Basic Outdoor WiFi Network Planning

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Intended Audience

- This is a basic level presentation intended for someone who is getting started with outdoor WiFi networks
- For each slide here, there are probably 5 to 10 more slides of details, exceptions and other nuances that could be covered
- For more detail, there are countless sources already available from equipment vendors and others
- After reviewing this presentation, pick your favorite Internet search engine and begin …

Assumptions

- We assume the following has already been defined:
- Clear statement of the problem to be solved
  - Who, what, when, where, why, how
  - Clear set of requirements: traffic types, quantities, characteristics, people, …
- Clear reasoning for solving the problem
  - Key assumptions, clear expectations, clear metrics to measure the results
- WiFi selected as the best solution
  - Based on the problem to be solved and the reasons for solving it, WiFi has been determined to be the right choice

Agenda

- Site selection
- Topology selection
- Link analysis
    - Line of Sight Analysis
    - Band Selection
    - Link Budget Analysis
- Technology analysis
- Other considerations are also important (financial, functional, sustainability, …) but we won’t cover that here

Site Selection

- Most problems can be avoided by careful attention to detail at the mechanical and physical layer
- The right characteristics at each site can support a “set it and forget it” operation, eliminating the need for constant tinkering and fixing

Site Characteristics to Consider

- Power
  - What is available? Under emergency conditions?
- Environment
  - Exposure to weather, temperature, humidity, dust, …
- Structure
  - Safe, permissible for mounting antennas, equipment, …
- Access
  - Can you get to it when you need to?
- Security
  - Will the equipment be secure against intentional tampering and unintentional disruption?
  - Who has user access? Can users access the network without your knowledge? (Part 97 consideration)

Site Characteristics to Consider

- Maintainability
  - How easy is it to work on the equipment?
- Remote monitoring and control (alarms, telemetry)
  - Do you know what's happening with power, environment, security, … even when you're not there?
- Other parties
  - Interference from/to others?
  - Co-channel, adjacent channel, intermodulation, …
- More …

Topology Selection

- Star / Hub-and-spoke
  - ☑ More deterministic performance (bandwidth, delay, jitter)
  - ☑ Single high location can support multiple low locations
  - ☒ Single point of failure
- Mesh
  - ☑ No single point of failure
  - ☑ Easier to deploy in an emergency using portable stations
  - ☒ Harder to find multiple locations (line-of-sight, power, …)
  - ☒ Less deterministic network performance
- Hybrid
  - Some of each
  - Example: hub-and-spoke from central site to individual neighborhoods, then mesh throughout neighborhood
- Be aware of hidden transmitter problems in all cases

