Project	**IEEE 802.16 Broadband Wireless Access Working Group <http://ieee802.org/16>**
Title	**A Proposed High Data Rate 5.2/5.8Ghz Point to Multipoint MAN System**
Date Submitted	**2000-10-24**
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Re:	Call for Contributions: 802.16h-00/10
Abstract	High speed (multimedia) urban wireless data communications systems operating in the 5.2/5.8 GHz License Exempt (UNII) require careful consideration of the limited EIRP and propagation characteristics which typify this band. This document describes the dependence of propagation path loss exponent on distance within the urban canopy; the effect of the urban canopy of side-lobe degradation and polarization isolation of directive antennas; and the effect of co-channel interference on high speed wireless systems using directive antennas. The document proposes the use of a highly sectorized, rosette based hub-centric system for urban LE communications.
Purpose	This document is intended to provide background information to sub-committee members. Emphasis is given to the necessity of specifying high directivity, low side-lobe antenna systems for outdoor sub-11 GHz wireless applications, especially License-Exempt applications where uncontrolled co-channel interference dominates performance.
Notice	
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Patent Policy and Procedures	

MILTON's Objectives

Design a high speed, scalable, multimedia wireless network capable of data delivery densities of 100 to 1000 Mbps/Km ^{2}. This highly reconfigurable network has to deliver high speed data to the urban home located within a highly foliated environment.

Defining Qualities

1.Uses 5 GHz because of its LE status and good propagation characteristics.
2.Developed around a frequency re-use/space division concept that minimizes and controls C/I, thereby enhancing overall network capacity.
3.Uses a MAC protocol and PHY layer that supports TCP/IP and Ethernet in a wireless environment.
4.Has a simple technical infrastructure that is robust, easy to use and install, and is easily interfaced with existing backhaul networks…but not dependent on any specific network.
5.Gives the "Mom and Pop" neighborhood service sector the ability to invest in the broadband wireless revolution: Invent an open-system architecture for wireless hardware: "Linux for High Speed Wireless Access".

The Proposed Wireless Network

- Uses a Micro/Macrocellular architecture to achieve frequency reuse and capacity objectives.

- Incorporates high directivity antennas to reduce Power Amplifier/RF constraints and simplify modem requirements by reducing delay spread and co-channel interference.

- Macrocell (Rosette) cell diameters are defined by EIRP limits, propagation, and by user take up and capacity requirements.

- Uses a high capacity Fiber Optical Backhaul.

- Assumes a distributed network of switches and servers, located on the FO Backhaul

- Anticipates high data density content such as video and other interactive media; has high bi-directionality.

Issue #1: The Performance of 5 GHz in the Foliated Urban Environment

Summary of Propagation through the Urban Canopy at LE 5.2/5.8 GHz

- A wireless network cannot be properly designed without an intimate knowledge of the propagation environment.

- With MILTON a Highly foliated urban environment with some blockage and obstructions is assumed.

- Limited Power of the LE Bands necessitates the use of highly directive antennas to achieve frequency reuse, minimize delay spread, limit C/I, and enhance link power (C/(No+Io))

- Experiments show that in foliated environment Path Loss Exponent varies with distance:

  $P_l = 0.0002*D + 2.559$ (D in meters).

  For hub antennas at 25 M, subscribers at 11 meters

- Link budget and propagation analysis show that reasonable rosette diameters are ~ 2500 meters.

- Highly directive antenna side-lobe isolation degrades by 5-12 dB because of the urban canopy.

- Fading rates for wind induced tree motion of up to 180 dB/sec; 15-25 dB fade depths.

- Polarization isolation can be used.

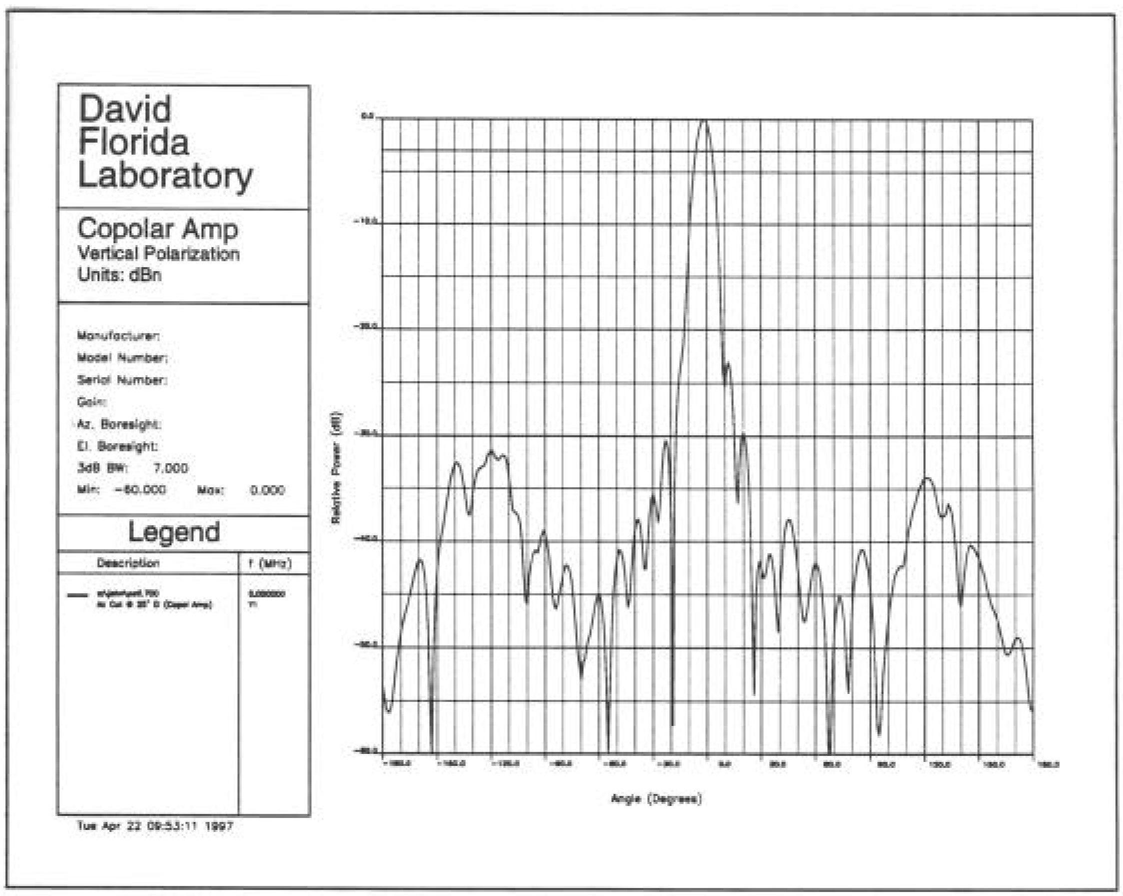
The Urban Canopy

Illustrated below is part of a 6 Km^2 test area where propagation studies and data transmission trials were undertaken. This area is an urban/residential neighborhood having about 1600 households per Km^2. Houses here have roof peaks 11-16 meters above street level. The area is heavily foliated with mature Maple and Oak trees, most of which are 15 meters and higher. This area is typical of the older neighborhoods which surround the urban cores of cities throughout the world and represents one of the most difficult propagation environments with which broadband wireless communications must contend. The distance between the point where this photo was taken and the stadium at the top left (on the horizon) is about 1500 meters. The height of the point from where the photo was taken is about 30 meters above street level.

