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Title	**A Proposal to Standardize Directive Antennas and Highly Sectored Cellular Hub Systems For Outdoor Point to Multipoint Applications: IEEE 802.16.3 PHY Layer**
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Re:	IEEE 802.16.3 PHY layer request for proposals
Abstract	High directivity low side-lobe antennas, when used for outdoor applications, significantly mitigate co-channel interference and enhance the data carrying capacity of a bandwidth allocation. For last-mile applications it is recommended that highly sectored cellular hubs, which incorporate high directivity, low side lobe antennas, be used to provide urban connectivity. Such hubs would operate as neighborhood WLAN switching centres and use a number of monitoring and adaptive techniques to maintain robust links to urban households.
Purpose	The proposals made herein are intended to establish relationships between the propagation environment, antenna directivity, cell sectorization, cell size, and data delivery capacity. Any attempt to give the 2-11 GHz bands a meaningful wireless data carrying capacity should consider these factors as part of the proposed IEEE 802.16.3 PHY standard.
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A Proposal to Standardize Directive Antennas and Highly Sectored Cellular Hub Systems For Outdoor Point to Multipoint Applications
A Contribution to IEEE 802.16.3 PHY Layer

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1.0 Introduction

This paper proposes that highly directive, low side-lobe antennas be included in the IEEE 802.16.3 standard for all outdoor point to point/multipoint communication systems. This is important to both licensed and unlicensed (UNII) band applications as it will have significant impact on the aggregate data carrying capacity of the allocated band.

Secondly, a proposal is made that a PHY layer standard be developed for a highly sectorized cellular hub architecture designed for urban last-mile applications. The hubs would be deployed within neighborhoods and form wireless access points to optical fiber backbone networks.

2.0 Antenna Directivity and Low Side-Lobe Level

It is well known that high antenna directivity lowers the susceptibility of a wireless receiver to co-channel interference. High directivity also lowers the Power Amplifier (PA) output requirements and can improve the noise temperature of a radio system. Lowering the PA output makes it simpler to design low cost and reliable wireless equipment. Furthermore it decreases the level of spurious emissions which has a beneficial effect to all users sharing bandwidth.

If the data carrying capacity of an allocation of bandwidth is to be maximized it is important to minimize the side-lobe levels of the directive antennas supporting the links. The graph given below (Fig 1) shows the probability of achieving a C/I level for a simulated communications link that spans anywhere from 500 to 10,000 meters. In the simulation the link shares the same bandwidth with 99 other links which are randomly oriented and spaced over a 400 Km^2 service area. All terminals are at the same EIRP; a propagation path loss exponent of 2.8 is factored into the link equations to simulate a foliated propagation environment. This scenario would be representative of a 5.2/5.8 GHz deployment of UNII terminals.

These simulations show the importance of having both directivity and low-side lobe level for outdoor wireless applications. Low side-lobe level antenna systems would be warranted for wireless applications where higher order modulation techniques are used because of the high C/I requirements of such techniques.

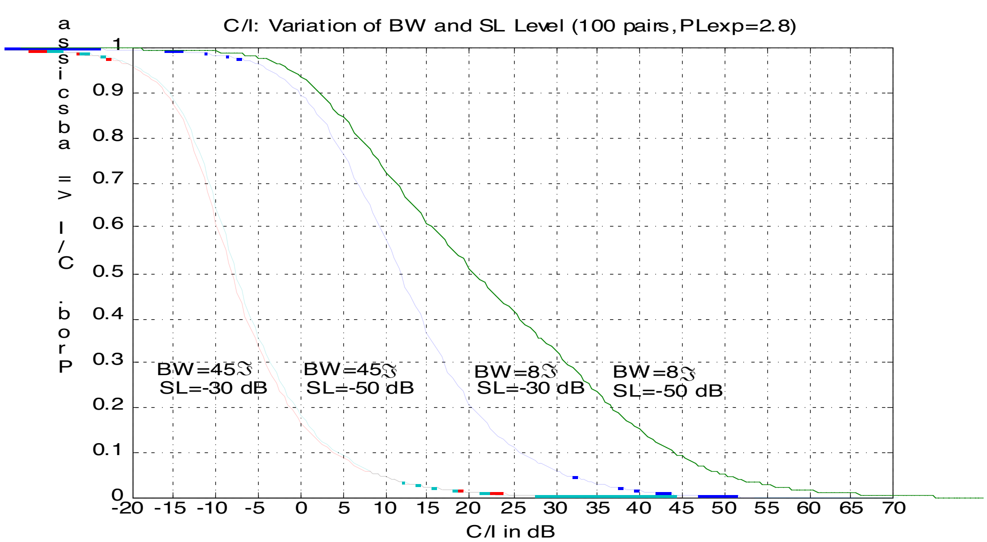


Figure 1: Probability of achieving a given C/I as a function of antenna directivity
100 Links randomly placed over a 400 km^2 Area.