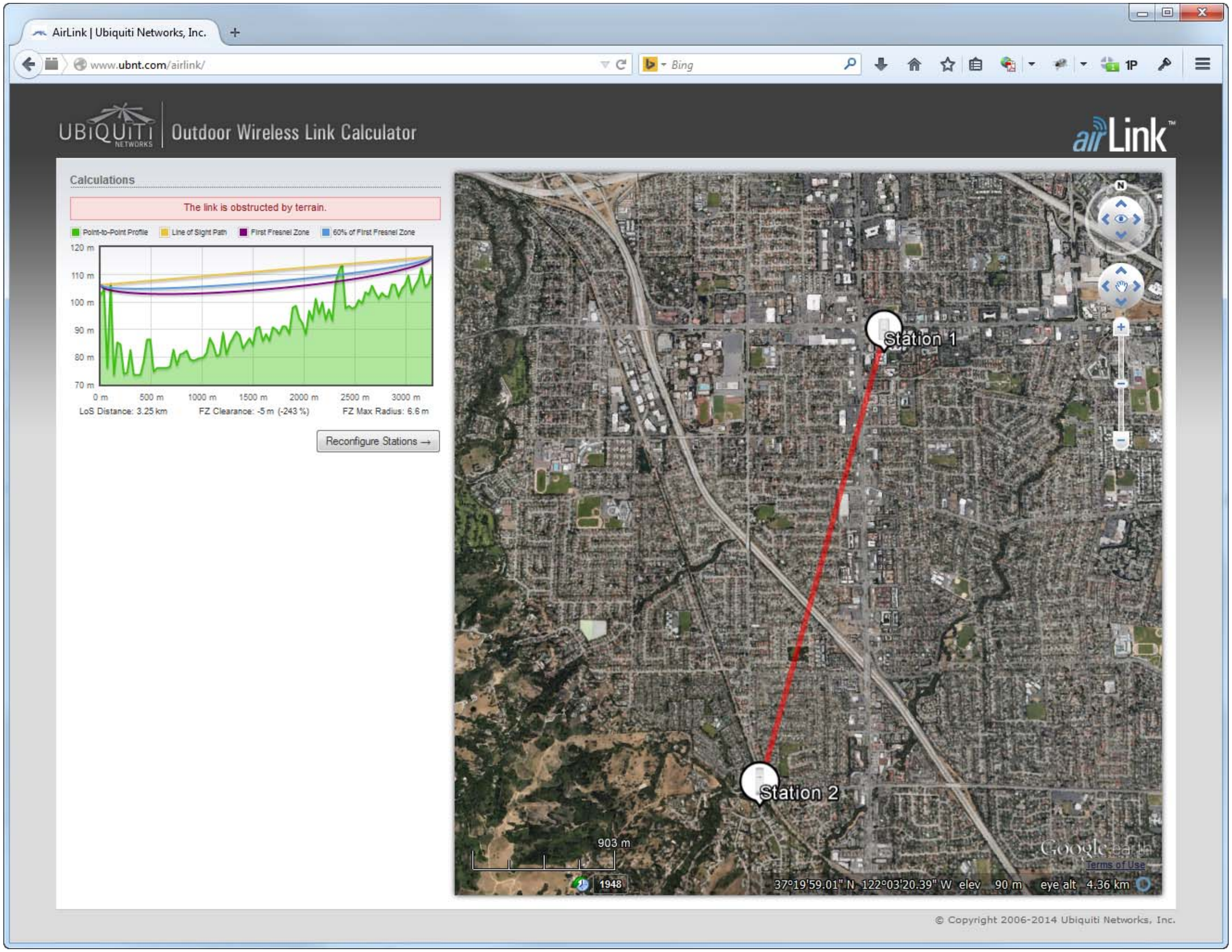
Link Analysis

- Line of sight
- Band selection
- Link budget analysis

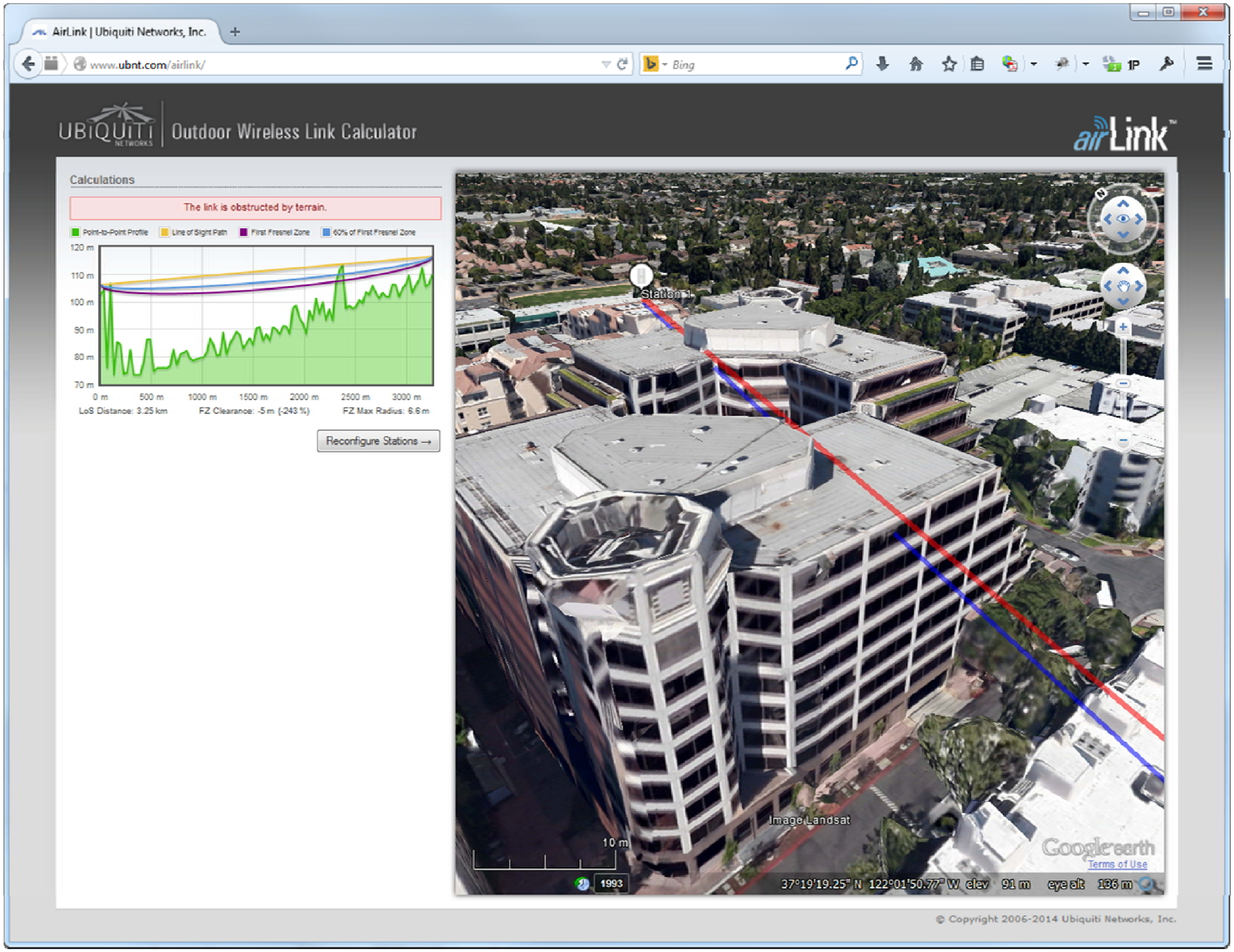
Line of Sight

- Strict line of sight
- Fresnel zone
  - Ideally, at least first Fresnel zone is clear
  - Clear 0.6 of first Fresnel zone is considered minimum
- Tools
  - Link Calculators
    - Ubiquity AirLink (http://www.ubnt.com/airlink)
      - Shows profile plus Google Earth path
  - Full propagation modeling software
    - Radio Mobile
      - Can export to .kml format for viewing with Google Earth