High Directivity Antennas

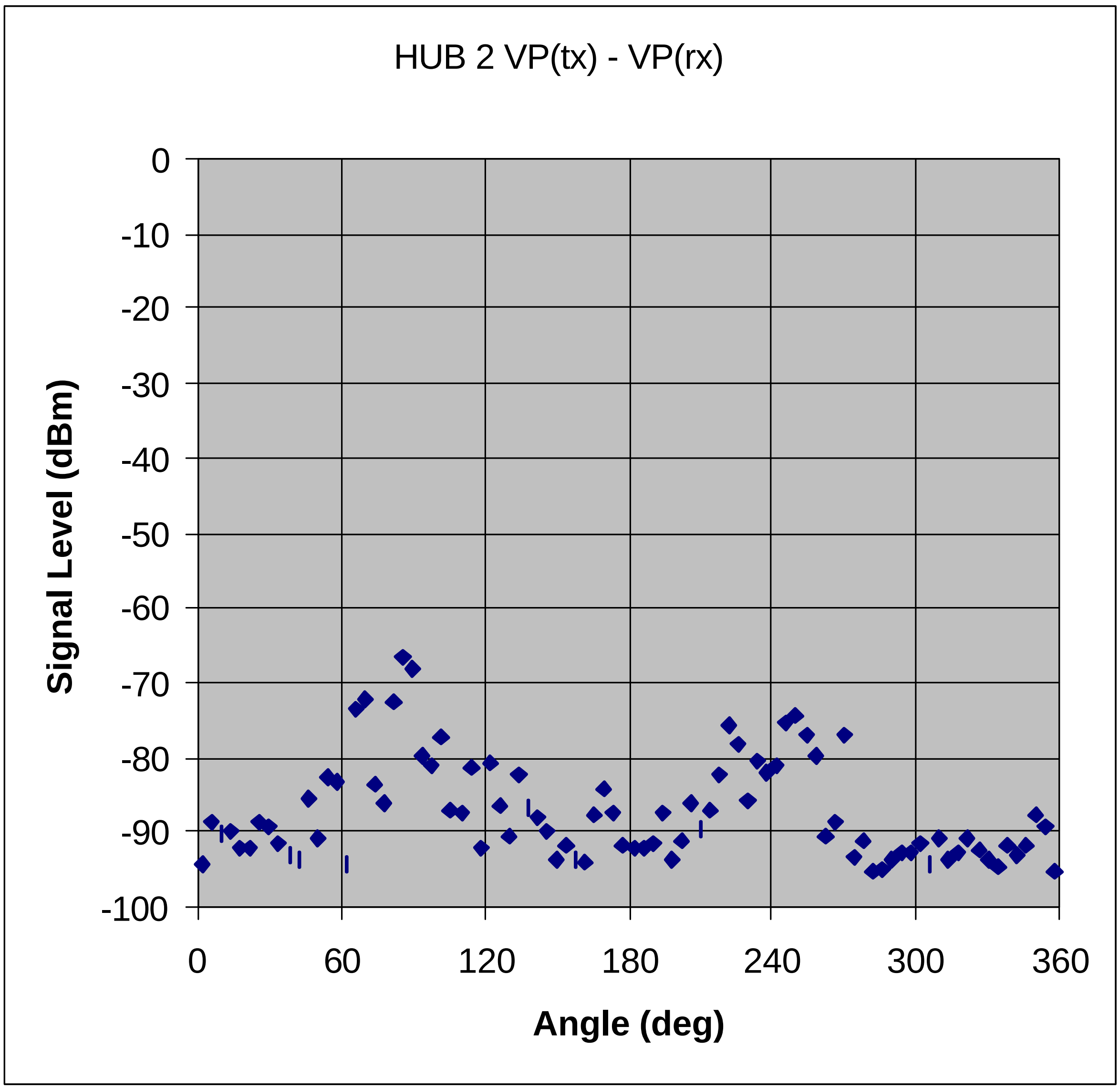
High frequency reuse, the mitigation of co-channel interference and delay spread, and the generation of link gain is attained by using high directivity, low side-lobe antennas. Multiple arrays of such antennas are used at the hub while single antennas are used at the subscriber's premises. Antennas with such characteristics were used in the propagation analysis and in the co-channel interference studies forming part of this study.

Shown below is the anechoic chamber measurement of a typical low-side lobe, high directivity antenna used in the study. The gain of the antenna is approximately 26 dBiC; side-lobe levels are typically –35 dB or better at angles +/- 45 degrees off boresite. The operational frequency of the antenna shown below is 5.2 GHz. The antenna was built using a DVB Ku band satellite dish with a modified, low side-lobe 5 GHz feed.



Multipath Generated by Discrete Distant Reflectors

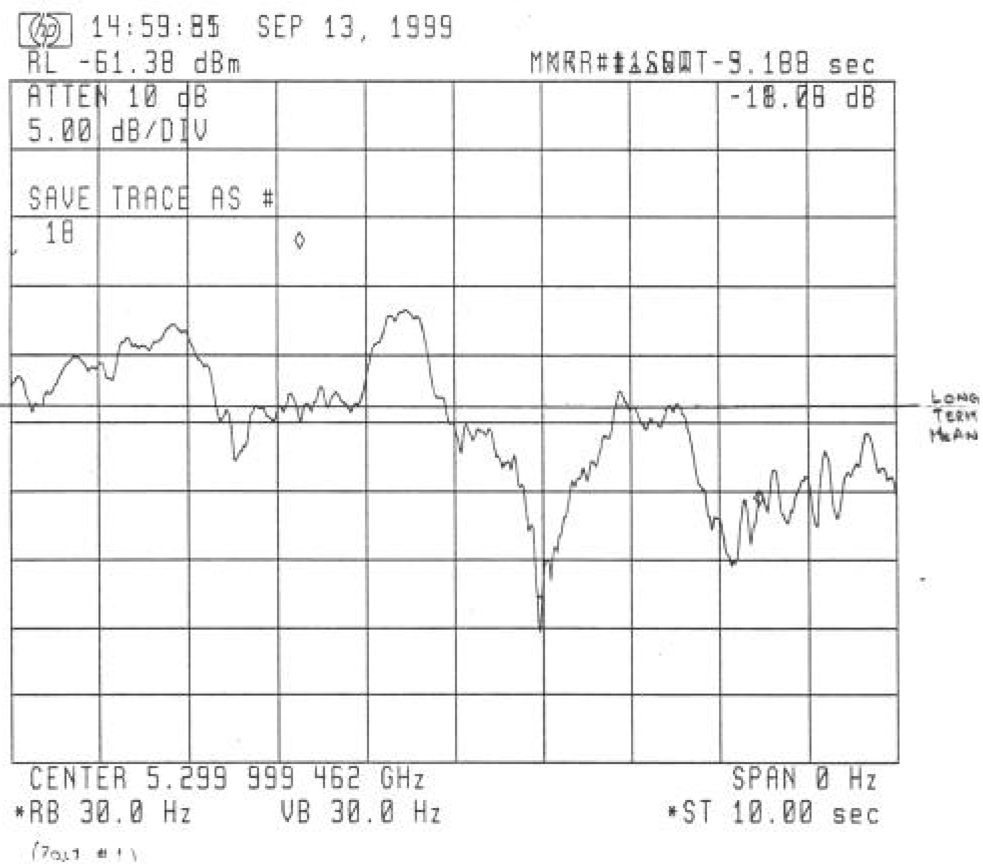
Example:
Using a highly directive source radiating into the urban canopy, a subscriber station located 1275 meters from the source sees three strong signals: the direct signal at ~ 85 degrees and two strong multipath signals at ~200 and ~260 degrees. Lower power multipath signals are seen at 120 & 170 degrees. A highly directive antenna aimed at 75 degrees would effectively suppress the multipath interference. Such multipath is due to discrete distant reflectors such as buildings or steel utility poles.



