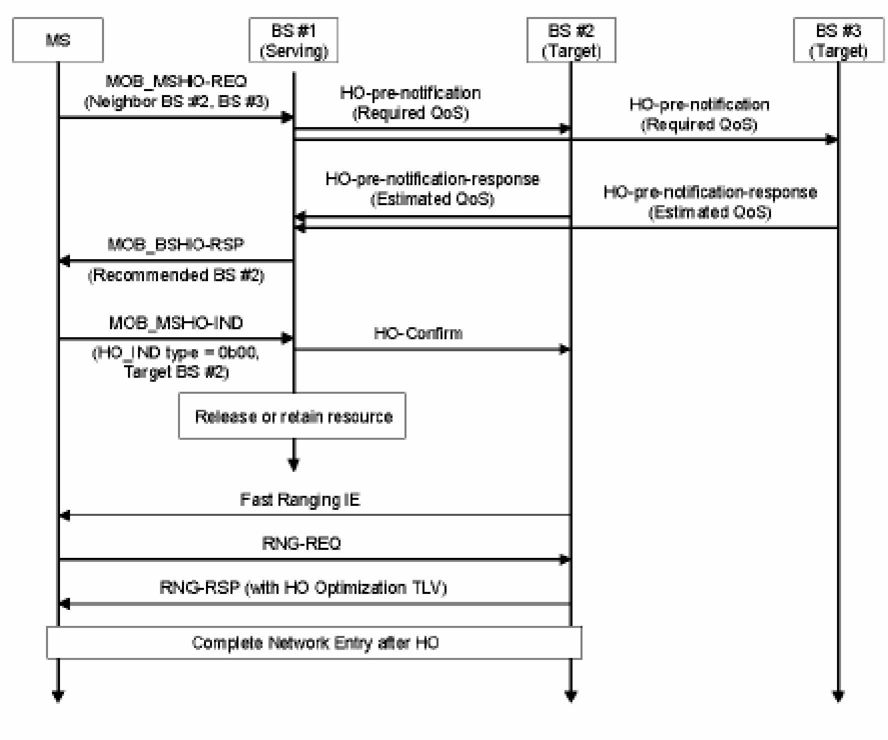

Figure 7: IEEE 802.16e Handoff Procedure[22].

Fast Base Station Switching and Macro Diversity Handover:
These two types of handoffs are very similar and are defined as Make Before Break (MBB). This means that the service with the target BS can start before disconnection of the service with the previous serving BS.

In FBSS and MDHO scenarios the SS is registered to several BSs (Active Set) at the same time. There is also an entity called Anchor BS that the SS uses to send and receive data.

When the handoff occurs the SS changes its Anchor Station. In MDHO mode the SS can send and receive data from various BSs in a given interval, whilst in FBSS mode the SS can only send and receive data to the Anchor BS.

These procedures grant low latency Quality of Service but add high costs to 802.16e hardware making HHO the most common solution for the handoff procedure.

Figure 8 shows the Active Set of a Subscriber Station in a MDHO scheme when handoff occurs.

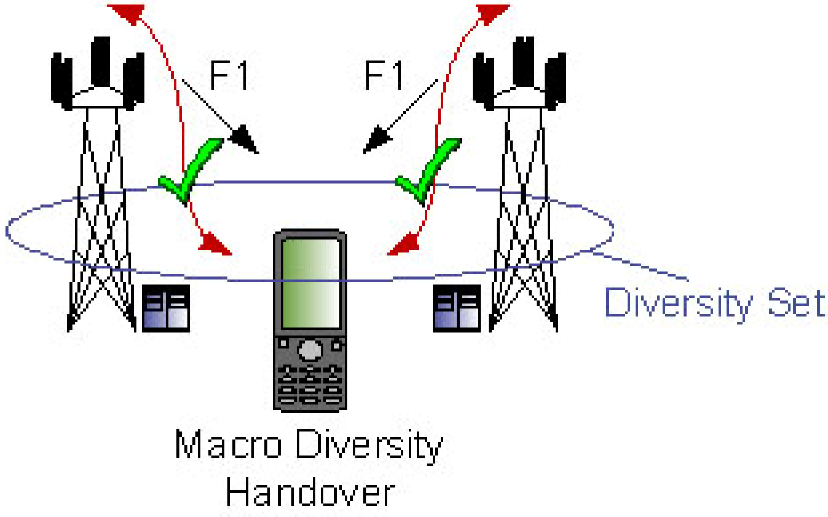

Figure 8: Active Set in MDHO scheme.

3.6 Special Issues

Since Mobile WiMAX can work in a wide range of frequency bands and each country has its own regulatory laws regarding the available spectrum, the WiMAX Forum has a WiMAX Spectrum and Regulatory Database[9]. This database gives updated information of the regulatory situation in each country and also provides the regulatory contact in each country. The table 7 sums up the situation of two countries from the trial version of the database.

Recently we are experiencing the roll-out from analog Television Broadcasting services to digital TV Broadcasting services. The analog TV occupies a large portion of the Sub-GHz spectrum. With this roll-out most of this spectrum will become available for alternative services, known as the Digital Dividend. Since the World Radio Conference (WRC-07) found suitable for IMT services a portion of this spectrum and due to the fact that WiMAX is an IMT technology, it is in position to claim this spectrum for its use. The spectrum in question, with regional differences, spans the range between 470 MHz and 862 MHz, commonly referred to as the 700 MHz Band[20].

As already stated, when the working frequency decreases the effective range of the link increases. The communication experiences less path loss, better RF obstacle penetration and lower Doppler shift. This is a remarkable benefit for Mobile WiMAX communications and allows long range links with high data throughput. It could allow more Vibrator Groups linked to the Recording Truck with a range farther than 10 km and services like surveillance cameras could be implemented, making the investment worth it.

[9] WiMAX Forum Spectrum and Regulatory Database - Trial Version LINK

Table 7 shows the regulatory situation of Egypt and Brazil, two countries which climate and environmental conditions can be very similar to the target country where the survey is to be done.

Country		Egypt
WiMAX frequency bands allowed		3.5 GHz & 5.8 GHz
Last Update		July 2006
Other Bands under study		2.3 GHz & 2.5 GHz
3.5 GHz Frequency Band	Frequencies	3400 – 3600 MHz
	Guard Bands	No restrictions
	Channelization	No restrictions
	Max. Output Power	No restrictions
	Mobile/Nomadic/Fixed uses and primary/secondary uses	Fixed primary Nomadic considered as Fixed
	Duplex Modes	No restrictions
	Usage restrictions	Licensed Band
5.8 GHz Frequency Band	Frequencies	5725 – 5850 MHz
	Guard Bands	No restrictions
	Channelization	No restrictions
	Max. Output Power	No restrictions
	Mobile/Nomadic/Fixed uses and primary/secondary uses	Mobile/Nomadic/Fixed Secondary
	Duplex Modes	No restrictions
	Usage restrictions	Unlicensed Band
Country		**Brazil**
WiMAX frequency bands allowed		2.5 GHz, 3.5 GHz & 5.8 GHz
Last Update		July 2006
2.5 GHz Frequency Band	Frequencies	2500 – 2690 MHz
	Guard Bands	Guard Bands needed
	Channelization	6 MHz (2500-2680) & 5 MHz (2500-2690)
	Max. Output Power	Not Relevant
	Mobile/Nomadic/Fixed uses and primary/secondary uses	Fixed primary. Nomadic considered as fixed. Mobile not allowed.
	Duplex Modes	FDD & TDD
	Usage restrictions	Licensed Band
3.5 GHz Frequency Band	Frequencies	3400 – 3600 MHz
	Guard Bands	Guard Bands needed
	Channelization	0.25 MHz blocks
	Max. Output Power	Max. power delivered to antenna: 3 dBW
	Mobile/Nomadic/Fixed uses and primary/secondary uses	Fixed primary. Nomadic considered as fixed. Mobile not allowed.
	Duplex Modes	TDD & FDD (duplex distance 100 MHz).
	Usage restrictions	Licensed Band
5.8 GHz Frequency Band	Frequencies	5725 – 5850 MHz
	Guard Bands	No restrictions
	Channelization	Minimum 6 dB channel bandwidth: 0.5 MHz
	Max. Output Power	Maximum output power: 0 dBW (with maximum antenna gain: 6 dBi). Power density shall not exceed 8 dBm in any 3 KHz band.
	Mobile/Nomadic/Fixed uses and primary/secondary uses	Fixed and Mobile secondary.
	Duplex Modes	TDD and FDD (no duplex distance restriction).
	Usage restrictions	Unlicensed Band

Table 7: Regulatory situation in Egypt and Brazil.

3.7 Preliminary Architecture

Lately the Telsima Corporation has developed and implemented a Sub-GHz Mobile WiMAX solution capable of delivering high data rates at a very long range[10]. Its highlighted feature is:

- o Telsima's 450 MHz solution successfully supported a 64 QAM modulation in the DL and a 16 QAM in the UL at a 50 km distance with NLOS environment.

The features of the Telsima Sub-GHz solution go farther than our needs but we have to keep a close eye on the development of solutions like this because maybe in a mid-term it could be interesting to deploy a Mobile WiMAX Sub-GHz system.

The preliminary suggested architecture is quite simple, we will equip the Recording Truck with a Base Station able to provide:

- o Coverage in NLOS environments at more than 10 km.
    - More than the required UL data bandwidth (1 Mbps of raw data).
    - More than the required DL data bandwidth (100 Kbps of raw data).
- o Enough capacity to link more than four Vibrator Groups at the same time.

Each Head Vibrator Group is going to be equipped with a Mobile WiMAX Subscriber Station.

The desirable working frequency band should be 2.3 GHz or 2.5 GHz due to its better propagation compared to higher frequency bands, but this will be subjected to the Regulatory Spectrum situation in the target country.

3.8 Equipment and prices

PosData is one of the first companies to receive Mobile WiMAX Certification from the WiMAX Forum. Their products will serve us as an example of BS and SS.

Flyvo RAS 6000 Series[11]. Main Features:

Feature	Value
Frequency	2.3 GHz, 2.5 GHz or 3.5GHz
Capacity	Up to 3 Carriers / Sector & Up to 3 Sectors / RAS
Channel Bandwidth	5 MHz, 8.75 MHz or 10 MHz
Transmitting Power	20 W / Sector or 8W / Sector
Price	60.000 $

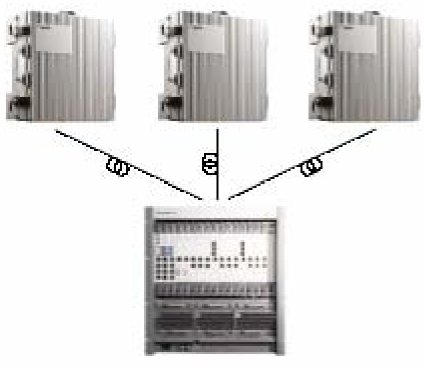

Table 8: Flyvo RAS 6000 Series features.

[10] *Telsima's Sub-GHz WiMAX™ system demonstrates a 50km (30mile) high capacity broadband Internet connection at 450MHz* LINK

[11] Flyvo RAS 6000 Series LINK

Flyvo USB Modem U100[12]. Main Features:

Feature	Value
Frequency	2.3 GHz (U100), 2.5 GHz(U101)
Channel Bandwidth	5 MHz, 8.75 MHz or 10 MHz
Max.Data Rate	DL: 18.432 Mbps, UL: 6.144 Mbps
Transmitting Power	Max 23dBm(200mW) / Min:-50dBm
Price	150 $

Table 9: Flyvo USB Modem U100 features.

To learn more about Mobile WiMAX systems I wrote several e-mails to relevant telecommunications companies. PosData did reply the questions regarding Flyvo equipment.

The scenario described to PosData was as follows:

- Cell Radius: 10 km.
- Up-Link Data Rate: 1 Mbps.
- Number of Mobile Stations: 10.
- Vehicular Speed of Mobile Stations: 10 kmph.
- NLOS environment.

In conversations with Mr. Tae Wom Ham, senior manager of PosData, he stated:

- In a rural NLOS environment the “conservative” Cell Radius shall be 5 – 6 km. Up to 9 km can be granted if clear LOS environment is provided.
- Up-Link Data Rate of 1 Mbps can be achieved but they should send the data sequentially because otherwise the overall UL bandwidth won’t be enough to handle the simultaneous traffic.
- Directional antennas should improve the coverage.

[12] Flyvo USB Modem U100 LINK

4 iBurst

4.1 Introduction

In 1997 ArrayComm started to develop the High Capacity SDMA standard, also known as iBurst, designed to provide affordable mobile broadband wireless Internet access to all subscribers anytime, anywhere. Nowadays with Kyocera as the leading vendor of equipment, HC-SDMA is being deployed in many countries, Norway is among them. By the hand of iBand AS, the city of Oslo has one of the first iBurst networks worldwide.

4.2 Standard

HC-SDMA standard:
Called High Capacity Spatial Division Multiple Access (HC-SDMA) radio interface standard (*ATIS-0700004-2005*) for wireless wideband access by the Alliance for Telecommunications Industry Solutions, it was finally ratified in 2005. It uses TDD with Time Division Multiple Access (TDMA) combined with SDMA and based on the Internet Protocol (IP) allowing transparent end to end transport of user data from any IP capable application by seamless interface with wired and backhaul IP network.

4.3 Main Features

The following table summarizes the main features of the iBurst System implemented by Kyocera.

Feature	iBurst
Frequency Bands	1.8 GHz, 1.9 GHz & 2.3 GHz
Channel Bandwidth	5/8 MHz per carrier
Physical Layer	TDMA, Time Division Duplex
Downlink Data Rate	Max. 1.061 Mbps on 24QAM
Uplink Data Rate	Max. 346 kbps on 16QAM
Max. vehicular speed	100 kmph
Handoffs	Yes
Antenna Technologies supported	Adaptive Array Antenna, SDMA
Range	Up to 12.75 km

Table 10: Kyocera's iBurst main features.

The iBurst system works with up to eight 625 kHz carriers in a 5 MHz block of spectrum. With a TDMA/TDD frame length of 5ms, there are 3 UL slots followed by 3 DL slots. But the uplink time slot length is half the DL slot length leading to an asymmetrical TDD frame.
The following picture shows the TDMA/TDD frame with the highest modulations achievable in iBurts, 24QAM for the DL and 16QAM for the UL.
Each DL slot has 353 kbps of capacity while each UL slot has 115 kbps of capacity, which means that if all the slots are allocated to a single user the maximum data rate achievable would be as stated in table 10.

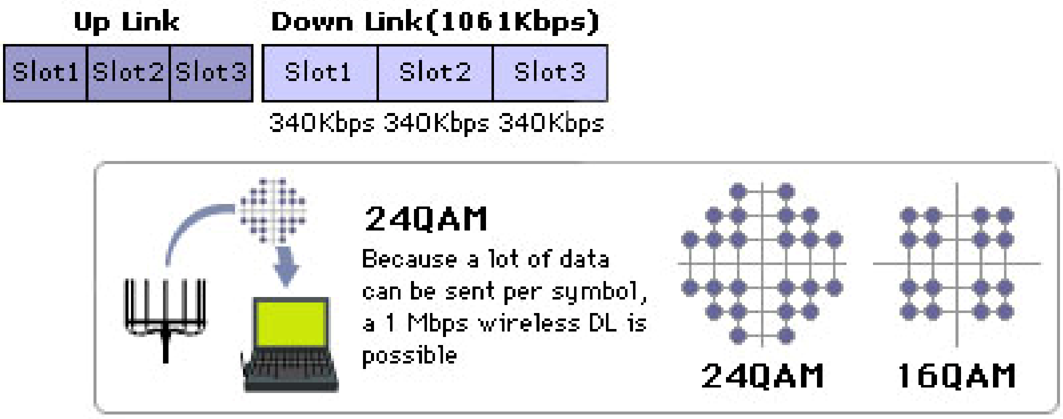

Figure 9: TDMA/TDD Frame.