Ubiquiti AirLink



Ubiquiti AirLink



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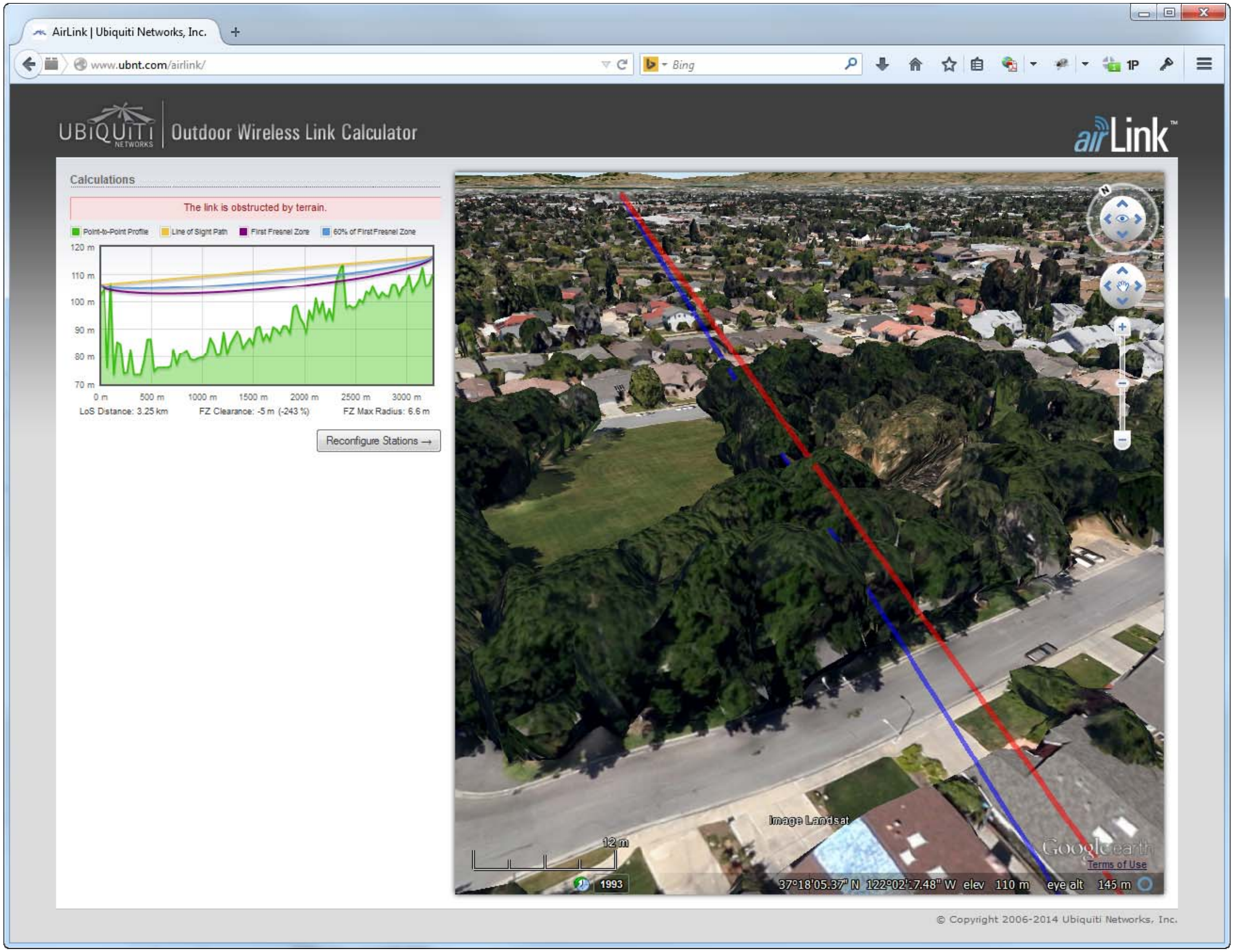

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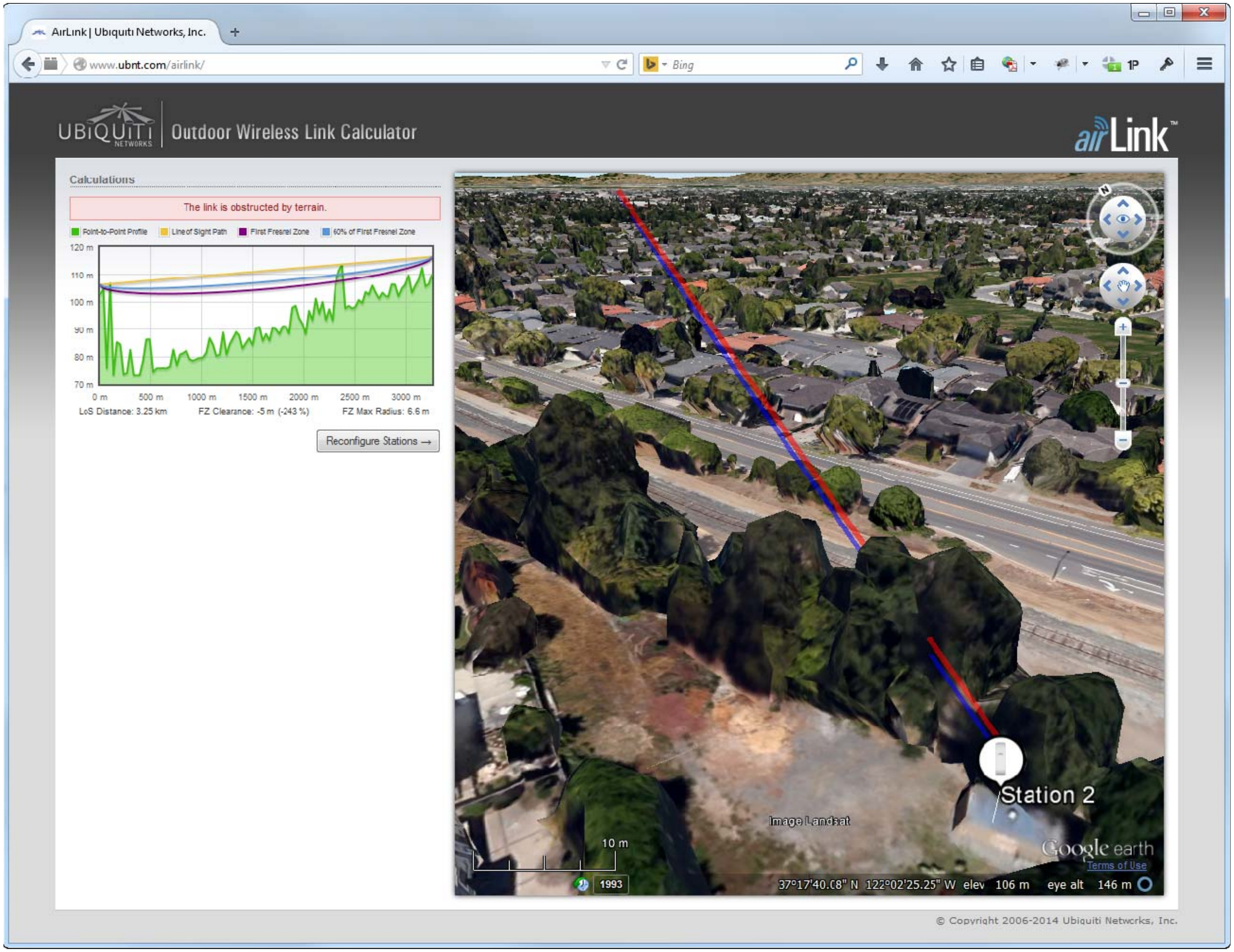