Multipath due to close-by Reflection/Diffraction

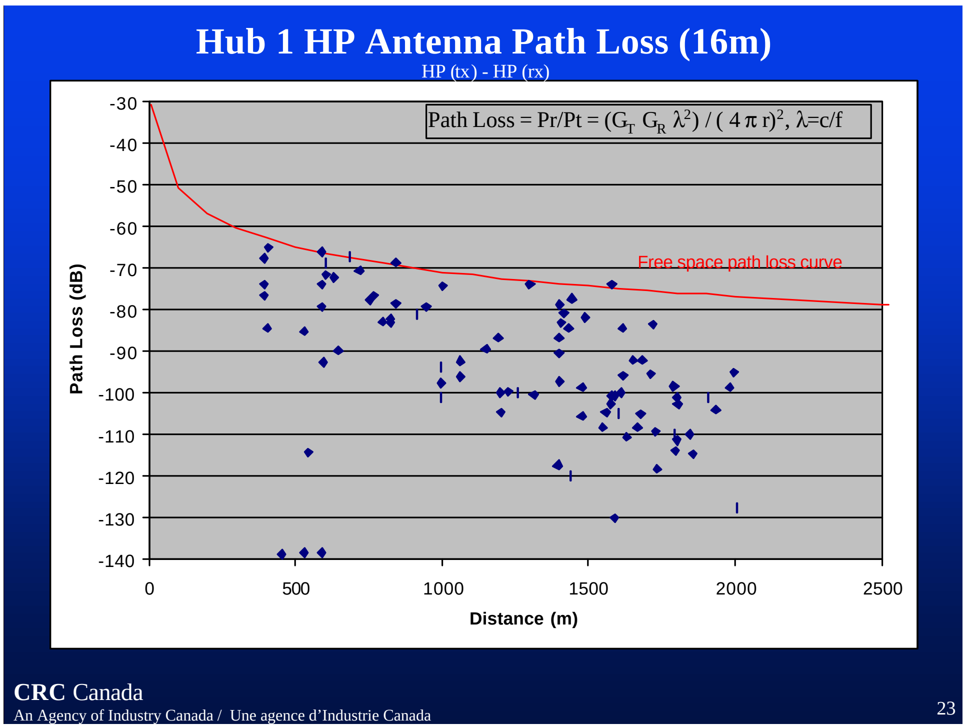
Diffraction, reflection, and attenuation of radio signals from the branches and trunks of trees illuminated by the directive antenna can cause rapid signal variation when the trees are in motion because of wind. These phenomenae will not cause significant delay spread or phase changes to the modulated signal but they will produce severe temporal amplitude variations which can be problematic to the operation of the modems operating on the link.

Shown below is the variation in signal level recorded with a 5.2 GHz signal passing through a 50 meter wide copse of Poplar trees. Transmitting and receiving antennas (highly directive) were on each side of the trees and separated by ~120 meters. Trees were in motion, moved by winds of 20 Km/hr. Span time is 9.2 second. Fade depths of –17 dB wrt the mean signal level were noted. Similar experiments have shown the fade rate to be as high as 180 dB/Sec. Fade depths can be up to 25 dB.



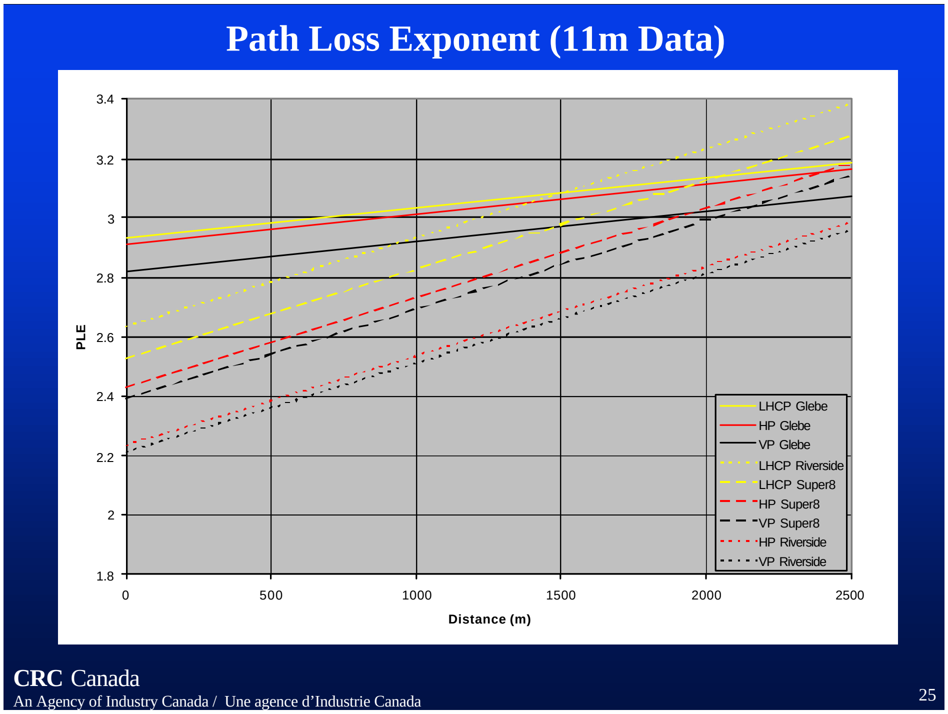
Propagation Path Loss

Shown below is the distribution of path loss exponent for signals passing through the urban canopy, with free space loss as a reference.



Note that at some sites (500 meters) there is a significant loss, showing total obstruction by buildings; other sites show loss at the free space level indicating an unobstructed view of the hub transmitter from the subscriber site. The majority of sites however indicate a loss in signal higher than free space alone….these are for sites obstructed by trees, roof edges, etc. The above data was for a site with the hub antenna at 27 meters above street level while each subscriber measurement was done at 16 meters above street level.

The propagation path loss exponent (P_{le}) varies as a function of distance, height of antennas, and polarization. By plotting P_{le} as a function for these variables for all the data collected during the 5 GHz propagation study (800+ measurements in a 2 km diameter urban canopy), we begin to see a clearer picture of the effect of these individual variables on the P_{le}, Notably, its increase with distance.

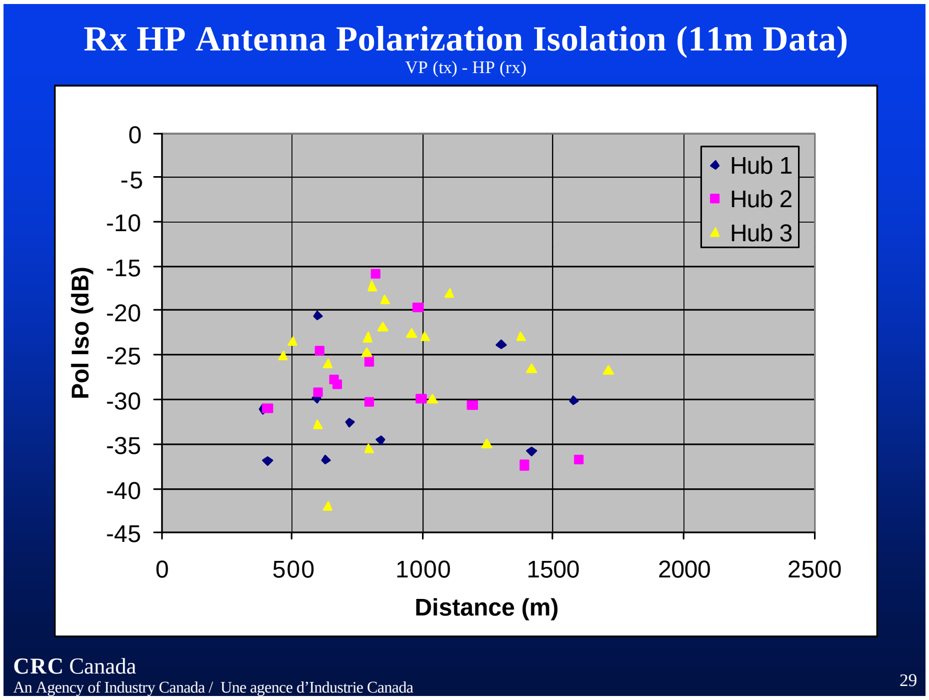


The above Path Loss Exponent graph was for all data collected at the 11 meter subscriber height; 3 polarizations, and TX station heights in ascending height (21, 27, 28 meters).