It is recommended that the IEEE 802.16.3 standard include antenna directivity and side-lobe performance criteria. This is especially important to users of standardized equipment who are expecting consistent grades of service and data rates in geographical locales where frequency allocations may be reused extensively.

3.0 Achieving High Data Delivery Density in Outdoor Systems

The performance of wireless network can be measured by its data delivery density (DDD), that is, the information rate that can be delivered per coverage area. Units for this parameter can be $Mbps/Km^2$ or Mbps/cell. For a fixed bandwidth and coverage area the DDD can be increased by several means. One way is to increase the modulation spectral efficiency. This is done at the expense of increasing power. A second way is by sectoring a coverage area by using directive antennas and re-using part or all of the bandwidth allocation in the newly created sectors. This is done at the expense of increasing co-channel interference. Ultimately the best trade-off is one that balances modulation complexity against sectoring in such a manner that the DDD is maximized.

4.0 Co-Channel Interference in Highly Sectored Cells

It is possible to estimate the co-channel interference created in a sectored cell. It is assumed that N sectors are formed in a cell by using highly directional antennas that have a mean side-lobe level of S_L. The sectors are assumed to be concentric, spaced evenly around a single hub. The full bandwidth (B) allocated is repeated in each sector.

It is important to ensure a high degree of isolation between sectors. Each sector receives co-channel interference from its N-1 adjacent sectors. The level of the co-channel interference received is $(N-1)*S_L$.

There are a number of ways of ensuring that isolation between sectors is maintained. One way to do this is to spatially distribute the bandwidth allocation within a sector by sub-sectoring and dividing the bandwidth among the sub-sectors. Such techniques are described in Ref. 1-3. Sub-sectoring is a practical way of lowering the S_L of a sector.

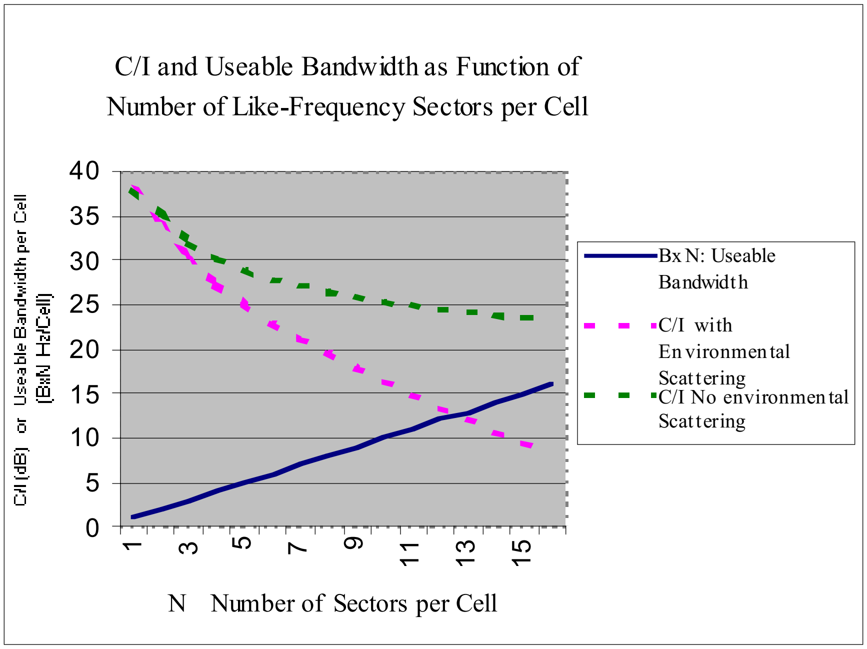
The mean co-channel interference that a subscriber (having a directional antenna equal to the one creating the sector) located within the cell will experience can be estimated by the following equation:

$$C/I = -\{10*\text{Log}\,(N-1)+S_L+a\} \quad N>1 \qquad \text{Eq. 1}$$

In this equation a represents the dB value by which the propagation environment degrades the side-lobe level. In effect, it represents the environmental scattering of the transmitted signal from one sector to the adjacent sectors. This value becomes larger as N increases; it is also dependent on the polarization, frequency, S_L of hub and receiving antennas, and the distance between the subscriber and hub. Our measurements at 5.2 GHz indicated that this value can be as high as 12-15 dB for N=8 for vertical polarization where S_L of the sector/subscriber antenna is 26 dB. For RHCP antennas with S_L of 35 dB, an a of 8 dB was observed. All measured values were for a highly foliated propagation environments with Path Loss Exponents of 2.8-3.2.