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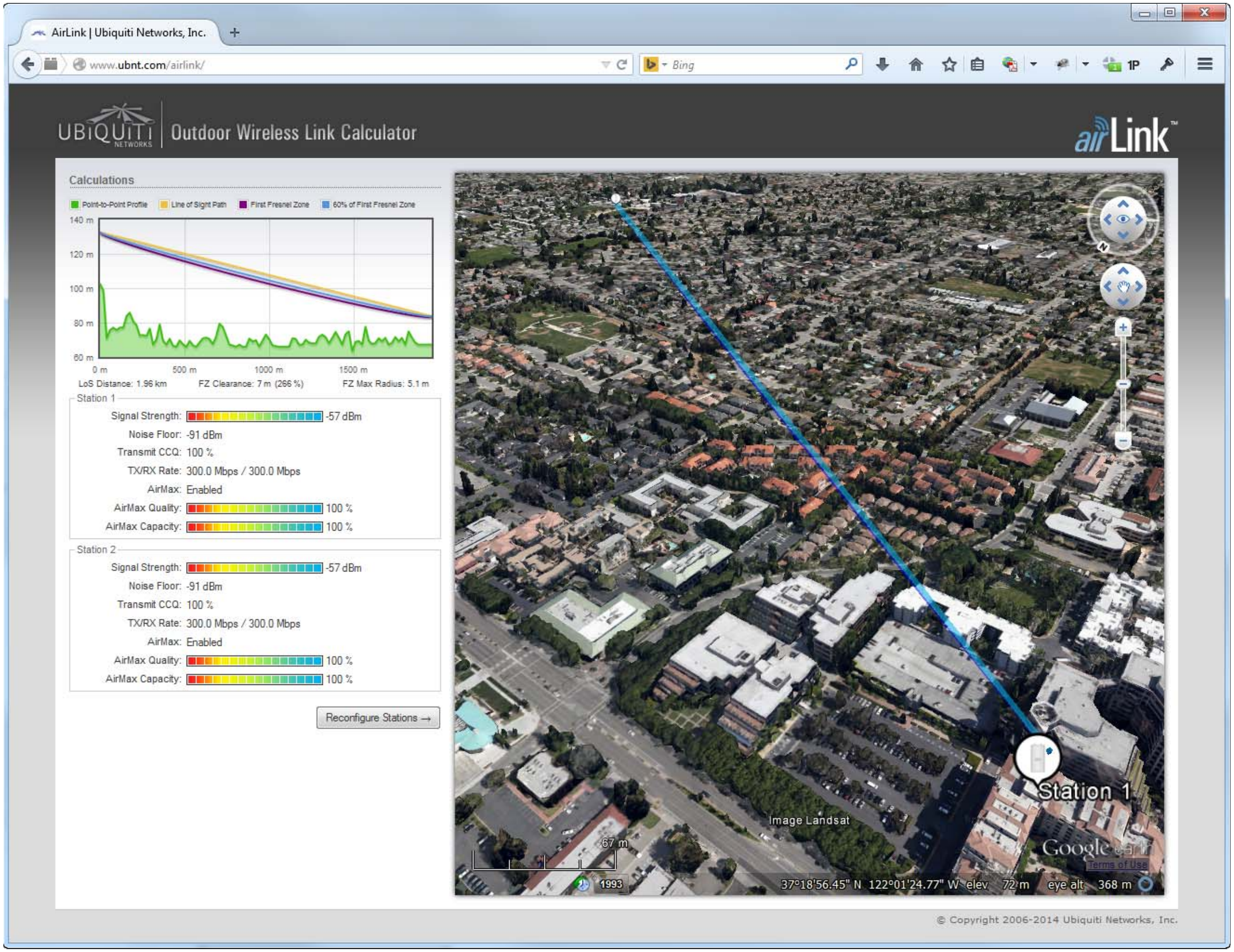
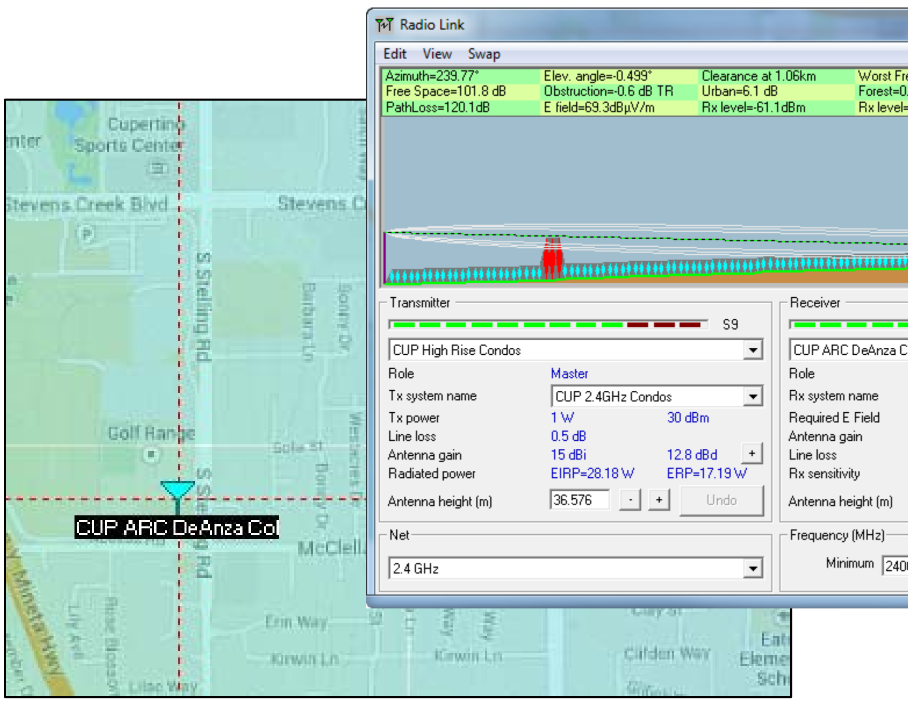
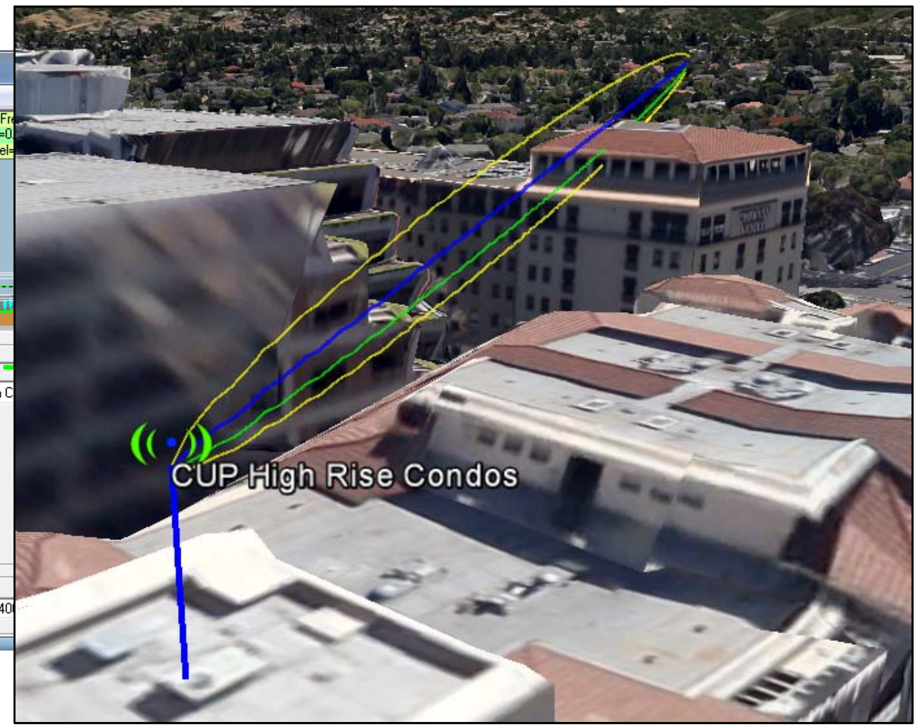