Polarization Isolation

Frequency reuse in MILTON may rely on polarization isolation, a technique whereby same frequency, adjacent macrocells are isolated from each other's interference by the use of different antenna polarizations. However, the concern is that the propagation medium, such as the urban canopy, will adversely affect polarization isolation by rotating one polarization into the other. This can occur by a series of progressive reflections and diffraction, and can be exacerbated by rain, wet vegetation, etc.

At 5 GHz the urban canopy can degrade cross polarization to as high as –15 dB (with antennas that typically had > -35db of measured cross polarization). However, in the majority of the data points the cross polarization was between –20 to –30 dB. The cross polarization also did not change with subscriber antenna height, nor did it change with distance…indicating that the cross-polarization phenomena is likely due to isolated occurrences, such as strong reflections off angled conductors. The results indicate that the urban canopy has only a nominal effect on depolarization.

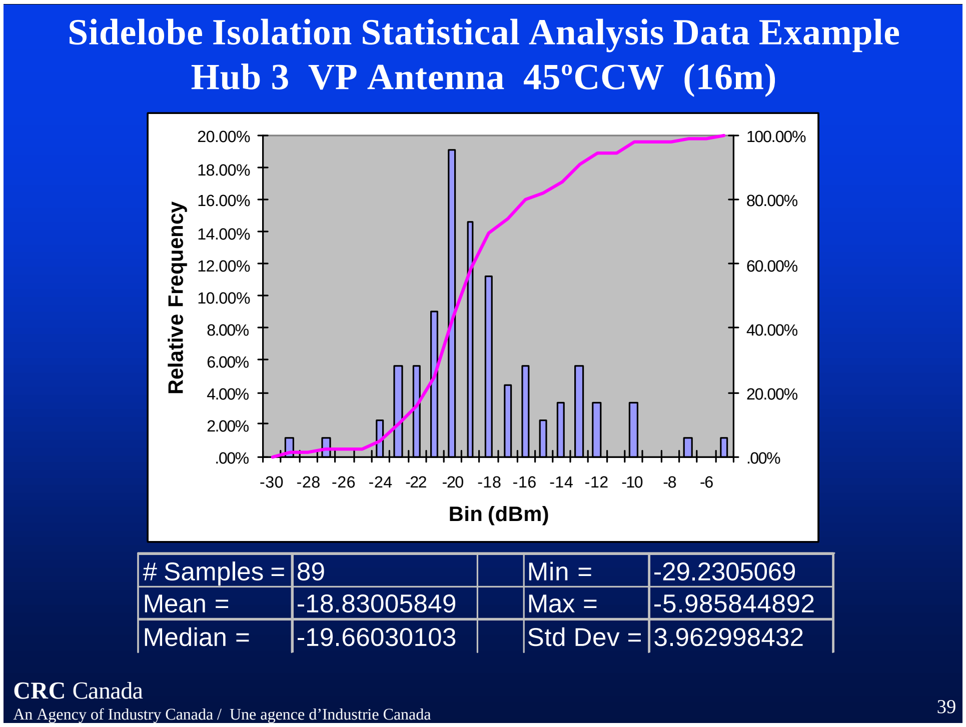


Beam Spreading

The MILTON wireless network is built around the premise that like-frequency microcells are spatially isolated from each other, and that this isolation is enhanced by the use of high-directivity, low-sidelobe antennas. However, the passage of a directed radio wave through a massive scattering medium such as the urban canopy will cause the beam to spread, filling in the side-lobe regions with scattered power.

During the propagation study an effort was made to gauge the effect of the urban canopy on beam spreading. The amount of spreading was quantified by calculating the increase of side-lobe power for the directive antenna. All the test antennas were calibrated in an anechoic chamber prior to field testing.

The graph below shows a PDF of the degradation of side-lobe isolation. The antenna is vertically polarized. Its anechoic chamber measurement at 45 degrees gave it a peak to side-lobe level of –25 dB. This same antenna, at 16 meters above street level, within the urban canopy scattering environment, has a mean side-lobe level of –19 dB. The scattering environment degraded side-lobe level isolation by 6 dB.



Detailed analysis of the beam-spreading data indicated a number of interesting facts. Horizontal polarization was less affected than vertical polarization. The phenomena also did not show significant dependence on distance. Also, the level of spreading was related to the measured level of the side-lobes; ie: the lower the overall relative side-lobe level of the antenna, the lower the level of spreading.

The cause of the spreading and side-lobe infill is not known. However, the indication is that horizontal polarization is least affected and that in the design of the MILTON microcell (Petal) antennas one should aim to achieve the lowest side-lobe level possible.

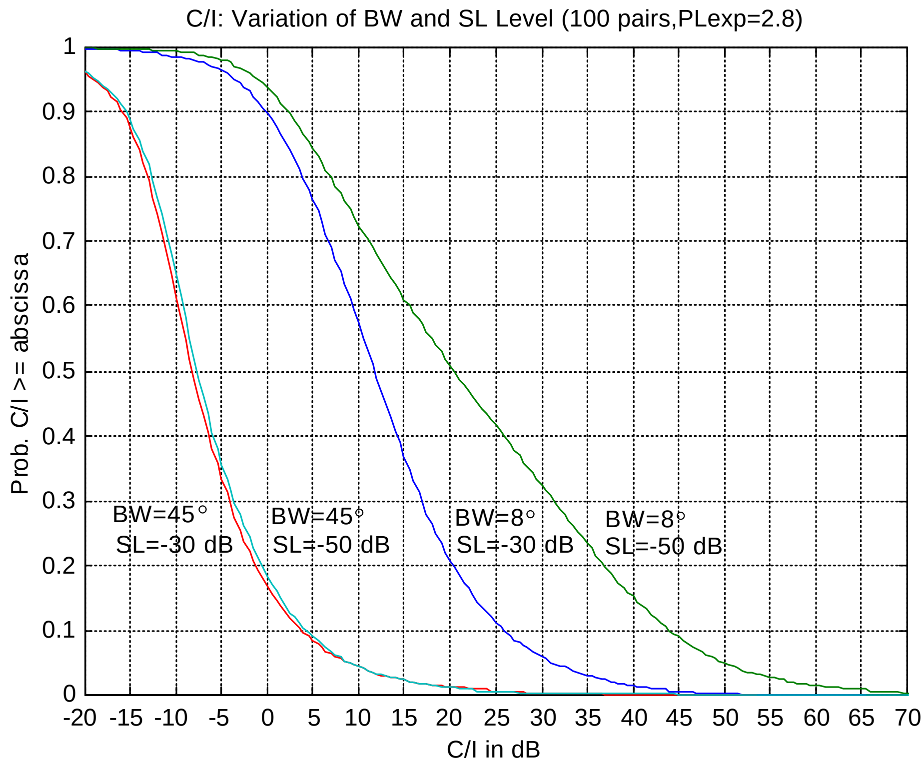
Issue#2: Develop a frequency re-use/space division concept that will minimize and control C/I.

Summary of Frequency Re-Use and Interference Control Using a MILTON Rosette/Microcell Architecture

- Co-Channel interference will set the performance limit on the MILTON License-Exempt wireless network.
- MILTON (and all other wireless) network co-channel interference is significantly improved by reducing the beam-width and side-lobe level of link antennas.
- Side-lobe level improves C/Io only when narrow beam antennas are used in wide-coverage wireless systems.
- The urban canopy will degrade the side-lobe isolation (see propagation work).
- Aggregating LE microcell-hubs into rosettes (concentric assemblages of oblong microcells, each created by a highly directive low side-lobe antenna) can more than double capacity of a LE wireless network compared to random placement of the same microcell-hubs.
- Rosettes can be rotated with respect to each other to reduce C/Io and improve capacity.
- Forward link power must be kept constant; return link must have power control to preserve useable C/Io.
- Significant performance enhancement is achieved by allowing subscribers to choose best of 3 adjacent rosettes.