The iBurst Base Station has an array of 12 antennas to take advantage of an intense use of Adaptive Array Antenna (AAA) and SDMA.
The main characteristics of AAA technology are:

- It enables the base station to concentrate terminal radio signal.
- It mitigates the interference by making null points in the direction of undesired signals.

This allows focusing the transmission power on the subscriber station in real time, while mutual interference from neighboring base stations is suppressed.

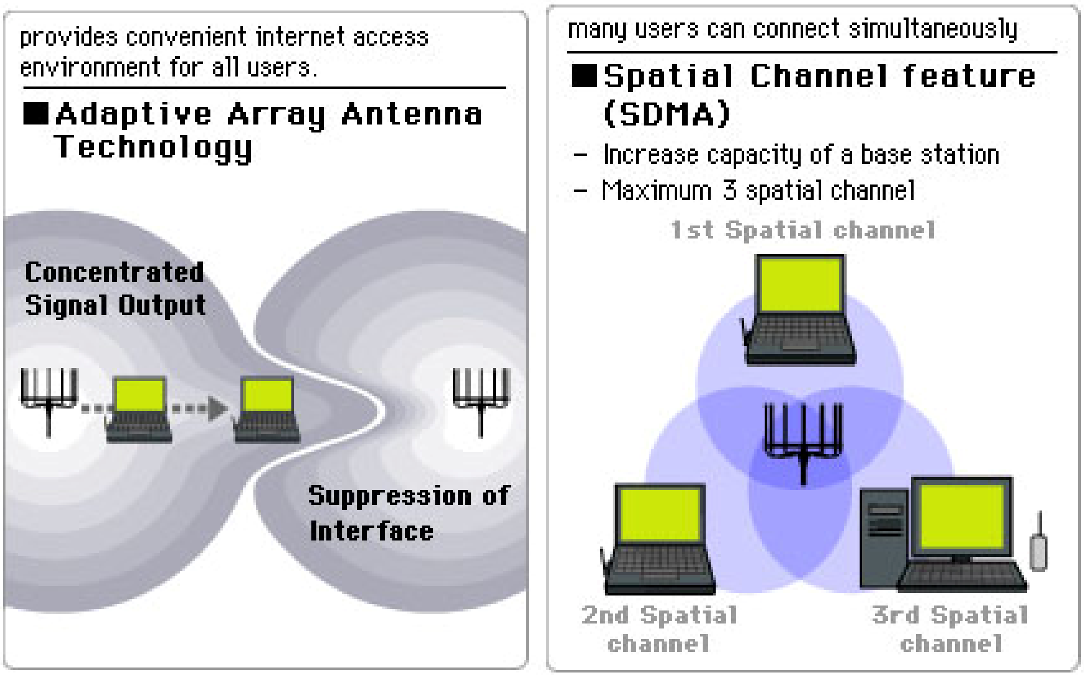

Figure 10: Adaptive Array Antenna and SDMA.

On the other hand, SDMA allows using the same spectrum more than once by multiplexing user signals based on spatial signatures. When used in conjunction with AAA, each Subscriber Station will be able to remove interference and maintain desired signal level. As a result communication over the same carrier and time slot is possible. With the 12 antenna array up to 3 spatial channels can be used.

Taking this into account iBurst is able to handle up to 72 data streams in both DL and UL:

- 8 carriers per 5 MHz.
- 3 time slots per carrier.
- 3 spatial channels per carrier.

Since one of the carriers in one spatial channel is used as control channel the maximum number of simultaneous data streams becomes 69: ($7 carriers \times 3 time\_slots \times 3 spatial\_channels + 3 time\_slots \times 2 spatial\_channels$).

4.4 Special Issues

Although the characteristics of iBurst at first glance seem not to fit with the wireless communication we are looking for, Kyocera announced last April that they will improve iBurst to meet higher data rates and ranges[13].
By the fourth quarter of 2009 Kyocera's BS and SS will be able to reach 4 Mbps in the DL and 1.384 Mbps in the UL. The throughput of the BS will also be increased to support up to 32 Mbps with 5 MHz block and 64 Mbps with 10 MHz block just for the DL. Support for 700 MHz frequency working band will also be added.
In other words, it provides an increased spectral efficiency and more users per BS with less propagation loss.

4.5 Preliminary Architecture

Just as the Mobile WiMAX case, the architecture of the system is quite simple:

- The Recording Truck will hold the Base Station.
- Each Head of the Vibrator Groups is going to be equipped with a CPE.

If we allocate the whole three UL slots in each frame for a Vibrator Group we can only reach an UL data rate of 346 kbps. As Asymmetric DSL does with the spectrum, the DL frame is bigger than the UL frame due to a commercial interest.
If we are able to use two of the three DL time slots for uplink purpose we will be able to reach 1 Mbps for the UL and 353 kbps in the DL making it suitable for our communication. In that way we could provide communication to 21 Vibrator Groups without using the spatial channels assigned to the control carrier.

4.6 Equipment and prices

Kyocera is the main vendor of iBurst equipment. That is why we are going to use its products as a reference for our architecture.

iBurst Base Station[14]. Main features:

[13] *KYOCERA Enhances iBurst® 3.9G Mobile Broadband Technology* LINK
[14] Kyocera's iBurst Base Station LINK

Feature	Value
Frequency	1.79 GHZ, 1.91 GHZ & 2.31 GHz
Channel Bandwidth	5 MHz
Max.Data Rate	DL: 1061 kbps, UL: 346 kbps
Transmitting Power	Max: 38 dBm/user
Environmental conditions	Operable within -20 ºC to 50 ºC
Price	97.875 $

Table 11: Kyocera's iBurst Base Station. Main Features.

iBurst PCMCIA card Modem[15]. Main Features:

Feature	Value
Frequency	1.79 GHZ, 1.91 GHZ & 2.31 GHz
Channel Bandwidth	5 MHz
Max.Data Rate	DL: 1061 kbps, UL: 346 kbps
Transmitting Power	Max: 20 dBm (100 mW)
Price	100 $

Table 12: Kyocera's iBurst PCMCIA card Modem. Main Features.

To learn more about Kyocera's iBurst Systems I wrote an e-mail to Kyocera Corporation. Mister Takayuki Kimura replied my e-mail and told me that the DL time slots can not be turned into UL time slots.

[15] Kyocera's iBurst PCMCIA card Modem LINK

5 Mid-Long Term Solutions: IEEE 802.20

5.1 Introduction

In March 2002, the Mobile Broadband Wireless Access (MBWA) Study Group was formed within the IEEE 802.16 committee to determine the interest and feasibility of a new broadband wireless standard. The conclusion of the study was that 802.16 and MBWA addressed the interest of two different markets, and thus the IEEE 802.20 working group was created.

The aim of the IEEE 802.20 MBWA, also known as MobileFi, is to reach the area coverage of a mobile phone system with truly high speed mobility and high data bandwidths.

Its purpose is to fill the gap between cellular networks (low bandwidth and high mobility) and other IEEE 802 wireless networks (high bandwidth and low mobility).

5.2 Main Features

The initial draft of the IEEE 802.20 has already been released allowing us to make a survey of its initial features. It follows five main criteria: broad market potential, compatibility, distinct identity, technical feasibility and economic feasibility.

Table 13 summarizes the IEEE 802.20 features specified in the first draft.

Feature		IEEE 802.20	
Frequency Bands		Below 3.5 GHz	
Channel Bandwidth		1.25 MHz & 5 MHz	
Physical Layer		OFDM, TDD or FDD	
Supported Modulations		QPSK, 8 QAM, 16 QAM & 64 QAM	
Down-Link	Channel Bandwidth	1.25 MHz	5 MHz
	Max. Data Rates	> 1 Mbps	> 4 Mbps
Up-Link	Channel Bandwidth	1.25 MHz	5 MHz
	Max. Data Rates	> 300 kbps	> 1.2 Mbps
Max. vehicular speed		Up to 250 kmph	
Handoffs		Intersector & Intercell soft handoff	
Antenna Technologies supported		Adaptive Array Antennas	
Range		Aprox. 35 km	

Table 13: Main Features of IEEE 802.20.

5.3 Comparison with IEEE 802.16e

Table 14 highlights some of the main characteristics of 802.20 and 802.16e. One of the key advantages of 802.20 is that it has been designed from zero up to a fully mobile system without the constraints of maintaining backwards compatibility, as in the case of 802.16e. That is the main feature of 802.20: it is optimized for wireless broadband data mobility.

	IEEE 802.20	IEEE 802.16e
Mobility	Fully mobile, high throughput data user	Mobile high data rate user
Data pattern	Symmetric data services	Symmetric data services
Services	Support of low latency data services	Support of low latency data services and real time voice services
Roaming	Global mobility and roaming support	Local/Regional mobility and roaming support
MAC/PHY	New PHY and MAC optimized for packet data and adaptive antennas	Extensions to 802.16a MAC and PHY
Technology	Technology is optimized for full mobility	Technology is optimized for and backwards compatibility with fixed stations
Bands	Licensed bands below 3.5 GHz	Licensed bands, 2 GHz – 6 GHz
Channel Bandwidth	BW ≤ 5 MHz	BW ≥ 5 MHz

Table 14: Relationship between 802.20 and 802.16e.

As shown on the chart, 802.20 shares many features with his brother 802.16e. This is not strange since it was originally gestated inside the 802.16 WG.

5.4 Future

The IEEE 802.20 standard is very ambitious in its purpose. It wants to provide users with high bandwidth, low latency, always on Internet service at home that also has the capability to be mobile. To achieve that, it has been build from the ground and does not have to pay the price of being backwards compatible. But this advantage can also be one of its weaknesses. Companies and users that already have invested money in 802.16e equipment probably do not want to throw their money away buying new equipment instead of upgrading it (from 802.16d to 802.16e).
Although it can provide significant benefits to mobile-centric business like the governmental ones (Police, Firemen, Emergency Services) its similarities with 802.16e would likely make the both end up competing with the actual last mile solutions (DSL, Cable). Maybe because when 802.20 was born as a working group the aim of 802.16 was different of what it has become now with the 802.16e amendment.

6 Mid-Long Term Solutions: 3GPP LTE

6.1 Introduction

LTE or Long-Term Evolution is the response of the Third Generation Partnership Project (3GPP) for the IEEE 802.16 standard in order to keep 3GPP's Universal Mobile Telecommunications System (UMTS) at the forefront of mobile wireless. Its study phase began late in 2004 and its key project objectives were set in the following areas: peak data throughput, spectral efficiency, flexible channel bandwidths, low latency, device complexity and overall system cost. One of the conclusions of the study phase was that the project objectives could not be achieved by continuing to evolve the existing W-CDMA air interface so they adopted OFDM instead. As a result, the LTE radio access network is based on a completely new OFDM air interface.

6.2 Main Features

OFDM has two big problems when compared with single carrier based systems. These problems have led 3GPP to choose a different modulation format for the LTE uplink named Single Carrier Frequency Division Multiple Access (SC-FDMA).
Table 15 shows the highlights of the LTE objectives.

Feature		3GPP LTE		
Frequency Bands		0.8 GHz, 1.5 GHz, 1.9 GHz, 2.3 GHz & 2.5 GHz		
Channel Bandwidth		1.4 MHz, 3 MHz, 5 MHz, 10 MHz, 15 MHz & 20 MHz		
Physical Layer	Down-Link	OFDM, TDD or FDD		
	Up-Link	SC-FDMA, TDD or FDD		
Supported Modulations		QPSK, 16 QAM & 64 QAM		
Down-Link 20 MHz Channel BW	Antenna	SiSo	2x2 MIMO	4x4 MIMO
	Max. Data Rates	100 Mbps	172.8 Mbps	326.4 Mbps
Up-Link 20 MHz Channel BW	Single antenna	QPSK	16 QAM	64 QAM
	Max. Data Rates	50 Mbps	57.6 Mbps	86.4 Mbps
Vehicular speed	Optimized	0 – 15 kmph		
	High Performance	15 – 120 kmph		
	Functional	120 – 350 kmph		
	Under Consideration	350 – 500 kmph		
Handoffs		Intersector & Intercell soft handoff		
Services		Packet-switched voice and data. No circuit-switched services supported		
Antenna Technologies supported		MIMO		
Range		30 km		

Table 15: 3GPP LTE. Main Features.

6.3 Future

As shown in picture 11 the first test of LTE will be later this year, expecting to have a commercial release some time during 2010.

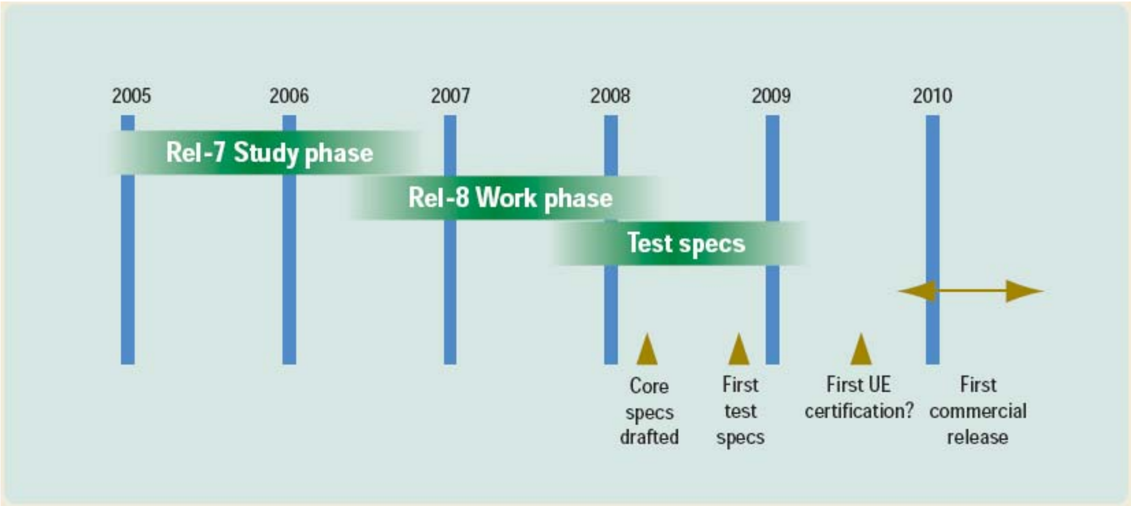

Figure 11: LTE Timing Line[25].

7 Conclusions: Part One

The following chart summarizes the most important aspects of the available technologies we have seen so far.

Technology	802.11g / Wi-Fi	802.16e / Mobile WiMAX	HC-SDMA / iBurst	802.20	3GPP LTE
Frequency Band	2.4 GHz	2.3 GHz & 2.5 GHz	1.8 GHz, 1.9 GHz & 2.3 GHz	≤ 2.5 GHz	≤ 2.5 GHz
Channel Bandwidth	20 MHz	5 MHz, 7 MHz, 8.75 MHz & 10 MHz	5 MHz	1.25 MHz & 5 MHz	1.4 MHz, 3 MHz, 5 MHz, 10 MHz, 15 MHz & 20 MHz
Physical Layer	OFDM, CSMA/CA	SOFDMA, TDD	TDMA, TDD	OFDM, TDD or FDD	TDD or FDD
Max. Down-Link Data Rate	54 Mbps	31.68 Mbps	1.061 Mbps	> 4 Mbps	OFDM 326.4 Mbps
Max. Up-Link Data Rate	54 Mbps	23.52 Mbps	346 kbps	> 1.2 Mbps	SC-FDMA 86.4 Mbps
Max. Vehicular Speed	Walking Human Speed	120 kmph	100 kmph	250 kmph	350 kmph
MAC Layer	Best Effort Service. Unsuitable for Low latency requirements	QoS oriented → Low latency services	Low latency in short cell radius	QoS oriented → Low latency services	QoS oriented → Low latency services
Antenna Technologies	Antennas can be added to improve diversity	Beamforming, STC & MIMO	Adaptive Array Antennas	Adaptive Array Antennas	MIMO
Range	140 m	50 km	12.75 km	35 km	30 km
Architecture Complexity	Complex. Recording Truck (BS), Repeaters & Vibrator Groups (SS)	Simple. Recording Truck (BS) & Vibrator Groups (SS)	Simple. Recording Truck (BS) & Vibrator Groups (SS)	Simple. Recording Truck (BS) & Vibrator Groups (SS)	Simple. Recording Truck (BS) & Vibrator Groups (SS)
Maturity	11 years since first Standard. Very Mature.	7 years since first Standard, First Certified Products 2008	3 years since Standard ratification. Developed 11 years ago	Not yet mature	Not yet mature
Price	Very Cheap	Expensive	Very Expensive	N/A	N/A
Special Conditions to meet the requirements?	Yes. Use of specialized antennas, repeaters. Vehicular Speed limited.	Yes. Use of specialized antennas.	Yes. Use more than one frequency carrier per user.	N/A	N/A

Table 16: Comparison of the presented wireless technologies.