Radio Mobile

- Free software; download/install or use online
- Full Longley-Rice propagation prediction
- Export to .kml file for viewing with Google Earth





Band Selection

- 900 MHz, 2.4 GHz, 3.6 GHz, 5.8 GHz
- Lower frequencies less susceptible to line of sight issues; higher frequencies more susceptible to line of sight issues
  - 5.8 GHz is relatively unforgiving
- Lower frequencies have larger Fresnel zones (greater chance that something will be inside the zone), but better ability to deal with it
- 900 MHz tends to be noisy (cordless phones, baby monitors, …)
- 2.4 GHz is crowded; only 3 non-overlapping channels
- 3.6 GHz requires license, dynamic frequency selection
- 5 GHz has three separate sub-bands w/ different power/use regulations

Link Budget Analysis Process

- Gather bandwidth requirements
- Determine RF parameters
  - Channel width, streams, modulation type, minimum SNR, TX power, RX sensitivity, gains, losses
- Calculate
  - Received Power, Link Margin, Maximum Channel Noise
- Check
  - Fade Margin
  - FCC regulations
- If necessary, make adjustments and repeat

Example Problem

- As we discuss each part of the analysis process, we'll apply a real-world example
- For our example, we will assume we need a point-to-point link between two sites that are 25 km apart
- The link serves a cluster of users at a remote site who will share the link bandwidth
- We will use the 5.8 GHz band

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Bandwidth Requirements

- Applications have bandwidth, delay, jitter requirements
  - E-mail generally requires little bandwidth (except for large attachments) and is insensitive to delay and jitter
  - VoIP is sensitive to both delay and jitter
  - Video is also delay and jitter sensitive and requires more bandwidth
- Bandwidth
  - WiFi is half duplex (i.e. simplex), plan accordingly
- Delay and Jitter
  - To minimize: use star topology, more bandwidth than necessary, QoS capabilities of commercial products

Bandwidth Requirements

- Determine per-client bandwidth requirements
  - For our example, we'll say 2 Mbps each
- Determine number of clients per link
  - For our example, we'll say there are 10 clients on the link
  - For example, this could be 10 users on a LAN or 10 sites that hub into a single backbone link
- Determine total client bandwidth required
  - 2 Mbps * 10 sites = 20 Mbps
- Determine raw bandwidth required
  - Raw WiFi bandwidth is about 2X the client (payload) BW
  - So raw bandwidth required = 20 Mbps * 2 = 40 Mbps

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802.11n Modulation and Coding Scheme (MCS)

- 802.11n allows different channel sizes, modulation schemes and spatial streams
- Channel width
  - 20 MHz is fairly standard; 40 MHz is greedy (its shared spectrum!)
  - For our example, we'll pick 20 MHz
- Streams
  - Most outside plant equipment today is either one or two streams
  - Each stream adds throughput: two streams is twice as fast as one
  - For our example, we'd like to use 2 streams
- Modulation schemes
  - In order of increasing complexity: BPSK, QPSK, 16-QAM, 64-QAM
  - Higher density modulations give higher speed, but less noise immunity
- The combination of the modulation scheme with the number of streams defines the Modulation and Coding Scheme (MCS)