The Advantage of Low Side-Lobe High Directivity Antennas

Simulations show that for the typical Urban Canopy environment with co-channel users forming a wireless network, the co-channel interference experienced by the users is highly dependent on the beamwidth and side-lobe level of the network antennas. Incorporation of low-side lobes improves C/I only when high directivity (narrow beam-width) antennas are used.



The above simulation was for 100 links randomly spaced over a 400 Km sq. urban area. Link distances were randomly chosen to be 500-10000 meters. All users were at the same EIRP. The capacity of a co-channel wireless network improves further if we assemble microcells into rosettes. For example, if all the 8 degree –30 dB sidelobe randomly oriented microcells are arranged in concenrtrically around hubs, the probability of having a link C/I greater than 15 dB increases to 0.95 (up from 0.39 in the random placement)

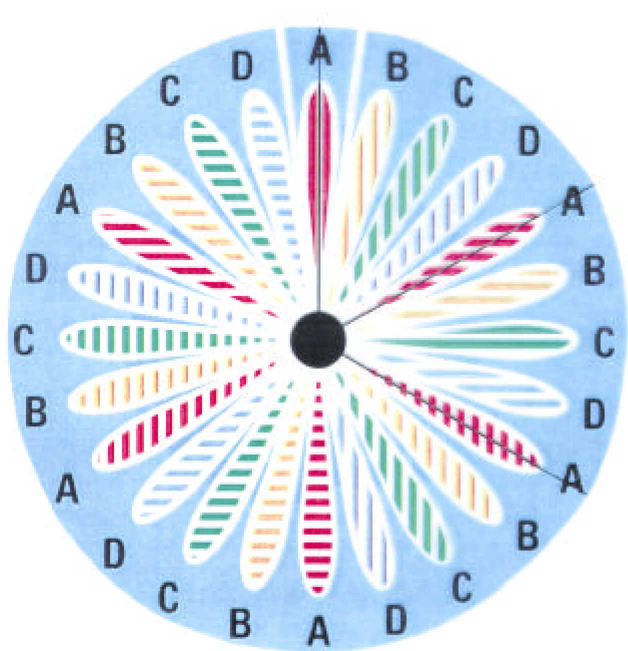
Rosette Architectures and Co-Channel Interference Control

Rosette cells are formed by placing highly directive antennas concentrically around a hub. Each antenna has the same radiation characteristics. Given N like-frequency bands, then if there are M total microcells (antennas) in a rosette, then there are M/N like-frequency microcells in the rosette. Like-frequency microcells are repeated and spaced every 360*N/M degrees. If S_L is the peak to sidelobe level of the microcell antenna at the angles of the repeated frequency microcells; then the co-channel intercell interference generated by rosette will be:

$$C/I_o = -\{10*\text{Log}((M/N)-1) + S_L + \alpha_S\}$$

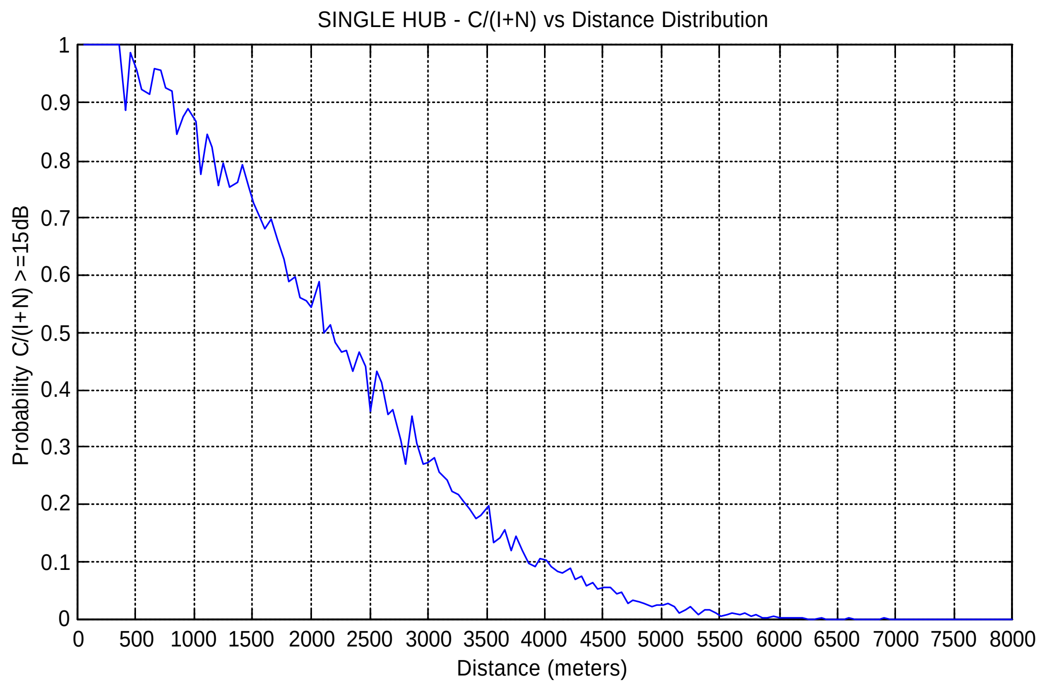
where α_S is the sidelobe degradation factor (in dB); C/I_o is the carrier power to co-channel interference ratio in dB.

In a rosette macrocell, the individual like-frequency oblong microcells are called petals. Illustrated below is a 24 petal rosette re-using 4 like frequency bands (A,B,C,D). Each rosette contains 6 petals of the same frequency.



Co-Channel Performance of a Single MILTON Rosette

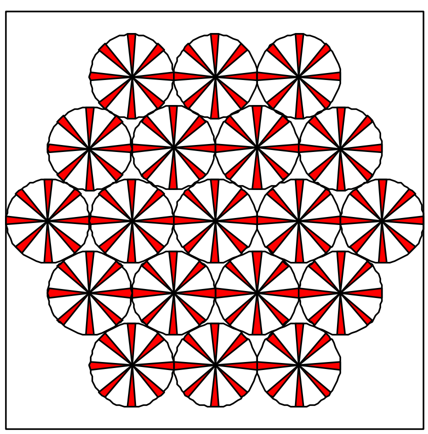
Shown below is the simulated Co-channel performance of a single rosette. The rosette hub was assumed to be at 25 meters height, operating at 5.2 GHz, having a side-lobe level of –35 dB, and operating in an urban environment having a side-lobe degradation of 7 dB. The rosette contained 32 petals and re-used 4 like frequency bands 8 times per rosette. EIRP was 34 dBm/MHz for each petal and the noise temperature of the receiver was taken at 290 K. Subscriber antennas had a gain of 16 dB and were positioned 11 meters above the street. The propagation path loss exponent, taken from real data, had a mean value of (0.0002*D+2.559). Included in the simulation was the variation in the path loss exponent, taken from measured data.

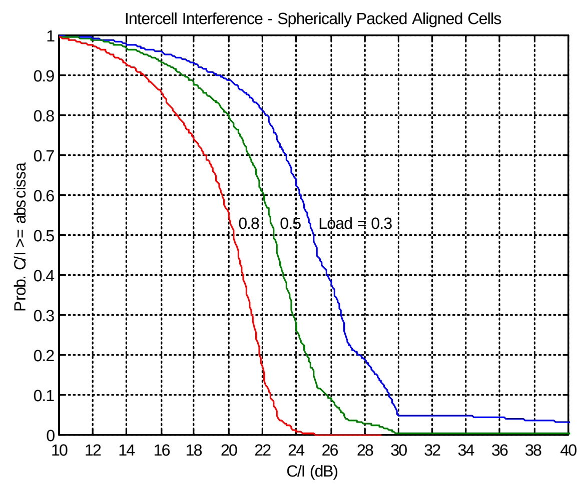


These data show the probability of achieving a C/(Io+No) of 15 dB. As can be seen, probability of achieving this performance objective drops off rapidly with distance. Beyond 1500 meters, there is less than a 70% probability of achieving the 15 dB criterion. At 3000 meters from the hub, the probability drops to 28%.