5.0 Bandwidth Generation by Highly Sectored Antenna Systems

If the allocated bandwidth (B) is repeated in every sector, then the total useable bandwidth generated is BxN. The useable bandwidth has a co-channel interference floor defined in Eq. 1. Shown in the graphs below is the relationship between the total useable bandwidth and the co-channel interference floor. Two C/I scenarios are examined; one in which a increases directly in proportion to N, representing a situation where scattering by the propagation environment is expected. In the second scenario it is assumed a is zero, representing an environment that has no scattering…..a setting with virtually no obstructions in the propagation path.



6.0 Choice of Modulations Schemes and Spectral Efficiency

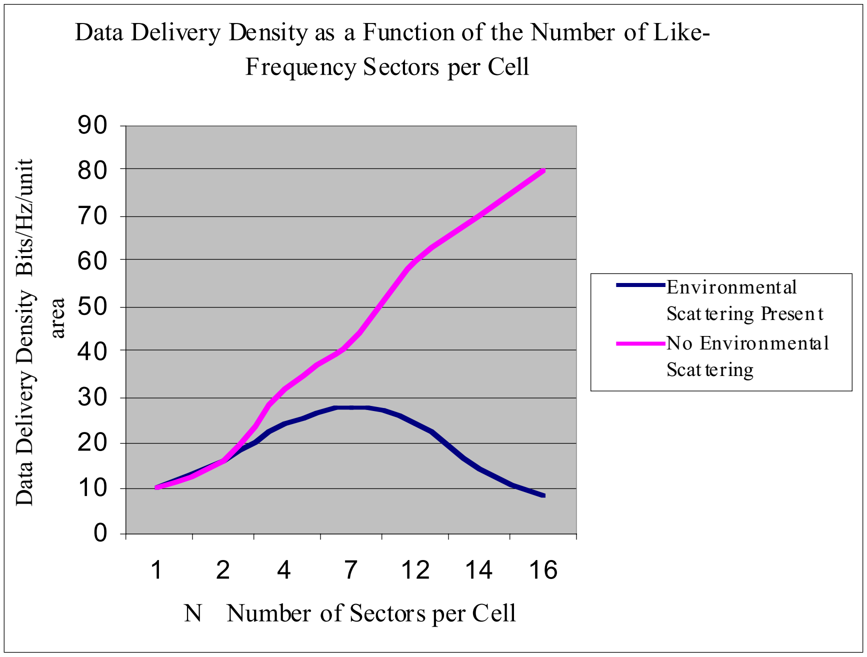
In the table listed below are a number of candidate modulation schemes that can be used for broadband wireless applications. The C/I necessary to achieve an uncoded BER of $1X10^{-6}$ for the modulation technique is given. In the analysis it is assumed that co-channel interference has the same statistical characteristics as thermal noise.

Modulation	Theoretical Spectral Efficiency (Bits/Sec/Hz)	C/I (dB) req'd for $1X10^{-6}$ BER (coherent demod)	Relative Power Per transmitted Bit (dB)	Max Number of Foliated Sectors per Cell for modulation
1024 QAM	10	38.5	7.5	1
256 QAM	8	32.6	6.5	~3
64 QAM	6	26.6	5.3	~4
16 QAM	4	20.4	3.5	~7
4QAM (QPSK)	2	13.6	0.5	~11
BPSK	1	11	0	~13

The spectral efficiencies of the various modulation techniques are shown, along with the relative power per transmitted bit. In the last column of the table it is indicated which of the modulation techniques would be supported under varying degrees of sectoring.

As seen in the table, higher spectral efficiency modulation techniques work best in cells which have low sectoring (and high C/I). Lower efficiency modulation techniques work well in highly sectored cells having the greatest bandwidth, but high C/I.

The data delivery density for a sectored cell can be calculated by multiplying the useable bandwidth of the cell by the spectral efficiency of the most appropriate modulation technique to use in the cell at a given C/I floor. This is done in the graph below.