Shown in table 16 are the most important aspects to take into account considering the scenario we are dealing with.

- o Frequency Band: To improve the coverage area the desirable frequency band should be as low as possible.
- o Channel Bandwidth: Should be as low as possible to concentrate the power in a narrower spectrum in order to increasethe effective range.
- o Physical Layer: There is no doubt that the best choice is OFDM, and that is why most technologies use it. OFDM is resistant to the damaging effects of multipath delay spread in the radio channel, or in other words is resistant against Inter-Symbol Interference (ISI).
- o Down-Link Data Rates: All of the technologies presented are Asymmetric, and the Down-Link is the one with higher data rates. It is reasonable since most of users need more Down-Link data bandwidth than Up-Link. The required 100 kbps Down-Link will be granted.
- o Up-Link Data Rates: Probably just Mobile WiMAX can grant 1 Mbps of speed. Although Wi-Fi and iBurst can address 1 Mbps, the first needs special conditions like low number of repeaters, and the second one will need a re-allocation of the time slots in order to reach 1 Mbps.
- o Vehicular Speed: The speed of the Vibrators Group should be as low as possible. Although most of technologies claim to support high vehicular speeds, the Doppler Effect will cause the Data Rates to drop as the speed increases.
- o MAC Layer: If the application requires low latencies for the Recording Truck to store the data correctly, then a QoS oriented Mac should fit well. Best Effort should be avoided.
- o Antennas Technology: Most of technologies cited above intend to reduce the interference caused by other users or base stations to our transmission. It is less relevant in desert areas, if no other RF interferences are present.
- o Range: In theory, just Wi-Fi will need the repeaters to increase its range.
- o Architecture Complexity: Because of its short range just Wi-Fi will present complex system architecture. A good placing plan for the repeaters has to be devised.
- o Maturity: Once again Wi-Fi is the most mature technology. The rest of them are just being deployed or expected to be in the near future.
- o Price: The Wi-Fi equipment is inexpensive in comparison to the Mobile WiMAX or iBurst.

Probably the most suitable option for the WesternGeco application should be Mobile WiMAX, even though at first glance it is a highly expensive solution. With the cost of a single Flyvo Base Station, two engineers can be paid nearly a whole year to reach a solution based in Wi-Fi.
Still the recent Mobile WiMAX Certified equipment is aimed to telecommunications companies willing to serve many users per BS. With little time and popularity, the hardware prices will decrease.

In the end, the suggested solution will be Wi-Fi or Mobile WiMAX. Table 17 will help us to make a decision.

Comparison criteria		802.11g / Wi-Fi	802.16e / Mobile WiMAX	Best Suited
Frequency band		2.4 GHz (ISM Band) Unlicensed Worldwide	2.3 GHZ & 2.5 GHz Licensed	802.11g
Price		Low price equipment < 1000 $	Very expensive equipment > 50.000 $	802.11g
Maturity		Mature technology widely proven	Trial deployments phase	802.11g
Availability		> 1000 Certified products	< 50 Certified products	802.11g
Architecture Complexity		Complex. Recording Truck (BS), Repeaters & Vibrator Groups (SS)	Simple. Recording Truck (BS) & Vibrator Groups (SS)	802.16e
Technical Features	PHY	Shared medium access (CSMA/CA)	TDD Duplex access	802.16e
		OFDM	SOFDMA	-
	Range	140 m	50 km	802.16e
	MAC	CSMA/CA Best Effort	QoS oriented	802.16e
		Hard Handoff ≈ 500 ms	Hard and soft Handoff ≈ 50 ms	802.16e

Table 17: 802.11g and 802.16e Comparison.

The technical features and the complexity of the system architecture clearly favor the use of Mobile WiMAX:

- The access method used in 802.11g does not allow full duplex communication. Although it will not be usual, the recording truck might also need to send data to the vibrator groups.
- The range of a normal 802.11g link is much shorter than the Mobile WiMAX and thus repeaters may be needed.
- The MAC layer of 802.11g is not the best one for low latency applications.

On the other hand, a solution based on 802.11g has the following benefits:

- The working frequency band of 802.11g requires no license acquisition. This greatly simplifies the deployment of the survey team worldwide. Still each country has its own regulations that must be followed.
- The price of the equipment is low. This is not only important because of its economical impact but also because it reduces the consequence of buying wrong equipment and allows buying equipment for testing purposes.
- The maturity state of the technology. It is a very mature technology and has been widely proven. This grants a high level of reliability difficult to reach with younger technologies.
- The availability. As a direct consequence of the maturity it is a technology available worldwide.

The intention of WesternGeco is to deploy the new wireless communication mechanism by the end of the year 2008, which might be too early to allow Mobile WiMAX to get mature and lower the equipment prices.

Considering all these facts the chosen technology is IEEE 802.11g.

8 Presenting the Solution

8.1 Introduction

In the conclusions of the previous chapter we finally chose 802.11g / WiFi as the best suited technology to use for the wireless communication mechanism WesternGeco needs.

Once the decision is taken and 802.11g is the platform for the solution the next step is to re-take the early system architecture. It consisted of four Wi-Fi CPE installed in the Recording Truck, four high gain directional antennas plugged to them, several repeaters deployed in the field and in each Head Vibrator another CPE with a high gain omnidirectional antenna. I chose this setup because I made the hypothesis to work only with four Vibrator Groups per Recording Truck.

8.2 The Repeaters

A key component of the system is the repeater. There are two main types of repeaters:

1. Physical Layer Repeater: This type of repeater regenerates and repeats each packet they receive in real time. The next figure shows the diagram structure of a physical repeater. It mainly consists of two RF emitter/receiver, two frequency mixers, four amplifiers and three filters. The two mixers allow changing the frequency in order to receive the signal in one channel and retransmit it in another to avoid interferences between them.

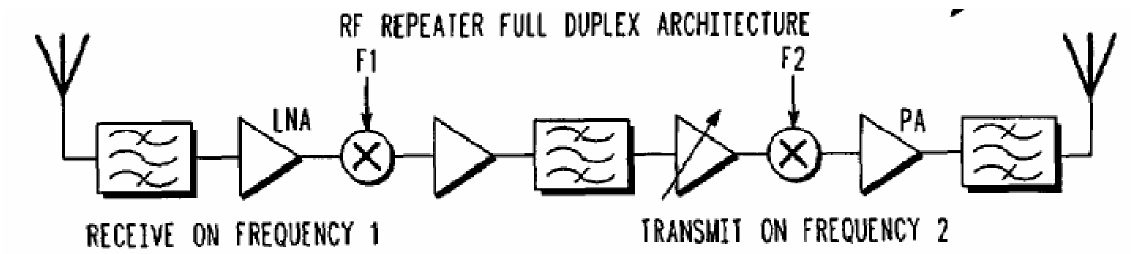

Figure 12: PHY Repeater.

2. MAC Layer Repeater: This type of repeater regenerates and repeats each packet they receive after processing it. The next figure shows the diagram structure of a MAC repeater. It only uses one RF emitter/receiver, thus only needs one free channel to function. It first receives data, stores it in a buffer and re-sends it afterwards. The ones referred in section 2.7 were MAC Layer repeaters

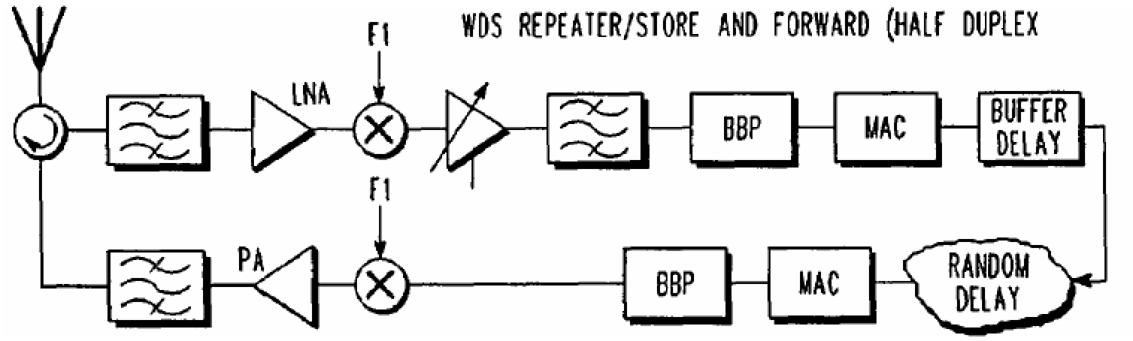

Figure 13: MAC Repeater, also known as Wireless Distribution System (WDS).

The use of one type or another depends on the needs a certain network has. Each of them has its own advantages and disadvantages; they are summarized in the following table.

	PHY Repeater	MAC Repeater
Advantages	- Maintains full throughput of the wireless network. - Preserves wireless protocols.	- In a Mesh Network can help address each packet to the correct receiver. - Only needs one channel to function.
Disadvantages	- Needs two free non-power overlapping channels to function. - When several repeaters are placed to serve a client, delays due to cascaded repeating can cause packet acknowledgements to be delayed. - ACK delays can imply the need of retransmission of the packet.	- Throughput reduction greater than 50%. - Security features can be compromised.

Table 18: Repeater's Advantages and Disadvantages.

8.3 Introducing the equipment

As for the rest of the equipment I searched further for 802.11g equipment and finally found a company specialized in long range wireless solutions. Their products will be used to do the practical approach of the suggested solution.

As they define themselves: "*NETKROM TECHNOLOGIES is a designer, developer and manufacturer of communications equipment antennas and accessories for wireless networking in licensed free radio frequency bands (900MHz, 2.4, 5.2 and 5.8 GHz), licensed Frequency Band (2.3 to 2.7GHz and 3.4 to 3.6GHz) and Public Safety Band (4.9GHz).*

The core technology behind NETKROM's products is revolutionary low-cost Wi-Fi and WiMAX technology. Because NETKROM TECHNOLOGIES use popular licensed and unlicensed frequencies, they cost less to install and maintain.[16]"

[16] Netkrom Technologies LINK

The following specifications sum up the main features of the equipment that can be used in the solution. This knowledge will be helpful when defining the architecture's characteristics.

AIRNET 2.4GHz / 5GHz 54Mb Outdoor AP/Bridge[17]. Order name: AIR-BR500GUHP.
This Access Point is intended to be installed in the Head Vibrator, but can also be installed in the Recording Truck. It is housed in a NEMA6/IP67 waterproof casing, and can work in severe environmental conditions (-30ºC ~ 70ºC). Probably the most remarkable features are the output power it can achieve (1 Watt) and the possibility to modify some CSMA/CA parameters for long range purposes.

Feature	Value
Frequency	2.400 GHz ~ 2.497 GHz (Progammable)
RF output Power	30 dBm (1 Watt)
RF Modulation	OFDM (BPSK,QPSK, 16-QAM, 64-QAM)
Sensitivity	-90dBm@6Mbps -70dBm@54Mbps
Range	50 km with 24dBi antenna
Price	399.00 $

Table 19: AIR-BR500GUHP

ISPAIR Multi-Band Base Station 500 Series[18]. Order Name: ISP-BS500AGUHP.
This BS is intended to be installed in the Recording Truck. It has an industrial die-cast thermal aluminum (NEMA-6/IP-67) enclosure to assure its proper function in extreme environmental conditions (-60ºC ~ 230ºC). It has four high power wireless ports and a long range parameters setup.

Feature	Value
Frequency	2.400 GHz ~ 2.497 GHz (Progammable)
RF output Power	30 dBm (1 Watt) @ 24Mbps per port, 26 dBm @ 54 Mbps per port
RF Modulation	OFDM (BPSK,QPSK, 16-QAM, 64-QAM)
Sensitivity	-95dBm@1Mbps -74dBm@54Mbps
Range	32 km with 24dBi antenna
Price	1499.00$

Table 20: ISP-BS500AGUHP.

WiMAX / Wi-Fi Multi-Band Dual Radio[19]. Order name: MB-MSAGUHP.
This multi-purpose dual radio is intended to be installed in a "Mobile" Repeater. Instead of placing repeaters in the field in a fixed position, Mobile Units

[17] AIRNET 2.4GHz / 5GHz 54Mb Outdoor AP/Bridge LINK
[18] ISPAIR Multi-Band Base Station 500 Series LINK
[19] WiMAX / Wi-Fi Multi-Band Dual Radio LINK

equipped with this dual radio repeater will be deployed to overcome some RF obstacles. It has the same enclosure and operating temperature as the BS.

Feature	Value
Frequency	2.400 GHz ~ 2.497 GHz (Progammable)
RF output Power	30 dBm (1 Watt) @ 24Mbps, 25 dBm @ 54 Mbps
RF Modulation	DSSS / OFDM (BPSK,QPSK, 16-QAM, 64-QAM)
Sensitivity	-95dBm@1Mbps -74dBm@54Mbps
Range	32 km with 24dBi antenna
Latency	1 ms – 3 ms
Price	199.00$

Table 21: MB-MSAGUHP.

In the future all these equipment can be upgraded to support WiMAX and 802.11n technologies.

In the next chapters the PHY layer, the MAC layer and the channel will be discussed in order to predict the behavior of the system under long distance conditions. The last chapter will present the final architecture of the system.

9 Physical Layer: OFDM

9.1 Introduction

OFDM stands for Orthogonal Frequency Division Multiplex and is the modulation used in 802.11g. To ensure backwards compatibility with 802.11b hardware, Direct Sequence Spread Spectrum (DSSS) is also implemented in 802.11g hardware.

OFDM is a combination of modulation and multiplexing:

- Modulation: a mapping of the information on changes in the carrier phase, frequency or amplitude or combination.
- Multiplexing: method of sharing a bandwidth with other independent data channels.

The key of its success is that it divides the data rate Rb Mbps among N parallel data subcarriers, each with a lower data rate of Rb/N Mbps, spaced Δf Hz and orthogonal to each other. In classic FDM (Frequency Division Multiplexing) each carrier needs a guard band to prevent a subcarrier from interfering one. In OFDM the subcarriers are spaced closely together without any guard band because they are mathematically orthogonal as shown in the figure 14.

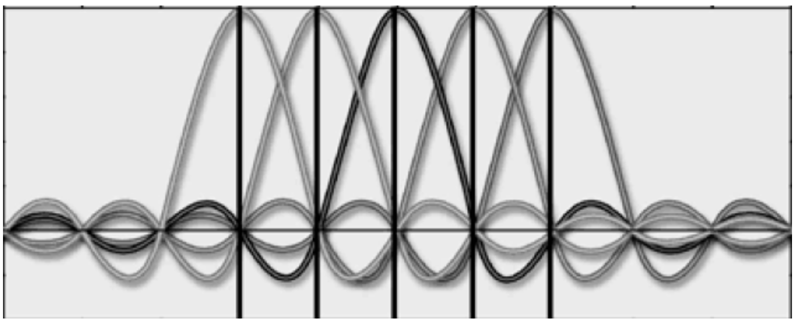

Figure 14: OFDM Subcarriers[11].

As can be seen in figure 14, at the peak of each subcarrier the other subcarriers present a null in their amplitude, allowing them to be spaced very closely and actually overlap in frequency conserving the overall bandwidth.
To achieve orthogonality the input digital bitstream is processed into a complex modulated spectrum of equally spaced but orthogonal subcarriers and then converted into a waveform that can be easily transmitted using an inverse Fourier Transformation (IFT). Since it is easier to implement a Fast Fourier Transform than a FT, the IFFT is used instead of the IFT.