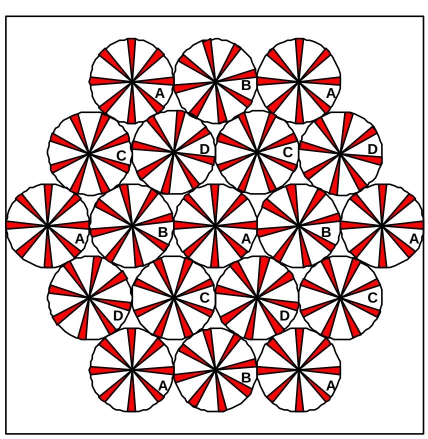
Assemblages of Rosettes; C/I Mitigation by Rosette Rotation

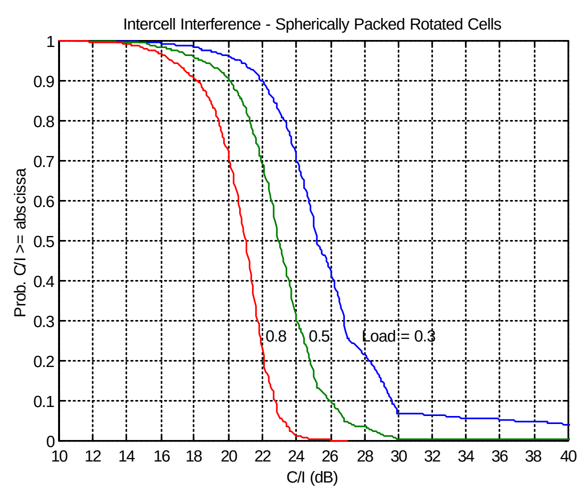
Rosette macrocells can be packed next to each other to form hexagonally packed assemblages, thus giving coverage to a wide area. In such packing architectures co-channel interference seen by the typical subscriber will be due to intra-cell interference, generated by the rosette to which the user is assigned, and inter-cell interference, generated by all the adjacent rosettes' like-frequency petals. The simulations shown below demonstrate the ability to mitigate the co-channel interference seen by the user by rotation of adjacent, like-frequency petals. Performance under different system loading is shown.





Aligned Like-Frequency Petals



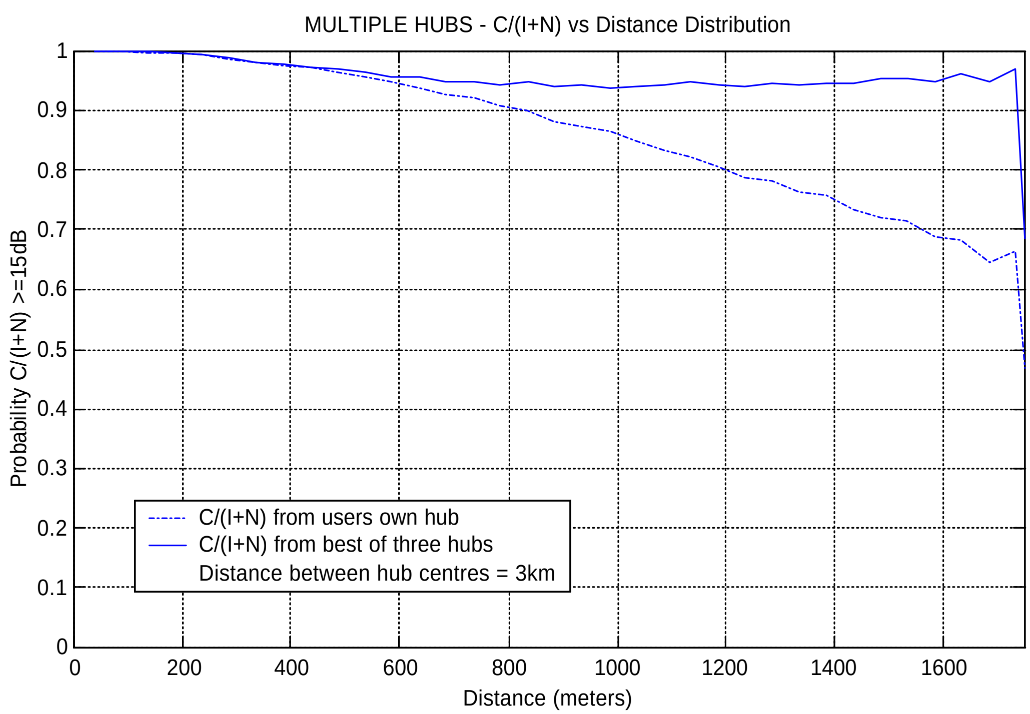


Skewed Like-Frequency Petals

Performance Enhancement by allowing Rosette Selection

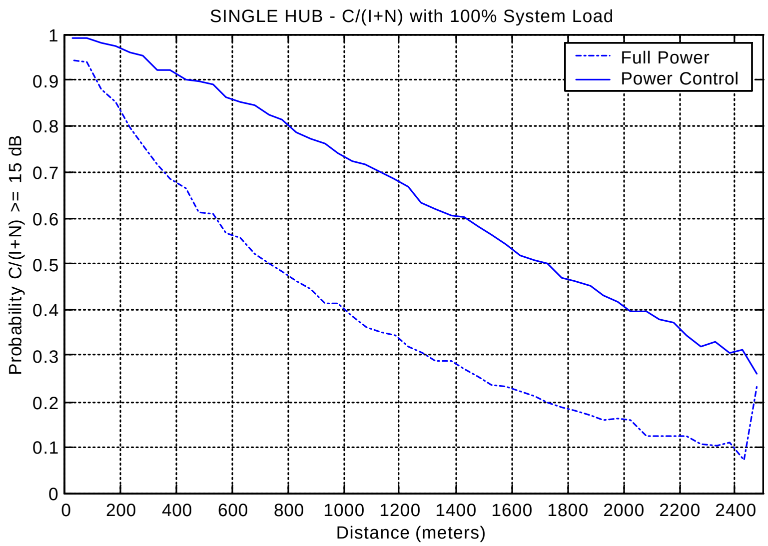
Many users, especially those close to the periphery of a rosette coverage area (1000+ meters from the hub) will see better quality signals with less co-channel interference emanating from adjacent rosettes.

The simulation plotted below, and based on the real world operating conditions and parameters given for the single rosette described above, shows the improvement in performance if the user has a choice of up to 3 rosettes. Separation of adjacent rosette centres is taken at 3 Km.