The graph shows that there is a practical limit to the number of sectors per cell when it is operating in an environment that has scattering. Such a limit also exists for a non-scattering environment at a significantly high number of sectors (not shown here). This analysis indicates that low complexity modulation schemes with low to moderate spectral efficiencies (QPSK/16 QAM) provide better performance in highly sectored cell deployments than higher complexity techniques. One issue that has not been discussed is the low power per bit needed to support the less complex modulations which can have a major impact on the cost and output power performance of the RF system.

7.0 Cell Diameters and Data Delivery Density

The size of the cell that provides a high speed data service to an urban neighborhood will be defined by the total data rate output by the cell, the take up of the service by the users (% of houses per square kilometer subscribing to the wireless access), and the average data rates that the subscribers will demand from the service.

Having these parameters will give the ideal dimensions of the cell. In reality the size of cell will depend on the EIRP of radio equipment and the propagation path characteristics of the neighborhood. Judicious design attempts to match the ideal size with the limitations imposed by regulations and environment.

Calculations conducted by the CRC indicate that for UNII systems the practical size of a cell, depending on the environment, is about 1 km radius. An example of this is given below.

For MMDS applications, larger radii cells are feasible because of more EIRP available to these bands. However, larger cells will have poorer data delivery densities, and will have difficulty supporting intensive internet-type applications as more users take-up the service.

<u>Example of a UNII Based Wireless Multimedia Delivery Service</u>

Cell Size: 800 meters radius

Population: 3200 Households
Take-Up rate: 6% (192 Households)
Full Load Worst case data demand per household: 4.5Mbps (information rate)
Total forward link demand: 864 Mbps (Information rate)
Available Bandwidth for downlink: 100 MHz (5250-5350 MHz)
Cell Sectoring: N=6
Useable Bandwidth: 600 MHz downlink
C/I Floor: 20 dB
Modulation: Rate _ QPSK with RS 204/188/ Viterbi Decoding: BER: $1X10^{-8}$ @C/No of 10dB: Modulation Efficiency of 1.45 bits/Hz
Total Downlink rate: 872 Mbps (information rate)
Link Fade Margin: 13 dB
Average EIRP: 17 dBm/MHz
Rx Antenna Gain: 22 dB (1 ft dish)
PA Output: 8 dBm
Rx Noise Figure: 6 dB
Propagation PLE=2.559+0.0002*D (D in meters)
Hub Height: 25 Meters
Subscriber Height: 11 meters
Environment: Foliated with tree tops and power lines; Mean peak roof line ~11 meters height
Probability of achieving a successful link on first installation: ~80% .

Small cell sizes (r<2Km) can give sub-11 GHz Broadband Wireless Access systems the same data delivery capabilities as ADSL and Cable Modem. The smaller the cell size, the higher the data delivery density of the cell. To have such wireless build-out it is necessary to specify a common hub station configuration which can be easily installed and used locally by the service providers.

8.0 Hub Stations

It is proposed that hub stations having short operating ranges (1-2 Km) be standardized in the IEEE 802.16.3 for use in last-mile applications. Such hubs, because of their low EIRP (~ 35 dBm/MHz) will have low cost RF systems and can use the same electronic subsystems specified for the subscriber terminals. As a minimum, the hubs should have the following characteristics:

-Use sector antennas with N=6 with sub-sectoring of sectors (Rosette Architectures)
-Be adaptive and capable of sensing adjacent hubs; in doing so modify their radiation patterns, frequency distribution schemes, and EIRP in a prescribed (automatic/adaptive) manner in the case of UNII deployments.
-Be remotely configurable for EIRP, frequency distribution scheme, and radiation pattern in the case of licensed system deployments;
-Use aggressive channel plans with minimum guard-bands thereby counting on the spatial separation of the channels to minimize adjacent channel interference;
-Incorporate propagation environment monitoring on an active basis by polling subscribers;
-Use unique ID headers embedded in both forward and return link traffic which will simplify the identification and source of spurious emissions;
-Operate with subscriber units having either high directivity/low sidelobe or adaptive antenna characteristics.
-Be designed for installation within the propagation environment, rather than above it; ie: hub stations should not be substantially higher than the community they service. This is esthetically more acceptable.
-Be capable of undertaking switching functions. Each hub would be a Wireless LAN. The hub would contain a Gigabit Ethernet Switch.