9.2 OFDM Data Rates

Table 22 shows the characteristics of OFDM implemented in 802.11g.

Parameter		Value (20 MHz Channel)	Value (10 MHz Channel)	Value (5 MHz Channel)
# Data Subcarriers		48	48	48
# Pilot Subcarriers		4	4	4
# Null Subcarriers		12	12	12
Subcarrier Frequency Spacing		$\Delta_F = \frac{20MHz}{64} = 0.3125MHz$	$0.15625MHz$	$0.078125MHz$
FTT period		$\frac{1}{\Delta_F} = 3.2\mu s$	$\frac{1}{\Delta_F} = 6.4\mu s$	$\frac{1}{\Delta_F} = 12.8\mu s$
Duration of the OFDM symbol		$4\mu s$	$8\mu s$	$16\mu s$
Guard Interval duration		$0.8\mu s$	$1.6\mu s$	$3.2\mu s$
Mod.	**Code Rate**	**Data Rate**	**Data Rate**	**Data Rate**
64QAM	CTC 3/4	54 Mbps	27 Mbps	13.5 Mbps
64QAM	CTC 2/3	48 Mbps	24 Mbps	12 Mbps
16QAM	CTC 3/4	36 Mbps	18 Mbps	9 Mbps
16QAM	CTC 1/2	24 Mbps	12 Mbps	6 Mbps
QPSK1	CTC 3/4	18 Mbps	9 Mbps	4.5 Mbps
QPSK	CTC 1/2	12 Mbps	6 Mbps	3 Mbps
BPSK3	CTC 3/4	9 Mbps	4.5 Mbps	2.25 Mbps
BPSK	CTC 1/2	6 Mbps	3 Mbps	1.5 Mbps

Table 22: OFMD in 802.11g[12].

The coding used is convolutional coding concatenated with Reed Solomon. This adds Forward Error Correction (FEC) capability to the signal. The data rate is calculated as follows:

- The modulation has a certain number of information bits per symbol.
- The coding adds bits for FEC purpose. 3/4 ratio means that 3 of 4 bits sent are information or what is the same 1 of 4 bits is used for FEC.
- Each data subcarrier transports a certain amount of information.

$$\frac{1}{t_{OFDM\_Symbol}} \times \# Data\_Subcarriers \times \frac{Information\_Bits}{Symbol} \times FEC\_rate$$

Equation 1: Data Rate Calculation.

For example: In a 20 MHz Channel the OFDM symbol lasts 4 μs, we use 64-QAM modulation (6 information bits per symbol) and 3/4 FEC.

$$\frac{1}{4\mu s} \times 48 Data\_Subcarriers \times \frac{6 Information\_Bits}{Symbol} \times 3/4 = 54Mbps$$

Each subcarrier transports 1.125 Mbps. Then depending on the strength of the received signal and the sensitivity of the equipment one modulation or another will be used. Following the reasoning the maximum spectral efficiency that 802.11g can achieve is 2.7 bits per Hz (54 Mbps / 20 MHz).

10 Medium Control Access Method: CSMA/CA

10.1 Introduction

Referred in the literature as the Distributed Coordination Function (DCF), CSMA/CA stands for Carrier Sense Multiple Access with Collision Avoidance. It is the fundamental access method of the IEEE 802.11 MAC layer, and is the access method implemented in all the 802.11 stations. It is designed to reduce the collision probability between multiple stations accessing the medium. CSMA/CA is especially efficient at the point where a collision is more likely to occur: when the medium becomes idle after a busy period.

Besides DCF, the MAC layer defines two more access modes: the Point Coordination Function (PCF) and the Hybrid Coordination Function (HCF). The DCF and PCF modes are the most common.

10.2 DCF Procedure and RTS/CTS Mechanism

CSMA/CA uses several time interval definitions to grant access priority such as:

- o DIFS: DFC Inter Frame Spacing, used for normal frames.
- o PIFS: PFC Inter Frame Spacing, used to switch between DFC and PFC modes.
- o SIFS: Short Inter Frame Spacing, used for control frames.

To assure priority these time intervals fulfill DIFS > PIFS > SIFS.

When a station wants to transmit a packet applies the following procedure:

1. If the medium is idle during a time equal or greater than DIFS →Waits Random Backoff and if still idle →Transmits.
2. If the medium is busy or becomes busy during DIFS:
   2.1. Wait until the medium becomes idle.
   2.2. Wait a time equal to DIFS:
      2.2.1. If the medium becomes busy during DIFS → Returns to point 2.1.
      2.2.2. If the medium is still idle → Waits a Random Backoff Timeout.
         2.2.2.1. Once finished the Timeout if the medium is idle → Transmits.
         2.2.2.2. If the medium becomes busy during the Timeout:
            A. Stops the Timeout and waits until the medium becomes idle.
            B. Waits a time equal to DIFS:
               I. If the medium is still idle → Continues with the Timeout and if the medium becomes busy returns to A.
               II. If the medium becomes busy during DIFS → Waits until the medium becomes idle and returns to B.
3. When the packet has been successfully transmitted (complete and without errors), the receiver waits a time equal to SIFS and sends an acknowledgement (ACK) frame to the sender.
4. In case of collision the receiver will not send an ACK. In that case the sender will assume that a collision has occurred and:
   4.1. Will re-transmit the whole packet again.
   4.2. Will wait a time equal to DIFS.

4.3. Will wait a Backoff Timeout.

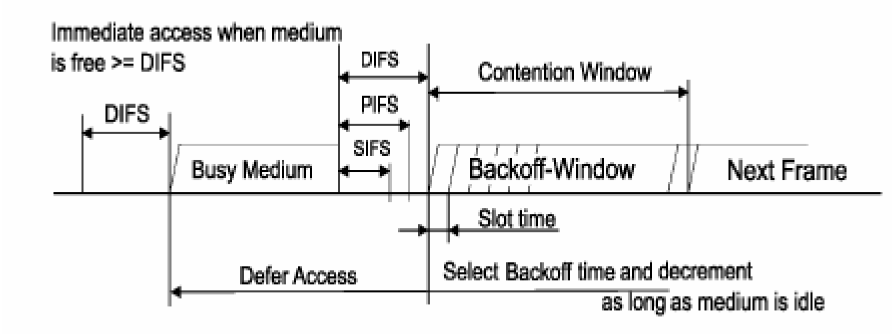

Figure 15: DFC Basic Access Method[12].

In addition to the physical medium sensing method just described, the DFC supports virtual medium sense by the exchange of Request To Send (RTS) and Clear To Send (CTS) frames. It can also distribute the Duration/ID field that sets the mean holding time within the RTS and the CTS frames. Before transmitting any data, the sender transmits a RTS frame to the receiver. The receiver must reply with a CTS frame if the transmission is permitted. Other nodes sensing the CTS frame cannot transmit during the holding time set in the Duration/ID field because they are close to the receiver. On the other hand, any node that only sees the RTS frame but not the CTS frame is free to transmit. This is because these nodes will not cause interference with the receiver. With this mechanism the problems of the hidden station and the exposed station are solved.

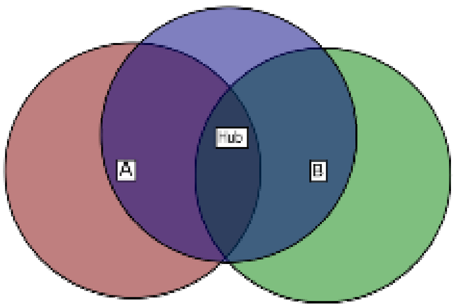

Figure 16: Hidden Node Problem: Each node can sense the hub, but they can not sense each other.

10.3 Long Range Parameters

As already discussed in section 8.3 the Netkrom equipment allows modifying some of the CSMA/CA parameters for long range purposes. The modifiable parameters in the AIR-BR500GUHP are:

- Slot Time: in CSMA/CA time is slotted and each time unit is called one Slot time
- ACK Timeout: the time allowed for the sender to receive the acknowledgment frame from the receiver. If the sender does not receive any ACK during this Timeout it will assume that an error has occurred and will attempt to re-send the packet.

- o CTS Timeout: timeout allowed for the sender of a RTS frame to receive the CTS frame. If no CTS frame is received the sender will assume the medium is busy and will wait before trying again.

This is because the AIR-BR500GUHP is based in Atheros eXtended Range (XR) chipset that allows modifying such parameters. Netkrom Technologies has also implemented a proprietary algorithm that suggests the right value for these parameters when the distance in meters is introduced. Most Access Points available in the market do not allow modifying such parameters.

I wrote an e-mail to Netkrom Technologies asking for the recommended values their algorithm display for 10 km link distance but I have not had a reply yet. The idea was to compare their values and the values I believe correct.

The final suggested solution will be based in long distance links between just two APs, one installed in the Recording Truck and another installed in the Head of a Vibrator Group. This implies that just they will fight for the medium, maximizing the net throughput. The following picture illustrates the timing in a successful transmission.

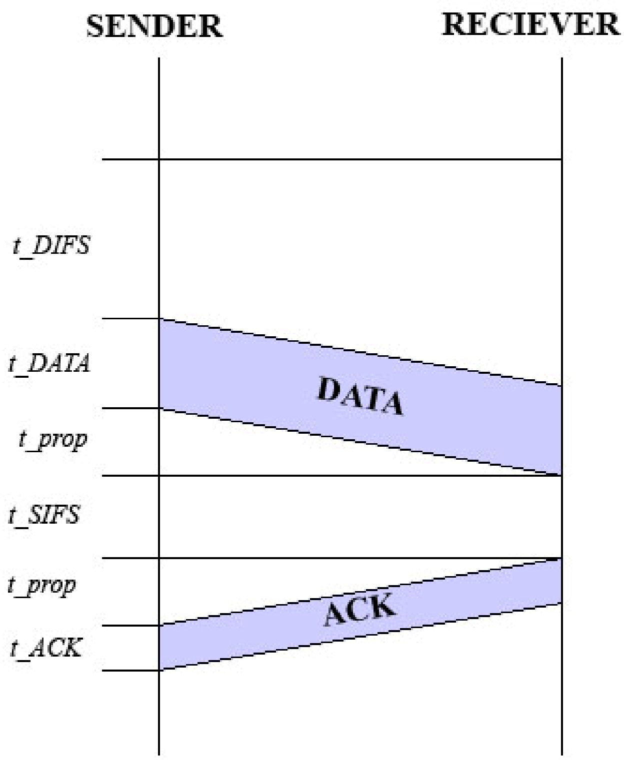

Figure 17: Timing in a successful transmission.

As was explained in the description of the CSMA/CA method and we can see now in the figure 17, once the sender has finished sending data it waits a time equal to 2 propagation times plus a SIFS time, that is the ACK Timeout. Analogically, the CTS Timeout works the same way.

The duration of the Slot Time, ACK Timeout and CTS Timeout is critical for the net Throughput of the link.
I am going to use the transmission model seen in figure 17 to illustrate the effect of the Slot Time in the net throughput of the link. Although it is a simplified model it is accurate enough for our purpose.

10.4 Throughput Calculation

In order to determine the net Throughput of the link we need to calculate the efficiency. Following the model in figure 17, the next equation determines the time needed to send a packet:

$$t_{TOTAL} = DIFS + t_{BACKOFF} + t_{prop} + t_{OFDM\_Header} + t_{TX\_DATA} + t_{Signal\_Extension} + SIFS + t_{OFDM\_Header} + t_{TX\_ACK} + t_{Signal\_Extension} + t_{prop}$$

Equation 2: Total Time needed to send a packet in the link.

With equation 2 we can know the total time that CSMA/CA needs to send a packet using only the physical medium sense method. The virtual medium sense method (RTS/CTS) is intended to be used when 802.11b users and 802.11g users are mixed in the same network. Since our link will consist only of 802.11g equipment, the virtual medium sense method will not be used and therefore equation 2 is valid.

After a station that is willing to transmit has waited DIFS it has to wait a Backoff time before attempting to occupy the medium.

The efficiency of a link is calculated as follows:

$$Efficiency(\%) = \frac{t_{DATA}}{t_{TOTAL}} \times 100$$

Equation 3: Efficiency.

Taking all this into account I am going to determine the efficiency of the link with the following conditions:

- Only 802.11g equipment. Two Access Points connected in Ad hoc mode.
- Rb = 54 Mbps, Mac Service Data Unit (MSDU) = 1500 bytes, ACK = 14 bytes.
- LOS
- No other RF interference present in the channel.
- 10 meters of link distance.

Time	Value	Notes
SIFS	10 µs	The usual value is ½ Long Slot Time (20 µs)
Fast Slot Time	9 µs	The Slot Time in 802.11g is 9 µs, but can be changed to 20 µs to preserve compatibility with 802.11b
DIFS	28 µs	2 x Slot Time + SIFS
Backoff	139.5 µs	The value depends of the Slot Time and the number of retries. 139.5 µs is the max. value for 0 retries.
Propagarion	≈ 0 µs	In very short distances its effect is negligible
OFDM header	20 µs	To preserve compatibility with 802.11b the header can be longer. When just 802.11g is present its value is 20 µs
TX_DATA	216 µs	$t_{TX\_DATA} = \frac{(MSDU + 28) \times 8}{Rb}$
DATA	212 µs	$t_{DATA} = \frac{(MSDU) \times 8}{Rb}$
Signal Extension	6 µs	Needed for convolutional decoding in every OFDM packet
TX_ACK	2 µs	$t_{TX\_ACK} = \frac{14 \times 8}{Rb}$

Table 23: Time Values.

With the values of the table 23 the total time is 437.5 µs and the time we are just sending data is 212 µs, so the efficiency is:

$$Efficiency(\%) = \frac{212 \mu s}{437.5 \mu s} \times 100 = 0.48457$$

And therefore the net Throughput of the link is 26.2 Mbps.

10.5 Throughput Calculation for a 10 km link

Retaking the early discussion about the modifiable parameters of the AIR-BR500GUHP, for a 10 km link their value should be as follows:

Time	Calculation	Value for 10 km
Round Trip Time (RTT)	$RTT = \frac{2 \times dist.}{c} = \frac{2 \times 10000m}{300\, m/\mu s}$	66.67 µs
Slot Time	$SlotTime(\mu s) = \left\lceil \frac{RTT}{2} \right\rceil + FastSlotTime + \delta$	43 µs δ = 0
SIFS	$SIFS = \left\lceil \frac{SlotTime}{2} \right\rceil$	22 µs
DIFS	$DIFS = 2 \times SlotTime + SIFS$	108 µs
ACK Timeout	$ACK_{Timeout} = \lceil RTT \rceil + SIFS$	89 µs
CTS Timeout	$CTS_{Timeout} = \lceil RTT \rceil + SIFS$	89 µs

Table 24: Highlighted the modifiable parameters for 10 km link distance.

- o RTT: Round Trip Time is the time that the signal needs to travel from the sender to the receiver and back.
- o Slot Time: The Slot Time is set in order to work according to the 802.11g standard in the distances where it is initially designed to work (up to 300 meters) plus the effects of the distance. We can also take into account that if we are in a NLOS scenario, the path for the signal may not be straight and thus the effective distance between sender and receiver can be greater. δ μs can be added to fight a relevant multipath casuistry.
- o SIFS: Used to give priority to control frames.
- o DIFS: As explained before DIFS is used to determine if the medium is idle or busy. In order to do so, its value has to be at least a RTT to function properly, and to maintain the timing priority a SIFS time is added.
- o ACK Timeout: Time that the sender will wait for an ACK frame.
- o CTS Timeout: Time that the sender will wait for a CTS frame. This time has no relevancy because the system is 802.11g only.

With these assumptions I will proceed to calculate the efficiency of the link when the distance between the nodes is 10 km under the following conditions:

- o Only 802.11g equipment. Two Access Points connected in Ad hoc mode.
- o Rb = 54 Mbps, MSDU = 1500 bytes, ACK = 14 bytes.
- o LOS, and therefore δ = 0 seconds.
- o No other RF interference present in the channel.
- o No errors occurred in the transmission of the data and reception of the ACK.
- o 10.000 meters of link distance.