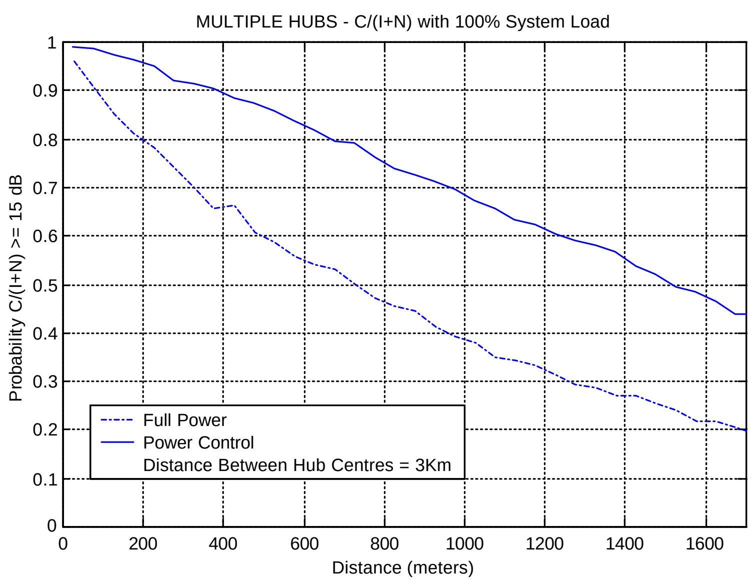


Power Control on the Return Link

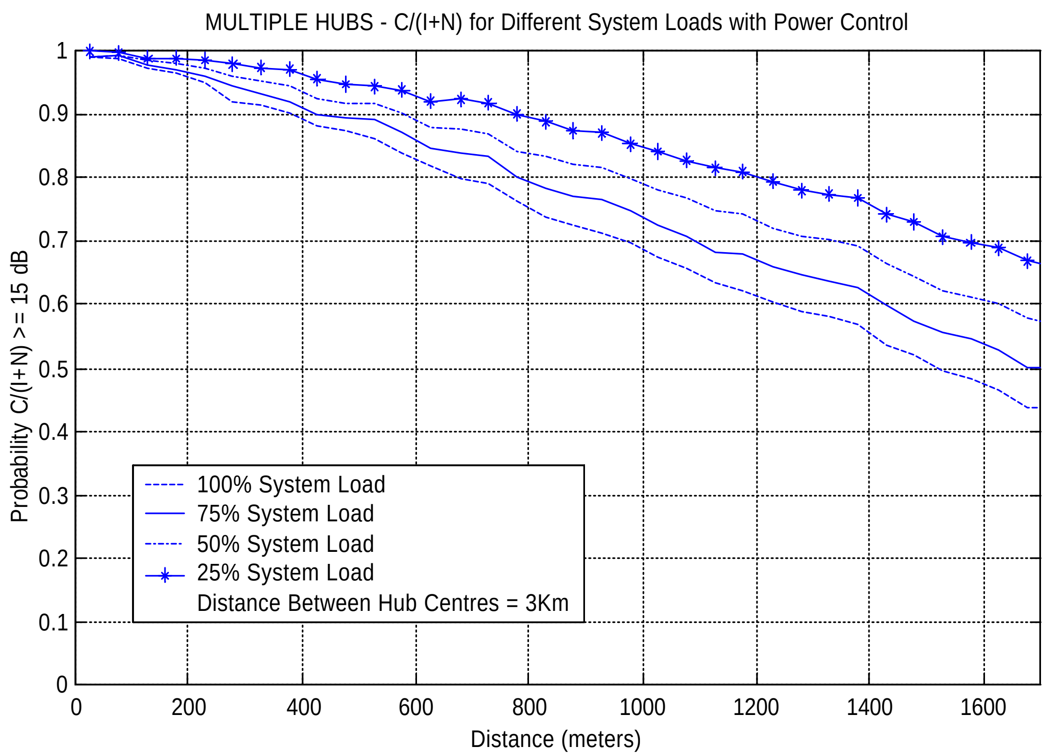
Though forward link power must be kept at a constant EIRP in order to provide all co-channel users with the same C/I, this strategy does not apply to the return link. Shown below is the probability of having a 15 dB or better C/I on the return link, given the single rosette system parameters described above. The simulation shown below assumes full return link loading.



For an assemblage of packed rosettes, the C/I is slightly worse, as shown below. Unlike the above case, intercell interference is present causing slight degradation in the C/I.



Since the return link is rarely fully loaded, there can be a (since it is usually the return channel for a TCP/IP interaction) significant variation in the co-channel interference.



Summary of MAC and PHY Layer Research

- Current MAC protocol based on a ETS 300 421 PHY layer; can be modified to IEEE 802.11a
- Designed around delays due to modems and measured user statistics for TCP/IP traffic
- Collision Avoidance Dynamic P-Persistence algorithm used which provides subscriber MAC's with a dynamically changing probability of accessing a contention slot.
- User terminals request specific bandwidth allocation; can be used for QOS applications.
- VOIP friendly
- Current design assumes a 3 Mbps ASK Burst modem capable of frequency agility.
- Burst modem has power monitoring: able to set power for worst case fading due to wind-induced tree motion.

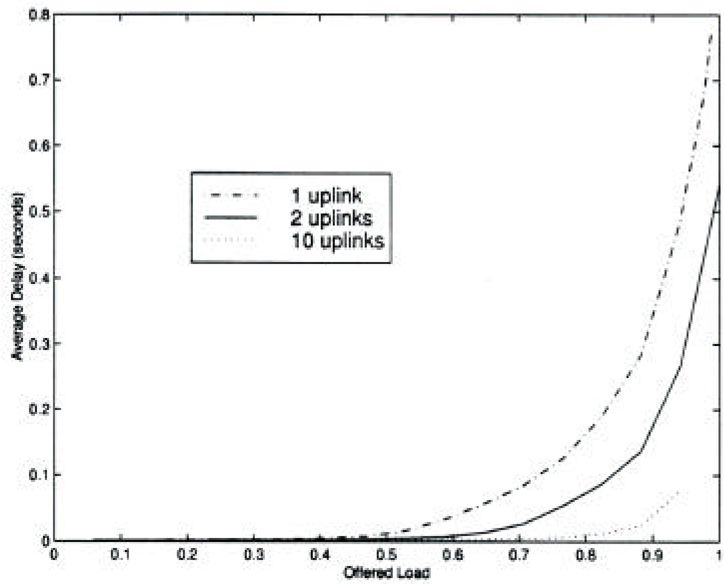


Figure 1

Offered Load	DPP delay mean (seconds)	ST delay mean (seconds)
0.02	8.68E-4	8.80E-4
0.19	1.27E-2	8.89E-3
0.76	5.96E-1	5.30E-1
0.86	1.17E0	1.98E0
0.92	3.80E0	4.19E0
0.95	7.98E0	1.05E1
0.99	4.48E1	5.47E1

Table 1. Mean packet delay using WWW traffic model

Offered Load	DPP delay variance (seconds)	ST delay variance (seconds)
0.02	2.52E-7	2.23E-7
0.19	6.55E-6	5.69E-6
0.76	3.43E-1	2.47E-1
0.86	2.10E0	1.73E0
0.92	6.22E0	5.80E0
0.95	1.28E1	1.22E1
0.99	1.34E2	1.30E2

Table 2. Packet delay variance using WWW traffic model

From Table 1 and Table 2 it can be seen that there is little difference between DPP and Spanning Tree.

Offered Load	DPP delay mean (seconds)	ST delay mean (seconds)
0.15	7.52E-3	5.52E-3
0.30	1.32E-2	1.10E-2
0.60	2.61E-2	2.32E-2
0.96	7.20E-1	7.28E-1
0.99	3.16E0	3.15E0

Table 3. Mean packet delay using the VOIP traffic model

Offered Load	DPP delay variance (seconds)	ST delay variance (seconds)
0.15	1.53E-5	1.30E-5
0.30	5.30E-5	4.98E-5
0.60	3.86E-4	2.13E-4
0.96	2.02E1	1.99E1
0.99	1.20E2	1.18E2