-All traffic to the subscriber is IP based. End to end interfaces to be built around common standards such as IEEE 802.3x. Move away from PCI drivers typical of IEEE 802.11

9.0 Size, Installation of Subscriber Units and Hubs

Compact high directivity antennas can be made for 2.5 to 5.9 GHz operation. CRC has developed sector antennas for the 5.2/5.8 GHz bands having side-lobe suppression. Antenna gains 14-16 dBi and –3 dB beamwidths of 15 degree are typical of such antennas which have their longest dimensions at about 16 inches. Offset reflector dishes with beamwidths of 8 degrees and gain of 26 dBIC and side-lobe levels of -35 dB have been made from modified DVBS antenna dishes (18 inch diameter).

Installation and deployment of subscriber units is always problematic with outdoor wireless systems. Alternatives to the above antennas are smaller adaptive antenna with gains of ~12 dBiC. Such antennas would have the ability to steer 1 or 2 nulls to isolate interfering hubs. Such antennas could be easily mounted on roof poles. Significant performance in the link budget is achieved when antennas are raised above the roof lines of houses and trees, the lack in antenna gain is compensated by the increased signal level, which can increase by 1-2 dB for every meter above the roof line (measured for 11-16 meter heights)

Hubs in the UNII band would be in the order of 2 feet diameter and 6 feet long. In the MMDS band the width would be in the order of 4 feet and height would be about 10 feet. MMDS systems can use larger cell diameters because of their higher EIRP. Hub stations at 10 GHz would be substantially smaller (1 foot dia. X 3 feet length) and could have high EIRP, however, the excessive foliage attenuation they experience will limit their cell radii.

10.0 Modulation Techniques

In a sectored antenna scheme it is important that the modulation techniques chosen have good C/I resiliency. It is proposed that the IEEE 802.11a QPSK or 16 QAM OFDM modulation techniques be used on the forward and return channels. It is anticipated that these schemes will operate effectively at C/I levels of 15 to 20 dB. The co-channel performance of these techniques is still an outstanding issue.

Since the modulation bandwidths of the IEEE 802.11a are ~16.6 MHz wide, it is recommended that a channel plan calling for 6 sub-bands be used for highly sectored cellular systems. The spatial isolation between sub-sectors will ensure that adjacent channel power spectra are suitably attenuated (> 15 dB).

A suitable alternative to QPSK-OFDM, especially for sectored systems where the link distances are less than 2 Km is ETS 300 421 QPSK. This technique, used for DBS satellite, is very resilient to co-channel interference (~10 dB for BER 10^{-6}) and has better spectrum efficiency than OFDM QPSK. ETS 300 421 chip sets are cost competitive with IEEE 802.11a devices. There are over 50 million DBS units deployed worldwide.

On the return link it is proposed that a BPSK-OFDM channel at 6 Mbps be used and that it be paired with a forward link channel (operating at 18-24 Mbps) carrying TCP/IP. Of all the IEEE 802.11a techniques, BPSK is expected to show the greatest resiliency to co-channel interference. It is also expected to be least demanding on the return link RF power amplifiers of the subscriber terminals.

11.0 Summary and Conclusion

It is important to control co-channel interference in all outdoor sub-11GHz applications. This can be done by the specification of antenna directivity and side-lobe level. It is proposed that outdoor antennas for point to multipoint applications in the sub 11 GHz bands have –3 dB beamwidths of no greater than 16 degrees and side-lobe levels of –35 dB when averaged over a 300 degrees of azimuth. Such antenna will be compact and offer sufficient resiliency to co-channel interference.

To make wireless access for appeal to mass-market, to-the-home applications, it is recommended that the IEEE 802.16.3 standard provide specifications for highly sectored cellular hub stations that would work in the 2-11 GHz band and be capable of being deployed within urban neighborhoods. Such cellular stations would operate over a 1-2 Km range and would work in concert with standardized subscriber units. The forward link modulation technique would use IEEE 802.11a OFDM QPSK/ 16 QAM , while the return link would use a 6 MBbps OFDM BPSK. It is recommended that the IEEE 802.11a PHY channel plan be modified to allow closer packing of the modulated spectra. Full duplex operation is also recommended with this proposal.

12.0 References:

1.RAWCON 2000 Proceedings Page 33 “A New Wireless Network for 5 GHz License Exempt Applications” John Sydor

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3. Proceedings of the 20th Biennial Symposium on Communications, Queens University 28-31 May 2000, Queens University, Kingston Ontario. “Co-Channel Interference in Rosette Microcell Configurations” S.Gulder, J. Duggan.