Time	Value	Notes
SIFS	22 μs	The usual value is ½ Long Slot Time (20 μs)
Slot Time	43 μs	Atheros Chipset implemented in AIR-BR500GUHP allows to modify it
DIFS	108 μs	2 x Slot Time + SIFS
Backoff	666.5 μs	$t_{BACKOFF} = \frac{31}{2} \times SlotTime$ when no retry has occurred
Propagarion	33.33 μs	$t_{prop} = \frac{dist.}{c} = \frac{10000m}{300 \, m/\mu s}$
OFDM header	20 μs	To preserve compatibility with 802.11b the header can be longer. When just 802.11g is present its value is 20 μs
TX_DATA	216 μs	$t_{TX\_DATA} = \frac{(MSDU + 28) \times 8}{Rb}$
DATA	212 μs	$t_{DATA} = \frac{(MSDU) \times 8}{Rb}$
Signal Extension	6 μs	Needed for convolutional decoding in every OFDM packet
TX_ACK	2 μs	$t_{TX\_ACK} = \frac{14 \times 8}{Rb}$

Table 25: Time values for 10 km.

Recalling equation 2:

$$t_{TOTAL} = DIFS + t_{BACKOFF} + t_{prop} + t_{OFDM\_Header} + t_{TX\_DATA} + t_{Signal\_Extension} + SIFS + t_{OFDM\_Header} + t_{TX\_ACK} + t_{Signal\_Extension} + t_{prop}$$

The total time we need now to send a packet is 1111.16 μs, and thus the efficiency is:

$$Efficiency(\%) = \frac{212\mu s}{1111.16\mu s} \times 100 = 0.1908$$

Therefore the new net Throughput is 10.3 Mbps. This Throughput is greater than 1 Mbps that WesternGeco asked for, although the working conditions are likely ideal and further degradation is expected.

10.6 Considerations

We have learned how CSMA/CA works, how to calculate the net Throughput and what the values of the modifiable parameters are in order to make a long distance link. In the case that an ACK or CTS frame gets lost in the transmission the sender will wait an ACK or CTS Timeout and then re-send the packet or RTS. If this Timeout is not correctly set up it will lead to a degradation of the net Throughput, either because the sender waits too long before retrying or because it does not wait long enough. The Backoff mechanism affects the net Throughput of the 10 km link greatly, a further fine tuning of the CWmin (Contention Window) and CWmax parameters can help to improve it.

It is important to note that the net Throughput calculated applies to the MAC layer and thus higher levels will experience a lower net Throughput because of the packets encapsulation. For example, if Transmission Control Protocol (TCP) plus Internet Protocol (IP) is used as the following layers of the stack then the net Throughput will be slightly inferior to 10.3 Mbps. This is because the headers of TCP/IP will have to be included within the MSDU. Each TCP acknowledge will be embedded in the CSMA/CA acknowledgements.

11 The Channel

11.1 Introduction

In order to estimate the signal parameters for the wireless system accurately it is necessary to estimate the system's propagation characteristics through the medium. Channel modeling is required to predict the path loss and to characterize the impulse response of the propagating channel.

The path loss is a measure of the average RF attenuation suffered by a transmitted signal when it arrives at the receiver and is defined by

$$PL(dB) = 10\log\frac{P_t}{P_r}$$

Equation 4: Path Loss Definition.

where Pt is the transmitted power and Pr is the received power. To make a good estimation of the signal strength at the receiver we can use a channel path loss model.

11.2 Path Loss Models

Table 26 compares the most important of them.

Model Name	Suitable Environment	Complexity	Experimental Data	Details of Environment	Accuracy	Time
Okumura Model	Macrocell	Simple	Based on experiments	No	Good	Little
Hata Model	Macrocell (early cellular)	Simple	No	No	Good	Little
COST-231	Microcell (outdoor)	Simple	No	No	Good	Little
Dual-Slope	Microcell and picocell (LOS region)	Simple	No	No	Good	Little
Ray-Tracing	Outdoor and indoor	Complex	No	Yes	Very Good	Very Much
FDTD	Indoor (small)	Complex	No	Every Detail	Best	Very Much
MoM	Indoor (small)	Complex	No	Every Detail	Best	Very Much
ANN	Outdoor and indoor	Complex	Yes	Detail	Very Good	Little

Table 26: Comparison of the path loss models.

Considering the needs of our link in terms of distance, the complexity of the analysis required and the accuracy obtained, the Hata Model is the most suitable for predicting the path loss.

11.3 Multipath Propagation

If there is LOS the signal goes in a straight line when traveling to the receiver. As a consequence of reflection in objects, buildings or hills it can also reach the receiver from other directions. This phenomenon is called multipath propagation and has severe consequences if it is not dealt with appropriately.

A delayed copy of the signal can reach the receiver, this is called an echo. There can be two types of echoes:

- Near echoes: The echo and the signal arrive at almost the same time at the receiver. This can lead to undesired amplitude, phase or even frequency variations that are independent of the transmitted power, causing error bursts.
- Distant echoes: when the echo of the signal is received one or more symbol periods after the main signal. That results in to what is called Inter Symbol Interference (ISI). ISI is the interference caused by a delayed symbol with the current one.

The communication will mainly deal with near echoes when the distances between nodes are short, approximately 40λ meters, where λ is the wave length of the signal. Likewise in long distances communications distant echoes will appear. For a frequency of 2.4 GHz:

$$\lambda = \frac{c}{f} = \frac{3\times10^{8}\, {}^{m}\!/\!{}_{s}}{2.4\times10^{9}\,Hz} = 0.125m \rightarrow 40\lambda = 5m$$

Therefore the communication in a 10 km link will mainly be affected by distant echoes causing ISI, or in other words the communication will face a dispersive channel.

Through several measurements of the power-delay relation of the channel a Power Delay Profile (PDP) is made in order to characterize the expected degree of dispersion.
We can think of the PDP as a characterization of the mean power of the different propagation paths.

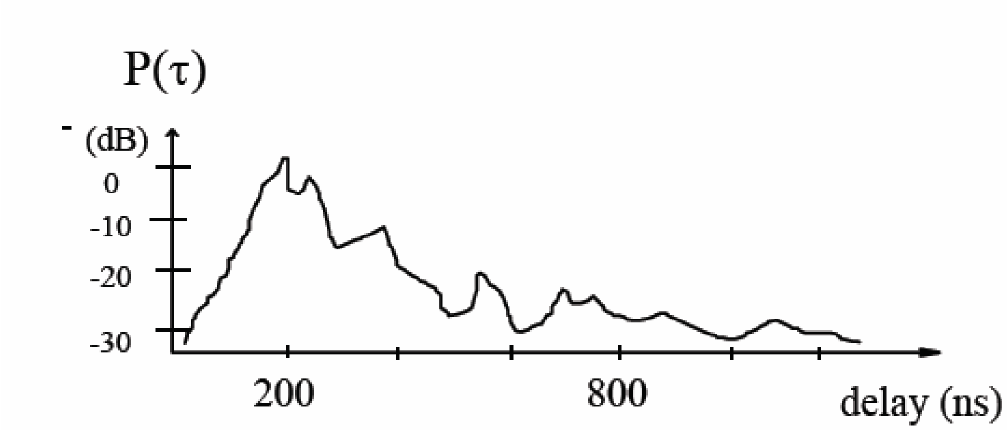

Figure 18: Typical Power Delay Profile.

From the PDP some delay parameters can be defined to precisely quantify the multipath dispersion. The most relevant are:

- Mean Excess Delay: It is defined as the first moment of the PDP.
  - $D = \int \tau PDP(\tau) d\tau$
- Delay Spread: It is defined as the square root of the second central moment of the PDP. It is the standard deviation of the mean excess delay. It gives an indication of the nature of the ISI and it is a good measure of the multipath spread.
  - $D_s = \sqrt{\int (\tau - D)^2 PDP(\tau) d\tau}$

The use of OFDM is crucial in order to avoid the effects of the signal spreading. In the beginning of each ODFM symbol there is a Guard Interval (GI) called Cyclic Prefix (CP) that protects the symbol from the ISI. To simplify things, if this GI is greater than the Delay Spread then the ISI is avoided completely as shown in figure 19.

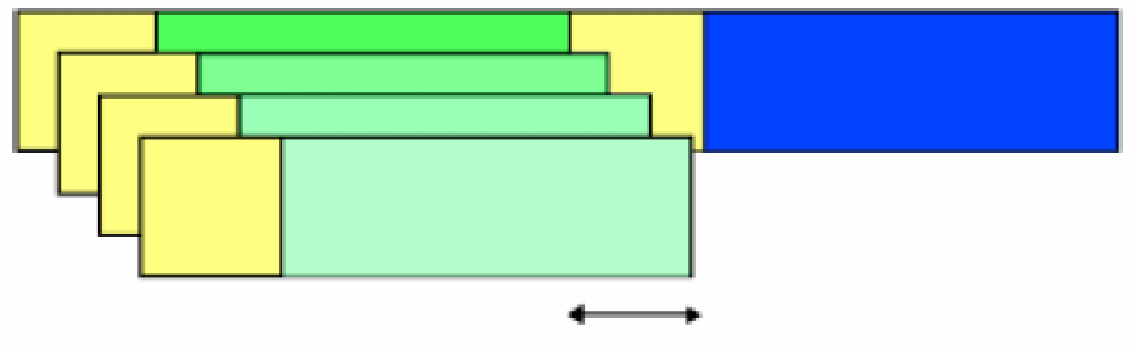

Figure 19: ISI. Delayed copies of the green symbol overlap with the guard interval of the blue symbol[21].

Also because OFDM uses several subcarriers instead of just one the symbol period is increased and thus OFDM is more resistant against Delay Spread. But as we can also see in figure 19 the GI does not prevent the green symbol from interfering with itself, this is called Intra Symbol Interference. That is why in practical systems the CP is used instead of the GI.
The CP is a copy of the last piece of information of a symbol placed in the beginning of it as a guard interval, making it also resistant to Intra Symbol Interference.
If we recall the guard time specified in the OFDM chapter we will have the duration of the CP. For a 20 MHz channel the guard time is 0.8 μs or 800 ns meaning that to completely avoid ISI, the Delay Spread should not be greater than 800 ns.

11.4 Antenna Height

Before proceeding to calculate the path loss suffered by the signal, a discussion on the height of the antennas must be done, since this is an input parameter of the Hata model.

When facing long distances in a communication link we can not longer consider the surface of the terrain to be flat. Instead we have to consider that it has a certain curvature. Thus in free space condition the heights of the antennas will determinate if the communication will have a direct line of sight or not. Besides the curvature of the Earth, the communication can face obstacles that will cause diffraction of the signal. In order to determinate the heights of the antennas a design condition is used.

$$h_{LOS} \geq 0.6 r_1 + \Delta f + H_{obs}$$

Equation 5: Height Design Condition.

In equation 5, r_1 is the first Fresnel Radius, Δf is the height caused by the curvature of the earth and H_{obs} is the height of the obstacle, as illustrated in figure 20.

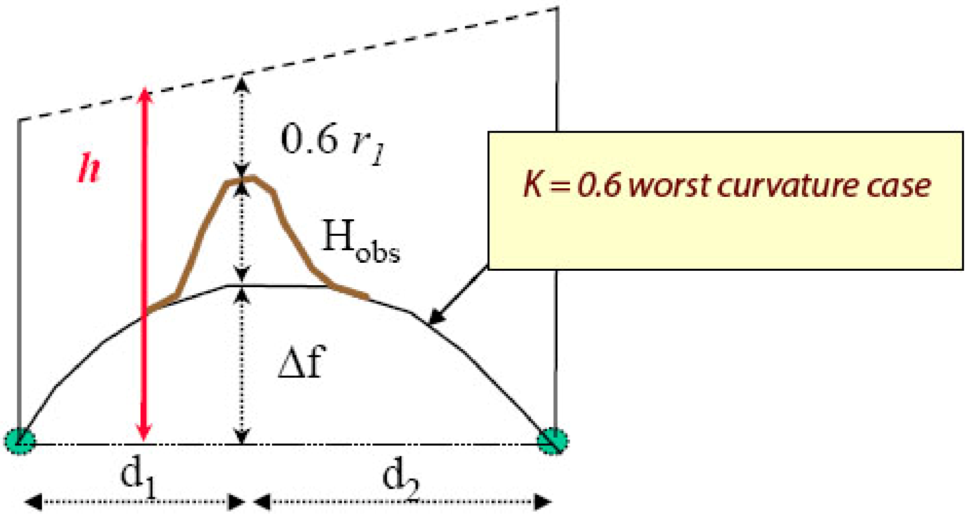

Figure 20: Height Design Condition.

Besides Δf and H_{obs}, an extra height must be added in order to avoid the attenuation caused by the diffraction. This extra height corresponds to the 60% of clearance of the first Fresnel Radius, then one can consider that a signal has direct line of sight.

Then equation 5 can be rewrite into equation 6, where d_1 and d_2 are the distances from the obstacle to the transmitter and the receiver respectively, d is the total distance, K is the earth curvature index and R_o is the Earth radius.

$$h_{LOS} \geq r_1 + \Delta f + H_{obs} = 0.6\sqrt{\lambda \frac{d_1 d_2}{d}} + \frac{d_1 d_2}{2 R_o K} + H_{obs}$$

Equation 6: Height Design Condition (II).

As we can see, the height depends on the position of the obstacle in the field. To make a worst case design we have to consider the worst obstacle position.

In equation 6 we have two variable contributions to the height, r_1 and Δf. Maximizing these two variables is equal to maximize the equation 7.

$$f(d_1) = d_1 d_2 = d_1(d - d_1)$$
$$\frac{\partial f(d_1)}{\partial d_1} = d - 2d_1 = 0 \rightarrow d_1 = \frac{d}{2} \rightarrow d_1 = d_2$$

Equation 7: Distance equation.

When the obstacle is in the middle of the distance the required height is maximum and thus this is the worst design condition.

The Recording Truck will stand still once deployed. This allows installing a mechanism to reach great antenna heights. For example, the pole of the antenna is lying in the roof of the Recording Truck. Once deployed, the pole is tilted to greatly increase the height of the antenna. The height of the antenna in the Head Vibrator will be fixed. Following this line of reasoning the roofs of the Recording Truck and the Head Vibrator can be 4 meters high. Then, using trigonometry we can determine the heights of the pole and the obstacle.

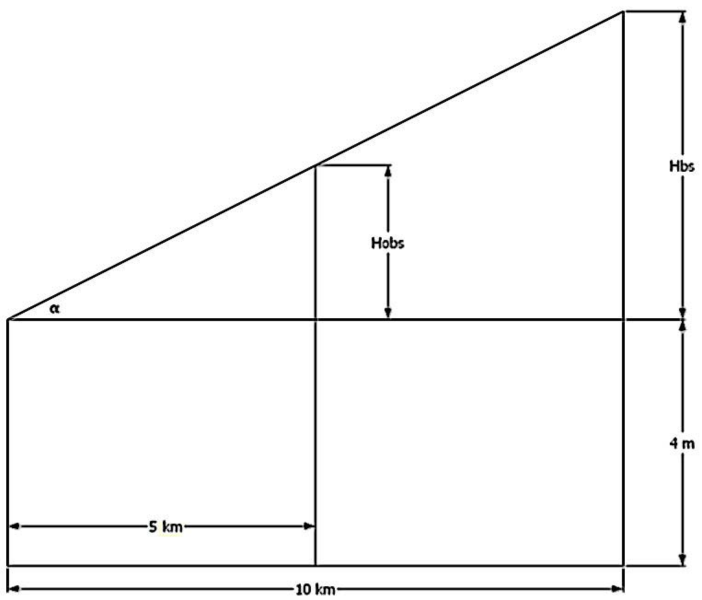

Figure 21: Trigonometry problem with antenna heights.

$$\tan\alpha = \frac{h_{obs}}{d/2} = \frac{h_{bs}}{d} \rightarrow h_{obs} = \frac{h_{bs}}{2}$$

Equation 8: Trigonometry Formulation.

Table 27 reflects the values of the heights and some other parameters.