A Note About “Streams” vs. “Diversity”

- 802.11n gear can transmit/receive multiple streams, at the same time, using more than one antenna or more than one polarization
  - Examples are equipment marked 802.11n MIMO
- Older 802.11a/b/g gear may have multiple antennas, but those are used for diversity; only one antenna is used at any given time
  - An example is the LinkSys WRTG series
- 802.11n gear can be configured for backward compatibility with 802.11a/b/g gear, but you give up the advantage of multiple streams

MCS Comparison

MCS	Streams	Modulation	Req'd SNR	Raw Data Rate (Mbps) 20 MHz Chan	40 MHz Chan
0	1	BPSK	7	7.2	15
1	1	BPSK	12	14.4	30
2	1	QPSK	14	21.7	45
3	1	QPSK	18	28.9	60
4	1	16QAM	22	43.3	90
5	1	16QAM	25	57.8	120
6	1	64QAM	29	65.0	135
7	1	64QAM	32	72.2	150
8	2	BPSK	7	14.4	30
9	2	BPSK	12	28.9	60
10	2	QPSK	14	43.3	90
11	2	QPSK	18	57.8	120
12	2	16QAM	22	86.7	180
13	2	16QAM	25	115.6	240
14	2	64QAM	29	130.0	270
15	2	64QAM	32	144.4	300

Note: Different vendors publish different SNR numbers for each MCS. Some are more conservative than others. Most are fairly similar.

- For our example, we need:
  - 40 Mbps data rate
- We also decided on:
  - 20 MHz Channel
- Two possible answers:
  - MCS4: 1 stream, 16-QAM
  - MCS10: 2 streams, QPSK
- Use of 2 streams allows lower SNR
- We choose MCS 10
- Minimum SNR is 14 dB

TX Power and RX Sensitivity

- Each radio will have specifications for TX power and RX sensitivity for each MCS
- Example from Ubiquiti Rocket M5 datasheet:

	DataRate	Avg. TX	Tolerance
11n / AirMax	MCS5	24 dBm	+/- 2 dB
	MCS6	22 dBm	+/- 2 dB
	MCS7	21 dBm	+/- 2 dB
	MCS8	27 dBm	+/- 2 dB
	MCS9	27 dBm	+/- 2 dB
	MCS10	27 dBm	+/- 2 dB
	MCS11	27 dBm	+/- 2 dB
	MCS12	26 dBm	+/- 2 dB

	DataRate	Sensitivity	Tolerance
11n / AirMax	MCS5	-83 dBm	+/- 2 dB
	MCS6	-77 dBm	+/- 2 dB
	MCS7	-74 dBm	+/- 2 dB
	MCS8	-95 dBm	+/- 2 dB
	MCS9	-92 dBm	+/- 2 dB
	MCS10	-90 dBm	+/- 2 dB
	MCS11	-87 dBm	+/- 2 dB
	MCS12	-84 dBm	+/- 2 dB

- For MCS 10
  - Worst case TX power = 27dBm – 2 dB = 25 dBm
  - Worst case RX sensitivity = -90 dBm + 2dB = -88 dBm

Gains

- Gains are typically of two types
  - Amplifier gain
  - Antenna gain
- At GHz frequencies, clean amplifiers are very expensive and not really practical for the amateur
  - Don’t use the garbage you see out on eBay or elsewhere; you’ll trash the band for everyone
- So, antennas are where you achieve gain
- Both antennas on a link contribute to gain
- So gain is typically the sum of the transmitter antenna gain and the receiver antenna gain
  - For our example, we’ll use a 30 dBi dish on each end
  - So our total gain is 60 dB

Losses

- Free Space Path Loss
- Cable Loss
- Other losses

Free Space Path Loss

- FSPL(dB) = 20log10(d) + 20log10(f) + 32.45
  - d = distance in km, f = frequency in MHz

Free Space Path Loss					
Distance (km)	Distance (miles)	Path Loss (dB) @ 900 MHz	Path Loss (dB) @ 2.4 GHz	Path Loss (dB) @ 3.6 GHz	Path Loss (dB) @ 5.8 GHz
0.5	0.3	86	94	98	102
1.0	0.6	92	100	104	108
1.5	0.9	95	104	107	111
2.0	1.2	98	106	110	114
2.5	1.6	100	108	112	116
5.0	3.1	106	114	118	122
7.5	4.7	109	118	121	125
10.0	6.2	112	120	124	128
15.0	9.3	115	124	127	131
20.0	12.4	118	126	130	134
25.0	15.5	120	128	132	136
30.0	18.6	121	130	133	137
40.0	24.9	124	132	136	140
60.0	37.3	127	136	139	143
80.0	49.7	130	138	142	146

For our example, we have a 25 km path at 5.8 GHz → 136 dB

Cable Loss

- Loss between radio and antenna
- Some devices have integrated radio & antenna
  - Cable loss = ~0
- Some devices have very short cables
  - Radio mounts on antenna with short jumper
  - Cable loss = 1 dB
- Some devices have remote antennas
  - Indoor radio connected to outdoor antenna
  - Loss will be greater at higher frequencies
  - Cable loss = 3+ dB
- For our example, we will assume 1 dB at each end

Other Losses

- Static obstructions
  - buildings, walls, fences, …
- Semi-static obstructions:
  - Obstructions that may present a different amount of loss at different times
  - Examples: trees full of wet leaves in the Spring can cause higher loss than dry trees with no leaves in the Fall/Winter
- Our biggest concern: with low-to-the-ground networks, these other losses will be the biggest unknown
  - Experimentation will be necessary
- For our example, we will assume 0 dB