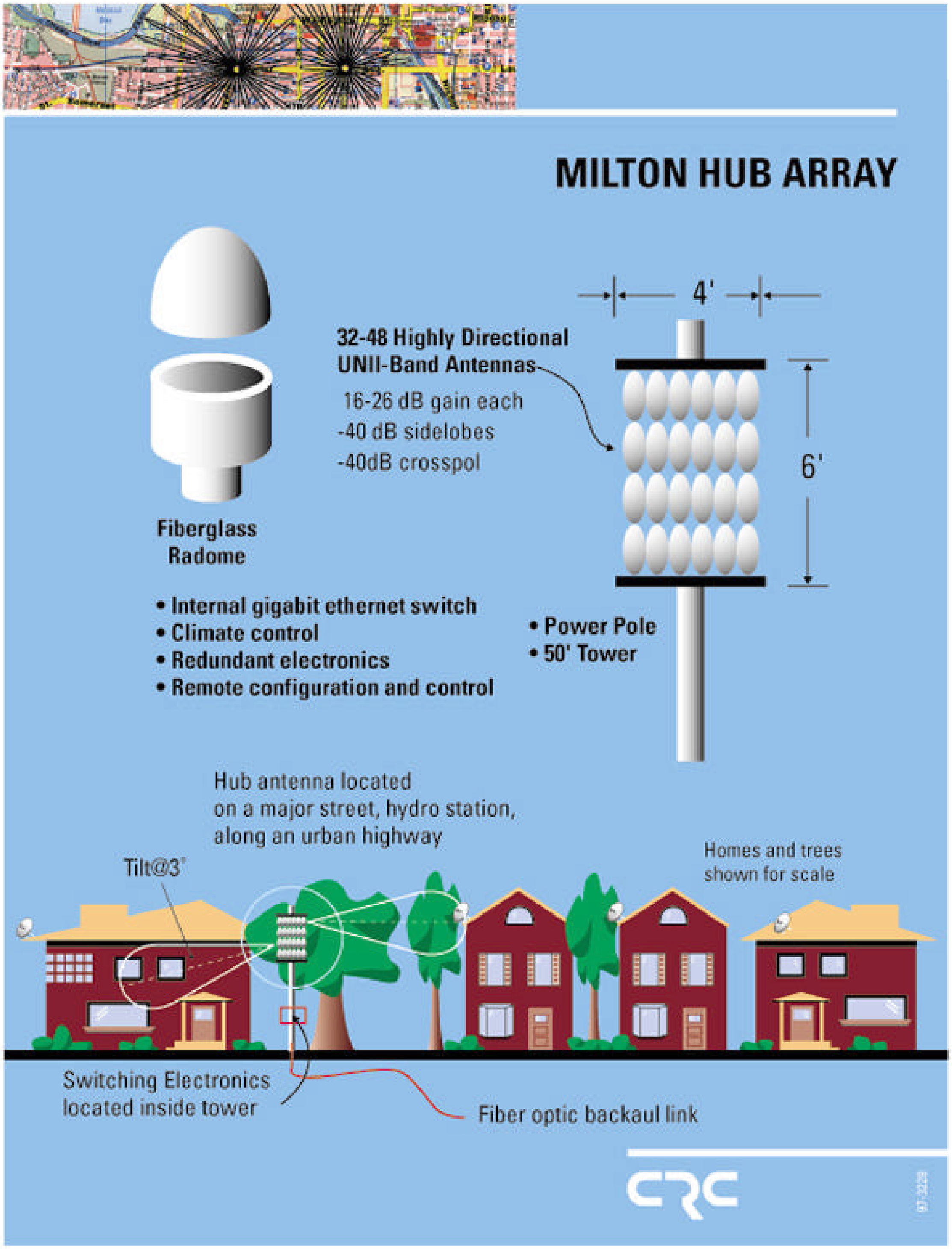
Table 4. Packet delay variance using the VOIP traffic model

Table 3 and Table 4 are generated using the VOIP traffic model. Again, the values for each are relatively the same.

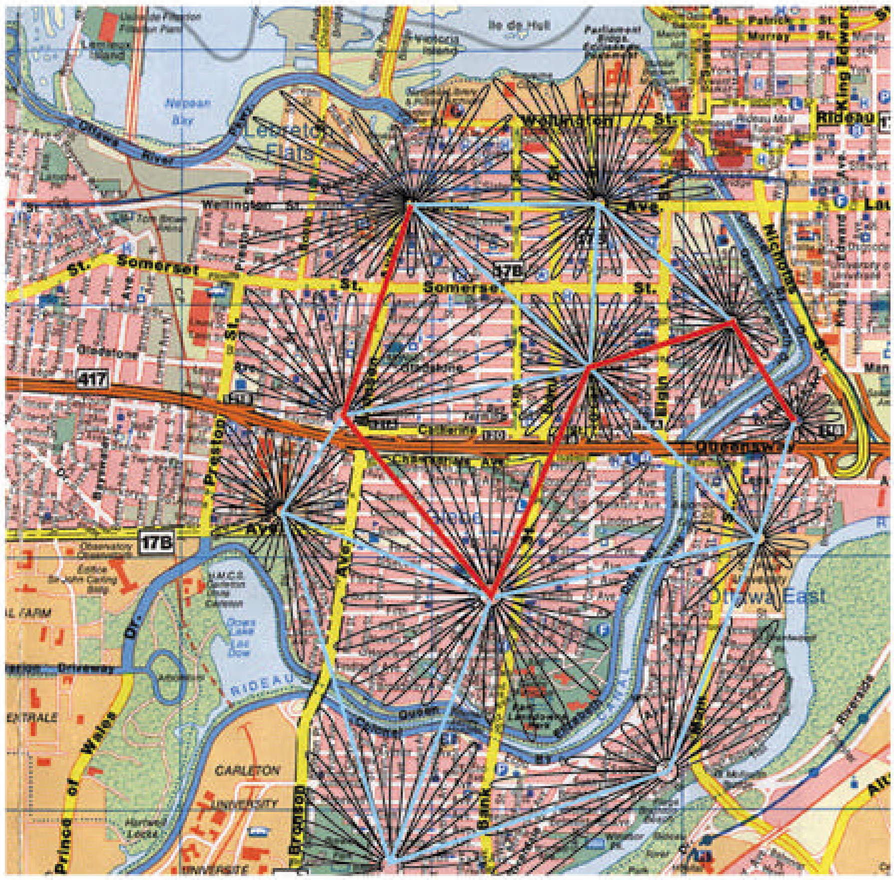
Issue#4 Technical Infrastructure

Hardware and System Implementation

- Forward link based on 22 Mbps/Petal link speed.
- Current Frequency plan has 6 x 16.6 MHz Like-Frequency Downlinks and 25 x 4 MHz Like-Frequency Uplinks.
- Current return link design based on 3 Mbps rate.
- QPSK ETS 300 421 Standard for forward link; high C/I tolerance (~10 dB); Eb/No ~ 8 dB for BER $1X10^{-10}$
- Design can accommodate IEEE 802.11a @ 54 Mbps
- Low cost subscriber hardware anticipated (~$150.00/QTY 10,000 with ASIC)
- Adaptive Subscriber Antenna Optional
- Gigabit Switching at Hub
- Systemic Co-Channel interference monitoring and control built into hub.
- Scalable with smaller radii rosettes located within large rosettes; polarization isolation used.
- Ongoing studies to support bandwidth on demand, mobile users, and 4G systems.
- Backhaul Network designed around optical OC 12/48 links to ATM switching centres.
- Video servers may be co-located at hub for low latency video-on-demand applications
- Tested with MPEG1 Video transport in a TCP/IP environment with good results (low jitter)
- QOS optional but may be redundant considering take-up, coverage area, and link rates…..eg: capacity of link may be significantly greater than user requirements.


MILTON HUB ARRAY
4'
32-48 Highly Directional
UNII-Band Antennas
16-26 dB gain each
-40 dB sidelobes
-40dB crosspol
6'
Fiberglass
Radome
• Internal gigabit ethernet switch
• Climate control
• Redundant electronics
• Remote configuration and control
• Power Pole
• 50' Tower
Hub antenna located
on a major street, hydro station,
along an urban highway
Tilt@3°
Homes and trees
shown for scale
Switching Electronics
located inside tower
Fiber optic backaul link

MILTON Deployment Over an Urban Area



Backbone Links

- High speed fiber optical (>2 GB/s)
- High speed microwave 24/38 GHz
- 5.250/5.350MHz or 5.725/5.825 MHz links to subscribers via IEEE 802.11a