<table>
<tr><th colspan="3">Parameter</th><th colspan="3">Expression</th><th colspan="3">Value</th></tr>
<tr><td colspan="3">Wave Length</td><td colspan="3">λ</td><td colspan="3">$0.125m$</td></tr>
<tr><td colspan="3">Worst Distance</td><td colspan="3">$d_1 = d_2 = \frac{d}{2}$</td><td colspan="3">$5.000m$</td></tr>
<tr><td colspan="3">Earth Radius</td><td colspan="3">R_o</td><td colspan="3">$6.378.000m$</td></tr>
<tr><td colspan="3">Worst Earth Index</td><td colspan="3">K</td><td colspan="3">0.6</td></tr>
<tr><td colspan="3">60% Clearance First Fresnel Radius</td><td colspan="3">$0.6\sqrt{\lambda \frac{d_1 d_2}{d}}$</td><td colspan="3">$10.6m$</td></tr>
<tr><td colspan="3">Height caused by the Earth Curvature</td><td colspan="3">$\frac{d_1 d_2}{2R_o K}$</td><td colspan="3">$3.3m$</td></tr>
<tr><td colspan="3">Total height for LOS</td><td colspan="3">$13.9m + H_{obs}$</td><td colspan="3">-</td></tr>
<tr><th>HV</th><th>RT+Pole</th><th>Hobs</th><th>HV+Pole</th><th>RT+Pole</th><th>Hobs</th><th>HV+Pole</th><th>RT+Pole</th><th>Hobs</th></tr>
<tr><td>4m</td><td>4m+19.8m</td><td>0m</td><td>4m+2m</td><td>4m+17.8m</td><td>0m</td><td>4m+4m</td><td>4m+15.8m</td><td>0m</td></tr>
<tr><td>4m</td><td>4m+29.8m</td><td>5m</td><td>4m+2m</td><td>4m+27.8m</td><td>5m</td><td>4m+4m</td><td>4m+35.8m</td><td>10m</td></tr>
<tr><td>4m</td><td>4m+39.8m</td><td>10m</td><td>4m+2m</td><td>4m+37.8m</td><td>10m</td><td>4m+6m</td><td>4m+13.8m</td><td>0m</td></tr>
<tr><td>4m</td><td>4m+49.8m</td><td>15m</td><td>4m+2m</td><td>4m+47.8m</td><td>15m</td><td>4m+6m</td><td>4m+33.8m</td><td>10m</td></tr>
</table>

Table 27: Height values table.

As we can see in table 27 if we were to install a 6 meters long pole in the Head Vibrator we would need another pole of 13.8 meters installed in the Recording Truck just to have direct line of sight. In order to overcome an obstacle 10 meters high the pole installed in the Recording Truck would need to have 33.8 meters.

Finally, the effective heights that will be used for the antennas will be 10 meters in the Head Vibrator and 17.8 meters in the Recording Truck.

11.5 Path Loss Calculation

Now we can begin calculating the path loss using the Hata model. The Hata model is an empirical formulation of the graphical path loss data provided by Okumura's model. The formula for the median path loss in rural areas is given by equation 9.

$$L(rural)(dB) = L(urban) - 4.78(\log f_c)^2 + 18.33\log f_c - 40.98;$$
$$L(urban)(dB) = 69.55 + 26.16\log f_c - 13.82\log h_{RT} - a(h_{HV}) + (44.9 - 6.55\log h_{RT})\log d;$$
$$a(h_{HV})(dB) = (1.1\log f_c - 0.7)h_{HV} - (1.56\log f_c - 0.8)$$

Equation 9: Hata Model Equations for rural areas.

Where f_c is the frequency in MHz, h_{RT} is the height of the antenna of the Recording Truck in meters, h_{HV} is the height of the antenna of the Head Vibrator in meters and d is the distance in km.
The path loss using the Hata model for the given parameters is 118.06 dB. We have considered that the base is the Recording Truck, and thus the path loss is valid for a downlink communication. If we switch the values of the heights and consider that the one who is emitting is the Head Vibrator as it will be

happening most of time then the path loss is 99.61 dB. The path loss in the downlink communication is bigger and thus the worst case path loss.

With the path loss we can estimate the power the Recording Truck will receive from the Head Vibrator and vice versa, in order to know if it is enough according to the sensitivity of the equipment. If the received power is bigger than the sensitivity then the link will be viable. The link will consist of two AIR-BR500GUHP plugged to high gain antennas, one omni directional (HV) and the other sectorial (RT). Table 28 shows the power parameters of the link.

Parameter	Value
Equipment	AIR-BR500GUHP
RF Output Power	30 dBm
Sensitivity	-90 dBm @ 6 Mbps, -70 dBm @ 54 Mbps
Worst Path Loss	118.06 dB
Antenna Gain Recording Truck	17 dBi
Antenna Gain Head Vibrator	9 dBi
Received Power	$P_R(dBm) = P_T(dBm) + G_{HV}(dB) + G_{RT}(dB)$ $-L_{HATA}(dB); P_R = -62.06dBm$

Table 28: Link Power Parameters.

The power received at the Recording Truck is approximately 8 dB greater than the sensitivity needed to support a 54 Mbps link, making the 10.3 Mbps net Throughput viable.

12 Final Architecture

12.1 Introduction

The final architecture of the system will consist of 4 poles installed in the roof of the RT, each pole holding two high gain directional antennas (W24-17SP90) and two AIR-BR500GUHP APs. Then, in each HV another pole will be installed holding a high gain omnidirectional antenna (W24-9O) and one AIR-BR500GUHP AP. The antennas are shown in tables 29 and 30.

Feature	Value
Code Product	W24-17SP90
Frequency	2.300 GHz ~ 2.700 GHz
Gain	17 dBi
Horizontal Beam Bandwidth	90 degrees
Vertical Beam Bandwidth	7 degrees
Polarization	Vertical
Price	251.00 $

Table 29: W24-17SP90 High Gain Directional Antenna[20].

Feature	Value
Code Product	W24-9O
Frequency	2.400 GHz ~ 2.483 GHz
Gain	9 dBi
Horizontal Beam Bandwidth	Omnidirectional
Vertical Beam Bandwidth	14 degrees
Electrical Downtilt	0 or 7 degrees
Polarization	Vertical
Price	200.00 $

Table 30: W24-9O High Gain Omnidirectional Antenna[21].

The idea is to have a maximum of radiation in every 45 degrees, using 90 degrees sector antennas. For that purpose two non overlapping channels are needed. Figure 22 shows the channel distribution and the placement of the poles with the equipment in the roof of the RT. North, East, South and West orientations are used for one channel and North-East, South-East, South-West, and North-West orientations are used for the other one.

[20] W24-17SP90 High Gain Directional Antenna LINK
[21] W24-9O High Gain Omnidirectional Antenna LINK

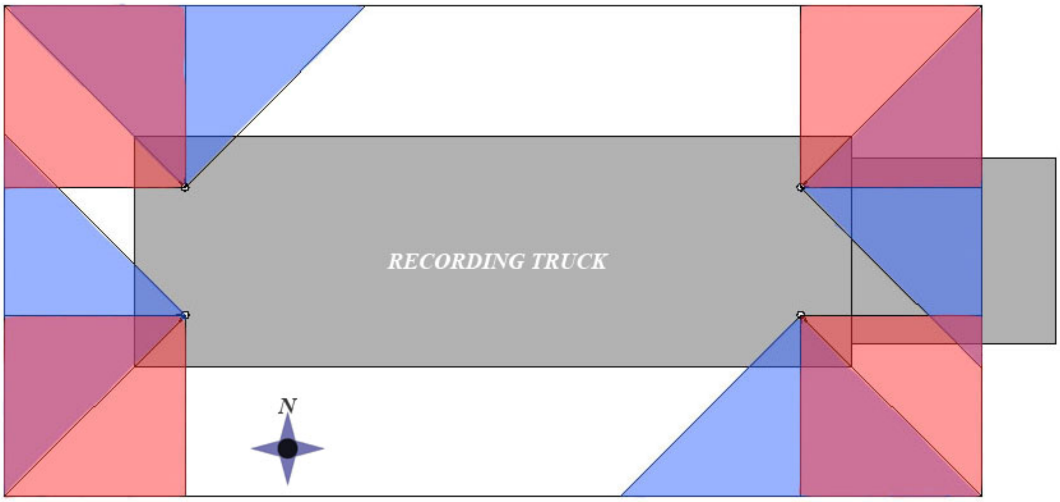

Figure 22: Channel Distribution in the Recording Truck.

12.2 Channel Allocation

As we previously saw the 802.11b/g technologies use 20 MHz channel bandwidth with a different channelization scheme depending on which country or region they are used in. The occupied spectrum goes from 2402 MHz up to 2494 MHz approximately. Table 4 shows the central frequency of each channel and its corresponding Channel Identifier (CI). We also saw that up to three channels can be used at the same time without overlapping. These are CI-1, CI-6 and CI-11 in North America and CI-1, CI-7 and CI-13 almost anywhere else.

In a Vibrator Group, the Vibrators use an 802.11b channel to communicate with the Head Vibrator. This leaves just two channels usable for the communication between the RT and the HV. Figure 23 shows the spectral power density of a 20 MHz OFDM channel bandwidth signal used in 802.11g.

In 802.11b instead of OFDM, CCK is used as the modulation giving place to a different power profile with greater main-to secondary-lobe rate. As can be seen in figure 23, at 11 MHz from the center, the power level is only 20 dB below the maximum (30 dB for 802.11b), and at 22 MHz away, the energy is only about 30 dB below (50 dB for 802.11b).

To make the interference between channels as low as possible only three channels will be used, CI-1, CI-7 and CI-13 (CI-1, CI-6 and CI-11 if the survey is to be done in North America) one for 802.11b and two for 802.11g.

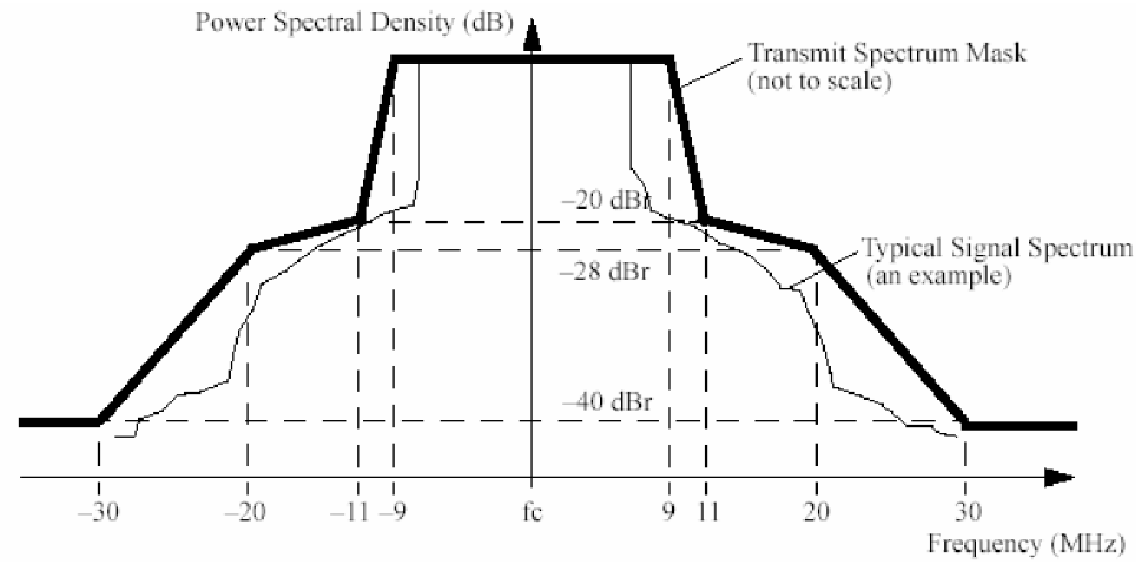

Figure 23: OFDM Power Density Spectrum[11].

Figure 24 illustrates how the spectrum would approximately look like if CI-1 and CI-13 were used for 802.11g, CI-7 for 802.11b and their maximum power level were the same. The interference level caused by the secondary lobes of CI-1 (Blue) to CI-7 (Green) is approximately 28 dB lower than the level of the main lobe of CI-7 when it reaches the useful bandwidth of CI-7 and decreases as it approaches to the central frequency up to 40 dB. The interference caused by the secondary lobes of CI-7 (Green) to the useful bandwidth of the other two (Blue and Red) channels is even lower. Therefore the three channels do not overlap and the interference level does not cause a significant degradation of the signal. Note that figure 24 shows the transmitter spectrum mask and thus the signal spectrum is expected to be lower.

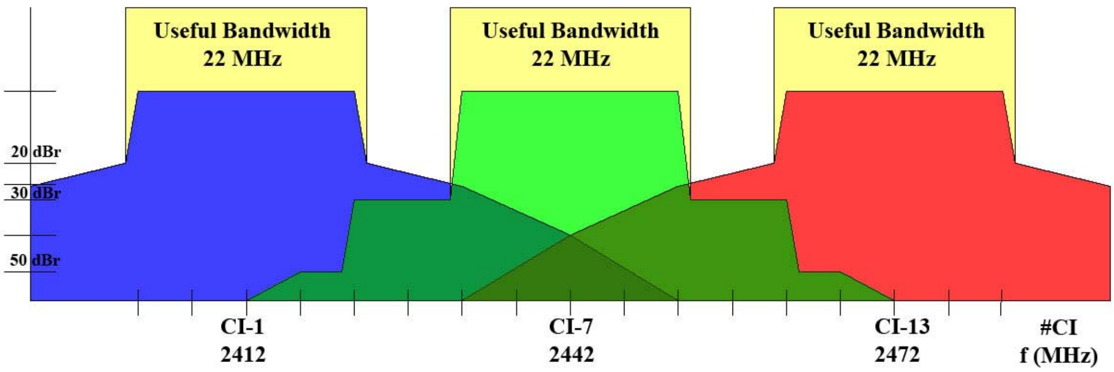

Figure 24: Spectral Power Profile of the used Channels.

Then, will using CI-1 and CI-13 for the 802.11g communication and CI-7 for the 802.11b communication guarantee no interference between them? The answer to that question is: It depends. To be more precise it depends on where we are. If we are in the RT, the spectrum will approximately look like the one shown in figure 24 without the green channel and thus no interference between the blue and red channels will occur. If we are in the Head Vibrator of a VG the spectrum will most likely be like the one shown in figure 25.

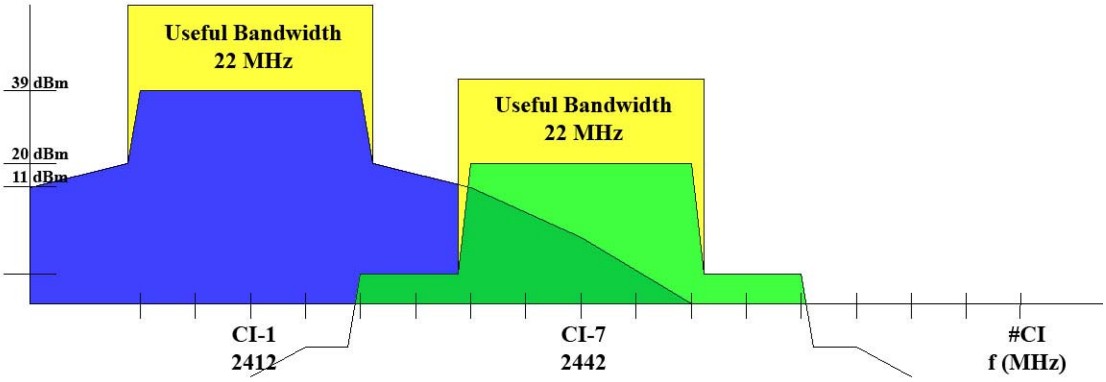

Figure 25: Spectrum in the Head Vibrator.

Besides the 802.11g equipment used to communicate the HV with the RT, all the Vibrators have 802.11b equipment installed. The standard emitting power of an 802.11b device embedded within a laptop is 20 dBm. The emitting power of the AIR-BR500GUHP plus the gain of the omnidirectinal antenna is 39 dBm. Figure 25 shows how the secondary lobe of the CI-1 (802.11g) reaches the useful bandwidth of CI-7 (802.11b) with a power level of 11 dBm, leaving only 9 dB of difference between useful signal and interference.