Summary So Far …

Parameter	Value
Required Per-User Bandwidth	2 Mbps
Required Total User Bandwidth	20 Mbps
Required Raw Bandwidth	40 Mbps
Channel Width	20 MHz
MCS	10
Minimum required SNR	14 dB
TX Power	25 dBm (27 dBm +/- 2 dB)
RX Sensitivity	-88 dBm (90 dBm +/- 2 dB)
Gain (antenna)	60 dB (30 dB at each end)
Loss (FSPL)	136 dB
Loss (cable)	2 dB (1 dB at each end)
Loss (other)	0 dB

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Received Power

- Received Power (dBm) =
  Transmitted Power (dBm) + Gains (dB) – Losses (dB)

- As previously determined:
  - Transmitted power = 25 dBm (for MCS10, Ubiquiti Rocket M5)
  - Gains = TX antenna gain + RX antenna gain
    - For our example, we are assuming 30 dB dishes on both ends
    - So, gains = 30 dB + 30 dB = 60 dB
  - Losses = FSPL + cable loss + other losses
    - For our 25 km example at 5.8 GHz, FSPL = 136 dB
    - For our example, cable loss is 2 dB (1 dB on each end)
    - For our example, other losses are 0 dB
    - So, losses = 136 + 2 + 0 = 138 dB

- Received Power = 25 dBm + 60 dB – 138 dB = -53 dBm

Link Margin

- Link Margin (dB) =
  Received Power (dBm) – Receiver Sensitivity (dBm)

- As previously determined
  - Received Power = -53 dBm
  - Receiver Sensitivity = -88 dBm (for MCS10, Ubiquity Rocket M5)

- Link Margin = (-53 dBm) – (-88 dBm) = 35 dB

Maximum Channel Noise

- Maximum channel noise (dBm) =
  Received Power (dBm) – SNR (dB)

- As previously determined:
  - Received power = -53 dBm
  - SNR = 14 dB (for MCS10)

- Maximum channel noise = (-53 dBm) – (14 dB) = -67 dBm

Link Budget Analysis Process

- Gather bandwidth requirements
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  - Channel width, streams, modulation type, minimum SNR, TX power, RX sensitivity, gains, losses
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  - Received Power, Link Margin, Maximum Channel Noise
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  - Fade Margin
  - FCC regulations
- If necessary, make adjustments and repeat

Fade Margin

- The Rayleigh Fading Model describes the relationship between the link margin and the link availability as a percentage of time

% Availability	Unavailable Time / Day	Fade Margin (dB)
90	2.4 hrs	8
99	14.4 min	18
99.9	1.44 min	28
99.99	8.6 sec	38
99.999	0.864 sec	48

- A value of about 10-15 dB is generally recommended
- If the signal fades below the requirements for the selected MCS, most equipment will automatically renegotiate to a lower MCS (i.e. speed), if available, to keep the link up
- If the signal fades enough that a lower MCS is not possible, then the link will go down

Fade Margin

- We just calculated
  - o Link Margin = 35 dB
    - Link Margin = Received Power – Receiver Sensitivity
  - o Maximum Channel Noise = -67 dBm
    - Max Channel Noise = Received Power – SNR
- Both are dependent on the received power
- But the actual received power will vary due to fading
  - o If it drops by more than 35 dB, it will be below the receiver sensitivity (i.e. the receiver can’t hear it)
  - o If it drops below the noise floor, the receiver will not be able to distinguish it from other noise
- So how good are the above two numbers?

Link Margin vs. Fade Margin

- Link Margin = 35 dB
- Checking the Rayleigh Fading Model table, we see that we should be able to maintain the selected MCS at least 99.9% of the time

% Availability	Unavailable Time / Day	Fade Margin (dB)
90	2.4 hrs	8
99	14.4 min	18
99.9	1.44 min	28
99.99	8.6 sec	38
99.999	0.864 sec	48

← **35 dB**

Max Channel Noise vs. Fade Margin

- Maximum Channel Noise = -67 dBm
- Noise floor values vary, depending on other signals and directionality of antenna
- Typical values in 5.8 GHz band are -88 dBm to -93 dBm, a difference of 21 dB to 26 dB from the calculated maximum channel noise
- According to the Rayleigh Fading Model, that is enough to predict at least 99% availability of our selected MCS

% Availability	Unavailable Time / Day	Fade Margin (dB)
90	2.4 hrs	8
99	14.4 min	18
99.9	1.44 min	28
99.99	8.6 sec	38
99.999	0.864 sec	48

← **21-26 dB**

FCC Restrictions

- Check to make sure your power and antenna selections are legal
- FCC Part 15 places restrictions on TX power and EIRP
  - Different for each band
  - Different for different parts of 5 GHz band
  - Different for point-to-point vs. point-to-multi-point
  - Well documented – suggest building a cheat sheet
- FCC Part 97 lessens those restrictions but includes other restrictions
  - Traffic content, control operator, no encryption, …
    - For example: Be careful of encryption at the user data level, such as someone using an SSL connection to their e-mail server, …

Example: Part 15, 5.8GHz, P-to-P

- Part 15.407(a)(3):
  - For Point-to-Point in the upper 5.8 GHz band, if antenna gain is > 23 dB, then reduce TX power by 1 dB for each increase of 1 dB in antenna gain
- In our example:
  - With a 30 dB dish and 1 dB of cable loss, we must turn down the TX power to 24 dBm
  - But the previous calculations used 27 dBm (+/- 2 dB)
  - Need to recalculate with a legal TX power!