Even though, having 14 dBm of interference level is unlikely to happen because the omnidirectional antennas (W24-9O) used have a poor coverage directly under the antenna and thus if the antennas are installed high above in the poles its radiation will poorly affect the 802.11b communication.
The omnidirectional antennas will have an effective height of 10 meters, a vertical beam bandwidth of 14 degrees and their electrical downtilt will be chosen to be 0 degrees. Considering that, then approximately at 82 meters of distance between the HV and the others Vibrators the discussed interference will gain some consideration. Even though, it will still be insufficient to cause a degradation of the 802.11b link.

Note that the HV is using CI-1 to communicate with the RT, and the CI-13 is not represented. But that does not mean that it is not present. A CI-13 signal coming from the RT or a nearby VG using CI-13 will be present, but highly attenuated because of the path loss.

12.3 BER and SNR

In section 11.5 we saw that the received power is greater that the sensitivity needed to maintain a 54 Mbps link. But the received power is not the only parameter that defines the sensitivity of a device. The bit error rate (BER) is used in conjunction with the power sensitivity to determine if the link is able to work at a certain data rate.
The BER mainly depends on the modulation used and the signal-to-noise-ratio (SNR) of the receiver. Figure 26 shows the relation between the BER and the SNR in an 802.11g OFDM system for 16 QAM and 64 QAM modulations. If we

look at table 22, we see that these two modulations are responsible for 24 Mbps up to 54 Mbps of data rates.

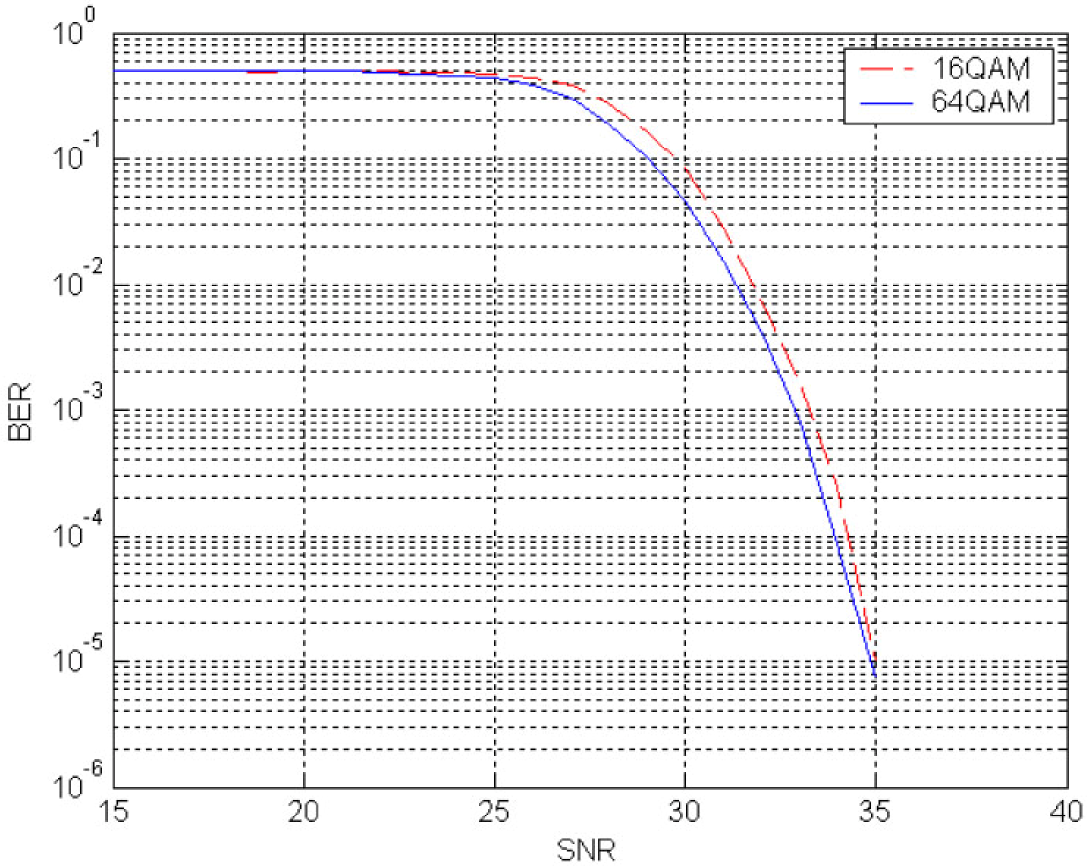

Figure 26: BER vs SNR in 802.11g[15].

For a desired BER level a certain SNR level has to be achieved. For example if the sensitivity needs 10^{-5} of BER then the SNR has to be approximately 35 dB.

The SNR can be calculated using equation 10,

$$SNR = \frac{P_R(Watts)}{P_N(Watts)}; SNR(dB) = P_R(dBW\_or\_dBm) - P_N(dBW\_or\_dBm)$$

Equation 10: SNR calculation.

where P_R is the received power and P_N is the power of the thermal noise.
The thermal noise is the electronic noise generated by the thermal agitation of the charge carriers (usually the electrons) inside an electrical conductor at equilibrium, which happens regardless of any applied voltage and it is calculated using equation 11,

$$P_N = FKT_O B$$

Equation 11: Thermal Noise.

where F is the Noise Figure (NF) of the system, K is the Boltzmann constant, T_O is the standard temperature and B is the spectrum bandwidth.
In order to calculate the Noise Figure of the system the Friis formula for noise figure is used (equation 12):

$$F_{eq} = F_1 + \frac{F_2 - 1}{G_1} + ... + \frac{F_N - 1}{G_1 G_2 ... G_{N-1}}$$

Equation 12: Friis Formula for Thermal Noise.

In the Friis formula, F_{eq} is the NF equivalent of the system, $F_{1...N}$ are the NF of the elements of the cascade and $G_{1...N-1}$ the gain of the elements of the cascade.

Because the NF and the BER are not defined in the specifications of the antennas and the AP, I asked Netkrom Technologies about them but failed to get a reply so far. Thus typical values will be used in the calculations of table 31 as an example.

Parameter		Value
Access Point RT & HV		AIR-BR500GUHP
RF Output Power		30 dBm
Noise Figure AP		7 dB
Sensitivity	Received Power	-70 dBm @ 54 Mbps, -73 dBm @ 48 Mbps, -76 dBm @ 36 Mbps, -79 dBm @ 24 Mbps, -82 dBm @ 18 Mbps, -85 dBm @ 12 Mbps, -88 dBm @ 9 Mbps, -90 dBm @ 6 Mbps
	BER	10^{-5} @ all data rates
Path Loss RT→HV		118.06 dB
Path Loss HV→RT		99.61 dB
Antenna Gain Recording Truck		17 dBi
Antenna Gain Head Vibrator		9 dBi
Noise Figure Antennas		3 dB
Received Power HV		-62.06 dBm
Received Power RT		-43.61 dBm
Equivalent NF in HV		$F_{eq} = 10^{0.3} + \frac{10^{0.7} - 1}{10^{0.9}} \approx 2.5$
Equivalent NF in RT		$F_{eq} = 10^{0.3} + \frac{10^{0.7} - 1}{10^{1.7}} \approx 2.07$
Power Thermal Noise HV		$P_N(W) = 2.5 \times 1.38 \times 10^{-23} \times 290 \times 20 \times 10^6 = 2.001 \times 10^{-13} W$ $P_N(dBm) \approx -97 dBm$
Power Thermal Noise RT		$P_N(W) = 2.07 \times 1.38 \times 10^{-23} \times 290 \times 20 \times 10^6 = 1.661 \times 10^{-13} W$ $P_N(dBm) \approx -97.8 dBm$
SNR HV		$SNR(dB) = -62.06 dBm - (-97 dBm) = 34.94 dB$
SNR RT		$SNR(dB) = -43.61 dBm - (-97.8 dBm) = 54.2 dB$

Table 31: SNR Calculation.

The SNR that the HV will have when receiving data from the RT will be just enough to support the required BER (10^{-5} for 35 dB of SNR) and thus a 54 Mbps link is viable. On the other hand, the SNR in the RT is far greater than the required making a 54 Mbps link viable.

It is important to note that these last calculations were made using typical values of NF and BER, but the real values of the equipment probably are different and a recalculation will have to be done. For simplicity only the Thermal Noise is being used as a font of noise in the SNR, but interference from other antennas, microwave ovens, Bluetooth equipment and the wire from the antenna to the access point will also affect the SNR.

12.4 Field Division

As previously seen in figure 22, the field around the RT can be divided in eight portions using eight 90 degree antennas and two channels. To assure 1 Mbps of data bandwidth from the HV to the RT, it was early decided to use one AIR-BR500GUHP access point of the RT to give service to one Vibrator Group. Therefore the minimum number of Vibrator Groups that one RT can supply is eight as figure 27 illustrates. The idea is that every VG make the survey in their correspondent Sector, although they are not restricted to them. For example if the VG-1 (Vibrator Group coming from Sector 1) needs to go to the Sector 2 it can, because it will have coverage until the adjacent half of the Sector 2 before a handoff occurs.

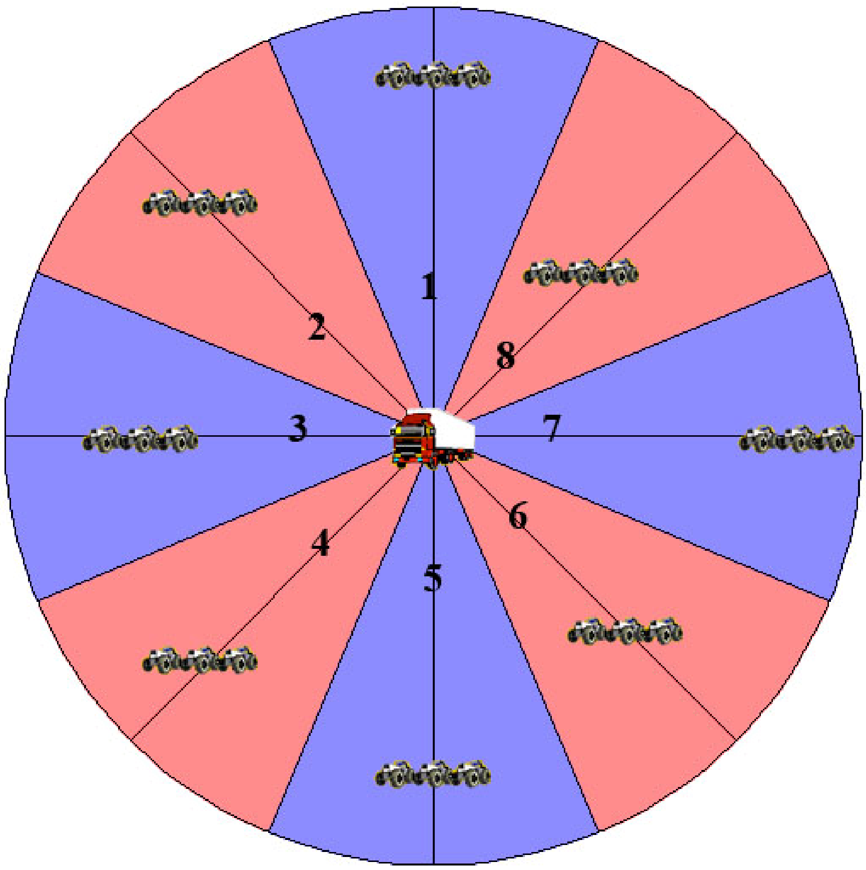

Figure 27: Eight sector Field.

The same scheme could have been achieved with 45 degrees antennas and using only one 802.11g channel, but it was less suitable for this application. A 45 degrees directional antenna has a maximum radiation in 0 degrees and the radiation is halved (3 dB lower) in 22.5 degrees and -22.5 degrees. Analogically, a 90 degrees directional antenna has a maximum radiation in 0 degrees and half the maximum in 45 degrees and -45 degrees. Recalling the example above, if the VG-1 reaches the edge of the adjacent half of the Sector 2 the power the RT will receive from the HV will be half the maximum power. If that is not enough to keep the communication at the desirable rate the VG-1 can join the AP of the Sector 2. There the RT will receive the maximum signal strength because it has a maximum of radiation.
In this way, the weakest direction (the edges) of a sector will be covered by the strongest direction of the adjacent sectors.

Then, the AIR-BR500GUHP AP's associated to Sectors 1, 3, 5 and 7 will be set up to use the channel CI-1 (2412 MHz) while AP's associated to Sectors 2, 4, 6 and 8 will be set up to use the channel CI-13 (2472 MHz). All of them will have the same Service Set Identifier (SSID) and encryption, configuring an Extended Service Set (ESS). One of them will act also as the DHCP server. At low vehicular speeds such as walking speed the VG's would be allowed to roam seamlessly between AP's. The AIR-BR500GUHP APs placed in the Head Vibrators will operate in the Wireless Gateway mode.

12.5 Deploying a Repeater

As calculated in section 11.4 the chosen effective height for the antennas was meant to allow communication with LOS with a total link distance of 10 km. But, when a RF obstacle is found in the middle of the communication path, where it is most harmful, the link can be lost. Figure 28 presents the relation between the relative position of the obstacle from either the RT or the HV and its maximum height in order conserve LOS in the communication path for 10 km of total distance.

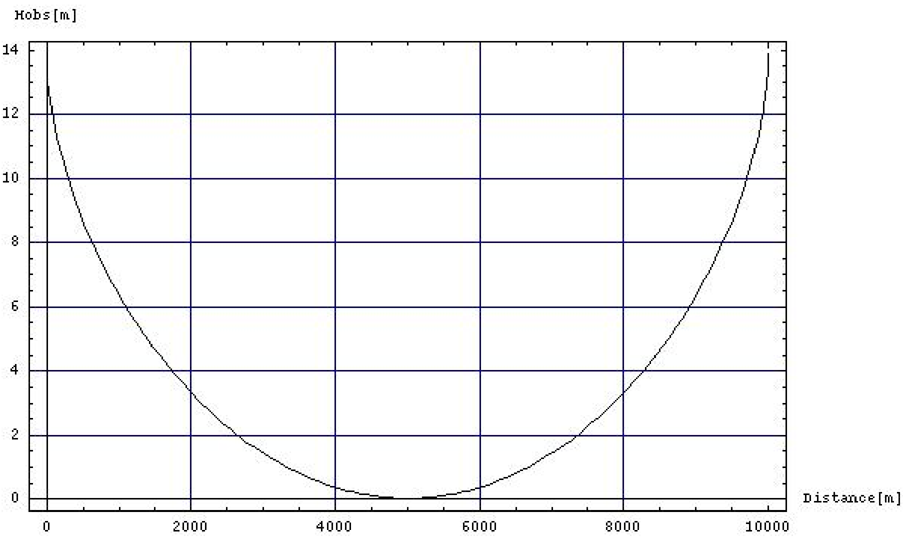

Figure 28: Obstacle Height vs Distance.

As the total distance decreases the height of the obstacle that can be overcome increases. For example, if the total distance of the link is 5 km, a RF obstacle placed 2.5 km away can be overcome if its height does not surpass 7.9 meters, as can be seen in figure 29.

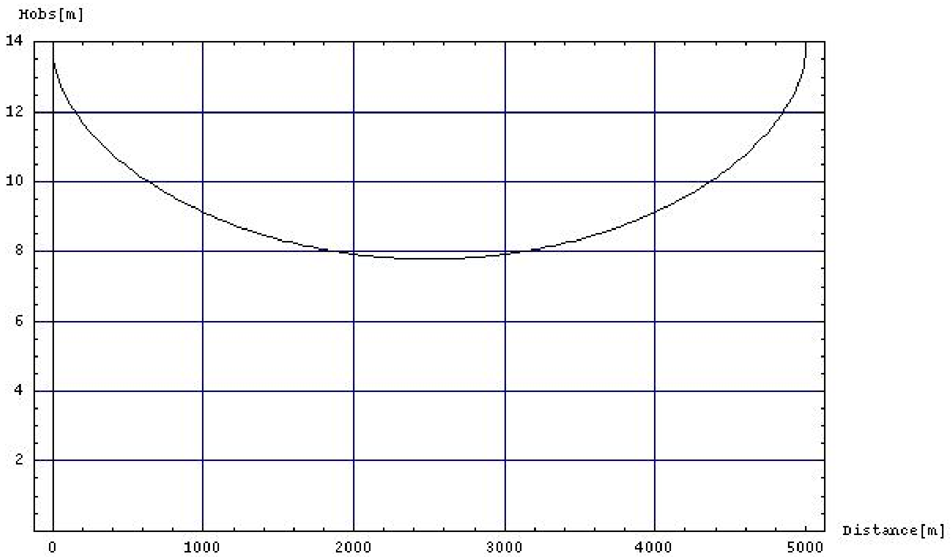

Figure 29: Obstacle Height vs Distance when total distance is 5 km.

Finally, considering that the obstacle is placed in half the total distance of the link figure 30 shows the maximum height it can have.

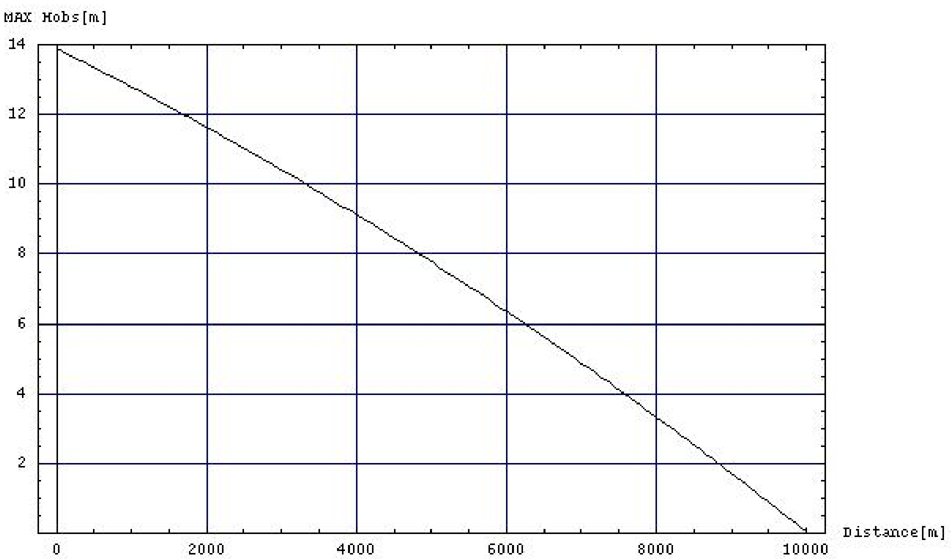

Figure 30: Maximum Obstacle Height.

For link distances greater than 6 km the height the communication will face problems when having to deal with obstacles, such as normal trees (3-5 meters), placed in the middle of the way.

When an obstacle completely covers the Head Vibrator of a Vibrator Group the direct line of sight will be lost. Additionally, if the communication can not be kept at the desirable level the Mobile Repeater (MB) will be deployed.

One of the working modes of the AIR-BR500GUHP is to act as a layer two repeater. Therefore a Mobile Repeater will consist of an all-terrain vehicle with an AIR-BR500GUHP AP and an omnidirectional antenna (W24-9O) installed on it.

Although a layer two repeater halves the data rate bandwidth it has the advantage that it only requires one channel to function properly, making it compatible with the channel distribution of the system. When the repeater is deployed it will use the same channel as the sector of the isolated VG. If we take a look at figure 31 we can see that the LOS is being obstructed by a little hill. Instead of climbing the hill and placing a fixed repeater, the Mobile Repeater is deployed and creates a new LOS with the VG and the RT and while used it will stand still. Because it uses the same channel it will not cause any interference with other VG surveying the adjacent sector.

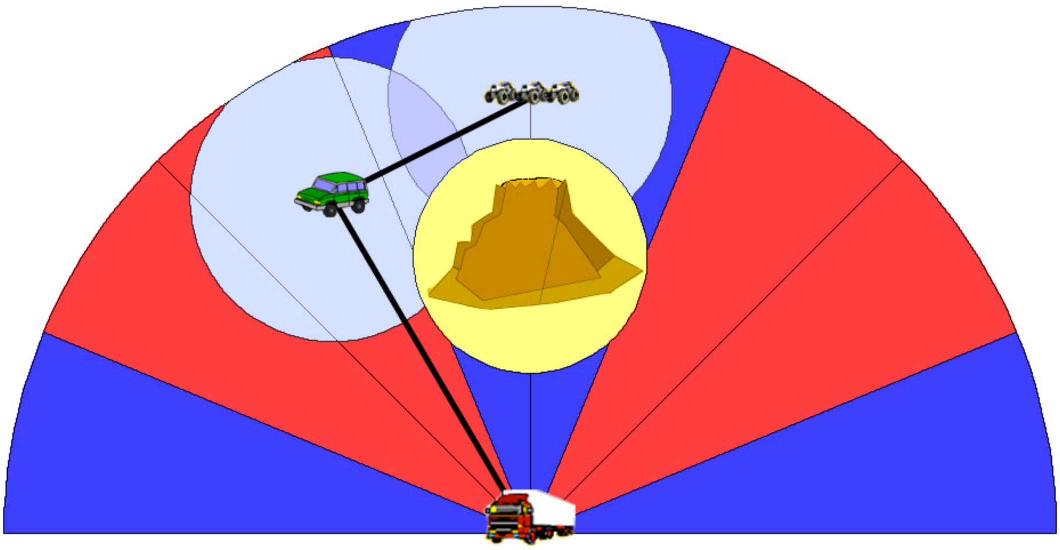

Figure 31: Repeater deployed in the field.

It will use the same configuration as a normal VG, which implies using the same antenna and the same effective height. The calculations of path loss previously done can be applied now, so the repeater can be placed even at 10 km far from the RT. The best position to place the repeater to overcome an obstacle will depend basically on the physical dimensions of the obstacle meaning, that a certain level of knowledge of the terrain has to be provided beforehand.

For example, if the distance between the HV and the RT is 10 km, the obstacle is placed equidistantly and its shape can be approximated with a circle of 1 km radius, then one of the best positions to place the repeater would be the one shown in figure 32. There, the repeater, will have LOS with the HV and the RT and will cover all the area that is shadowed by the obstacle to let the VG move freely around the area.

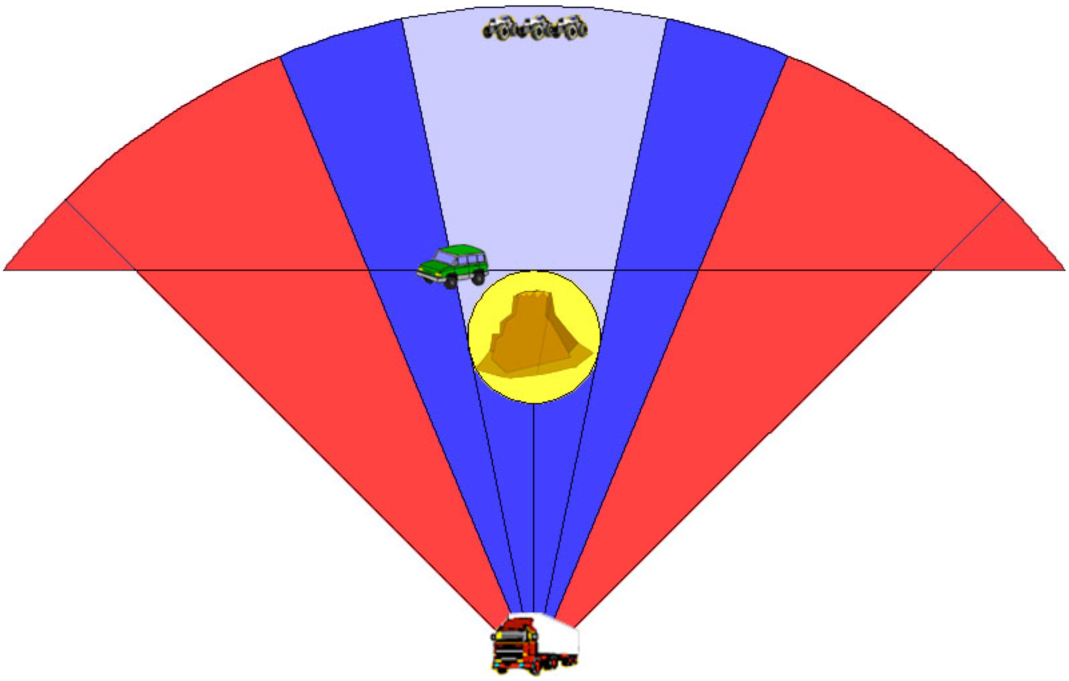

Figure 32: Positioning the Repeater.

The distance from the RT to the MB is 5.8 km and thus the path loss in both directions will be lower than the one calculated in the Channel chapter. On the other hand, the distance from the HV to the MB is 4.2 km. If we recalculate the path loss using the Hata Model we have a path loss of 108.37 dB in each direction, and the power received in the HV and the MB is -60.37 dBm, approximately 10 dB greater than the required sensibility making, once more, a 54 Mbps link viable.

Although the link will have 54 Mbps the Throughput will not be 10.3 Mbps anymore, at least it will be halved because of the nature of the repeater. Besides, the ACK Timeout will have to be modified to be coherent with the delay the repeater will cause, so the minimum ACK Timeout value will be:

$$NEW\_ACK_{Timeout} = \lceil RTT \rceil + SIFS + t_{TX\_DATA} + t_{TX\_ACK} + 2 \times t_{PROC\_REPEATER}$$

Equation 13: New ACK Value.

Where an additional transference time of the data and the ACK is added plus the time needed for the repeater to process each packet. Figure 33 shows the different time contributions to the value of the ACK Timeout. When the total distance is 10 km the RTT equals to two propagation times, here the addition of the four propagation times will be slightly higher than the RTT.

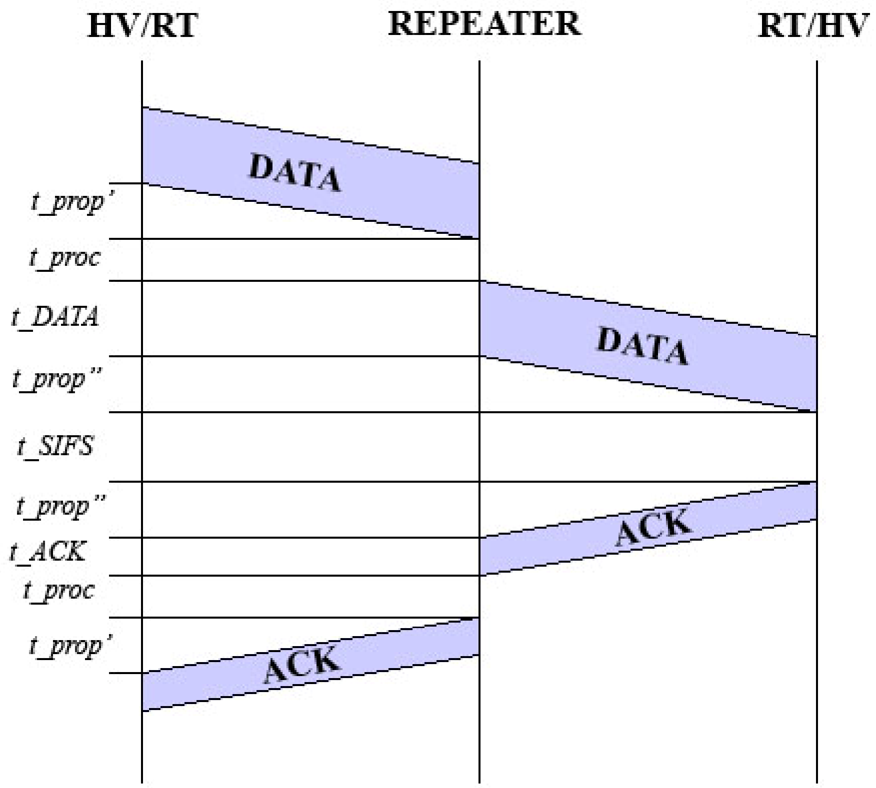

Figure 33: New ACK Timeout.

13 Conclusions: Part Two

13.1 Conclusions

Table 32 summarizes the main features of the wireless communication system.

Code Product	**AIR-BR500GUHP**		
Product Type	Access Point		
RF Output Power	30 dBm		
Sensitivity – Received Power	-70 dBm @ 54 Mbps, -73 dBm @ 48 Mbps, -76 dBm @ 36 Mbps, -79 dBm @ 24 Mbps, -82 dBm @ 18 Mbps, -85 dBm @ 12 Mbps, -88 dBm @ 9 Mbps, -90 dBm @ 6 Mbps		
Price	399.00 $		
Code Product	**W24-17SP90**		
Product Type	Directional Antenna		
Gain	17 dBi		
Horizontal Beam Bandwidth	90 degrees		
Price	251.00 $		
Code Product	**W24-9O**		
Product Type	Omnidirectional Antenna		
Gain	9 dBi		
Horizontal Beam Bandwidth	Omnidirectional		
Electrical Downtilt	0 degrees		
Price	200.00 $		
Feature	**Recording Truck**	**Head Vibrator**	**Repeater**
Number of Poles	4	1	1
Access Point	AIR-BR500GUHP	AIR-BR500GUHP	AIR-BR500GUHP
Antennas per Pole	2	1	1
Antennas	W24-17SP90	W24-9O	W24-9O
Antenna Effective Height	17.8 m	10 m	10 m
Feature	**Value**		
Technology	802.11g		
Vehicular Speed	Walking Human Speed		
Max. Link Distance	10 km		
Physical Layer	OFDM		
Frequency	2.4 GHz		
Channel Bandwidth	20 MHz		
Delay Spread Resistance	800 ns		
MAC Layer	CSMA/CA		
Efficiency	19%		
Net Throughput	Max. 10.3 Mbps @ 54 Mbps Link Data Rate		
Antennas Height for LOS	13.9 m		
Path Loss	Max. 118.06 dB with Hata Model		
Number of Sectors	8 Sectors of 45 degrees		
Max. Radiation Directions	N, N-E, E, S-E, S, S-W, W, N-W		
Channel Allocation – RT	(CI-1 & CI-13) or (CI-1 & CI-11)		
Channel Allocation – HV	[(CI-1 or CI-13) & CI-7] or [(CI-1 or CI-11) & CI-6]		
Channel Allocation – Repeater	(CI-1 & CI-13) or (CI-1 & CI-11)		
Number of Recording Trucks	1		
Number of Group Vibrators	8		
Number of Repeaters	4		
Total Price Equipment	12.388 $		

Table 32: Wireless Communication System.

The suggested wireless communication system:

1. Is able to deliver data rates greater than 1 Mbps in the uplink and 100 kbps in the downlink using high gain antennas and high power access points.
2. Can reach link distances of 10 km maximum when the proper setup of the CSMA/CA parameters is done.
3. Does not interfere with the deployed IEEE 802.11b wireless communication system, aimed to communicate each Vibrator with the Head Vibrator, or with itself.
4. Has direct line of sight up to 10 km thanks to reasonable effective antenna height.
5. Can deploy mobile repeaters to overcome radio frequency obstacles when the effective antenna height is not enough.
6. Operates in a license free band and thus no license acquisition is required.
7. Is available worldwide, highly reliable and cheap.

Hence, the suggested wireless communication system is capable of responding to what WesternGeco needs.

13.2 Further work

The system can be improved in several ways and further investigation can be done in order to assure its reliability:

1. Acquiring test equipment and testing it according to the conditions presented in this thesis.
2. Further study of the performance of the CSMA/CA when facing long link distances. Study of the following layers of the stack.
3. Study of a tracking system for the antennas in order to improve the coverage and range.
4. Further study of 802.11b and 802.11g systems coexistence. Alternatives to 802.11b for short range communications.

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