Cable Loss (dB):	1			
	Max PTP TX Power (dBm)			
	26 dB BW = 20 MHz		26 dB BW = 10 MHz	
Antenna Gain (dBi)	Upper	Middle (DFS)	Upper	Middle (DFS)
6	31.0	25.0	28.0	22.0
7	31.0	25.0	28.0	22.0
8	31.0	25.0	28.0	22.0
9	31.0	25.0	28.0	22.0
10	31.0	25.0	28.0	22.0
11	31.0	25.0	28.0	22.0
12	31.0	25.0	28.0	22.0
13	31.0	25.0	28.0	22.0
14	31.0	25.0	28.0	22.0
15	31.0	25.0	28.0	22.0
16	31.0	25.0	28.0	22.0
17	31.0	25.0	28.0	22.0
18	31.0	25.0	28.0	22.0
19	31.0	25.0	28.0	22.0
20	31.0	25.0	28.0	22.0
21	31.0	25.0	28.0	22.0
22	31.0	25.0	28.0	22.0
23	31.0	25.0	28.0	22.0
24	30.0	24.0	27.0	21.0
25	29.0	23.0	26.0	20.0
26	28.0	22.0	25.0	19.0
27	27.0	21.0	24.0	18.0
28	26.0	20.0	23.0	17.0
29	25.0	19.0	22.0	16.0
30	24.0	18.0	21.0	15.0
31	23.0	17.0	20.0	14.0
32	22.0	16.0	19.0	13.0
33	21.0	15.0	18.0	12.0
34	20.0	14.0	17.0	11.0

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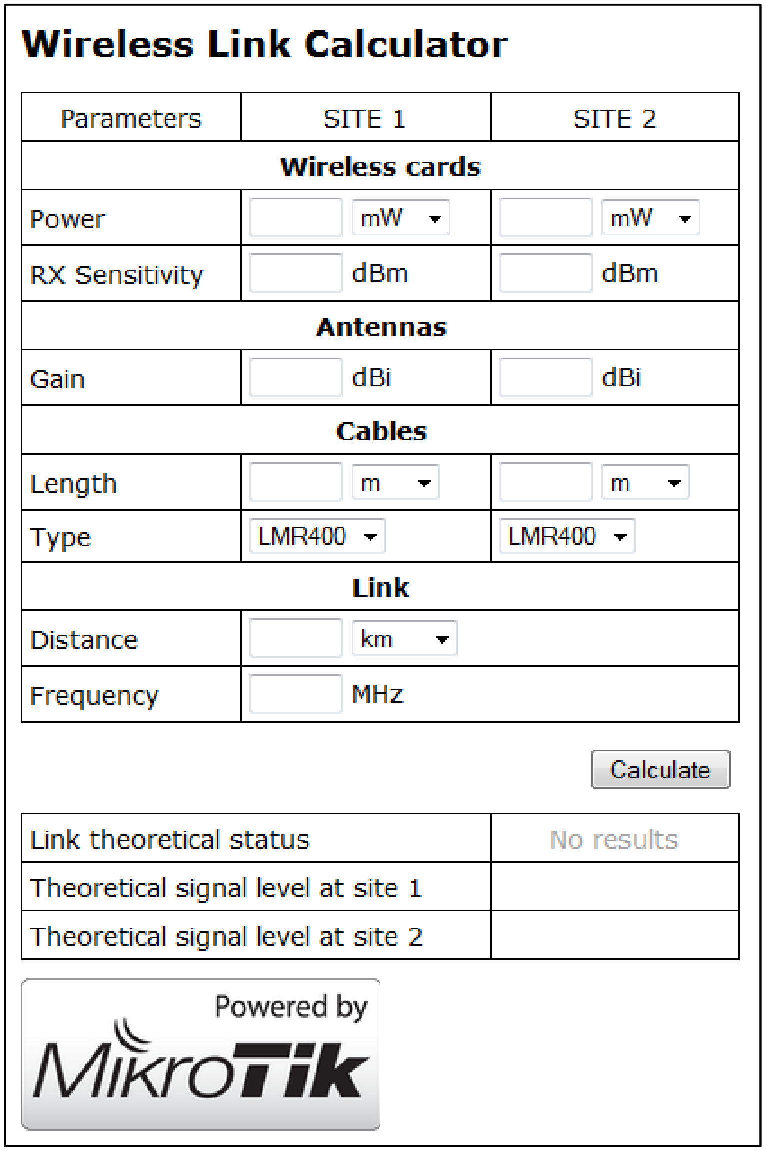
Adjustments

- If you have plenty of signal
  - Please turn it down (required in Part 97). We all have to share the band. Use only what you need.
- If you don't have enough signal
  - Use higher TX power (if legal)
  - Use higher gain antenna (if legal)
  - Use lower MCS
  - Select a different site
  - Select a different network topology
  - Select a different frequency band
- After you make any necessary adjustments, repeat the calculations using the new values

Other Calculations

- In the previous example, we calculated the margins from the other values
- But, by re-arranging the terms in the previous equations, we can figure out the answers to many other practical and useful questions, such as:
  - For a given situation, what is the minimum antenna gain?
  - For a given situation, what is the minimum transmit power?
- These are left as exercises for the reader
  - Don't you love it when you read that?!!!

Link Budget Calculators



- Popular
  - Ubiquiti Link Calculator
  - MicroTik Link Calculator
- Note:
  - You still need to come up with the right numbers to plug into the calculator!
- Full radio propagation analysis
  - Radio Mobile
  - Can display probability distribution

Technology Analysis

- So, Part 97 mesh, or Part 15 802.11, or some of both?

802.11 Carrier Equipment (Part 15)	**Broadband HamNet Software (Part 97)**	**Other?**
TDMA – no hidden transmitter problems	CSMA – hidden transmitter problems	??
Security (encryption)	No security (no encryption)	??
No content restrictions	Content restrictions – must control access	??
No control operator needed	Control operator needed	??
Limited EIRP (range)	EIRP (range) not as much of an issue	??
QoS (helps with disparate signal levels)	No QoS	??
Performance can be deterministic	Performance changes based on path	??
Pre-configuration, network planning req’s	Self-configuring, auto-discovery	??
Other ??	??	??

- It all comes back to “what problem are you trying to solve?”

Sequential vs. Iterative/Integrated

- This presentation showed a series of sequential steps
- In reality, the analysis is usually both iterative and integrated
- Bottom line
  - Start with a clear definition of the problem
  - You will save yourself a lot of time!

… there's a lot more …

… but that's enough for now.