WHITEPAPER

Small Cell Millimeter Wave Mesh Backhaul

The first step for Millimeter Wave Hotspot deployments

February 2013

Table of Contents

Introduction

Mobile data demand is growing at a rate that outpaces the improvements in spectral efficiency over recent years. Within 3GPP, only a 3x improvement in efficiency was seen over the 5 year period from HSDPA Release 5 to LTE Release 8. Wireless operators are intensely aware of the looming "capacity crisis" with projections showing an 18-fold increase over the next 5 years, equivalent to a 78% CAGR [1]. Small cells are emerging as the primary means that operators will use to solve this crisis, but they are dependent on cost effective solutions being provided by technology suppliers.

The backhaul for small cells is seen as the biggest challenge for small cell deployments. As the number of cell sites multiply to keep with capacity demand, so can the cost of the operator's backhaul network. While fiber is widely use for macro-cell backhaul, many operators are suggesting that the high cost of fiber installation and leasing fees will kill the small cell business case. Instead, operators are estimating that 80% of the small cells will be connected with wireless backhaul [2]. This leads to the technological challenge of finding wireless solutions that provide enough spectrum in a cost effective manner, and that can sustain the expected continued growth in capacity.

Wireless backhaul for small cell is currently a fragmented market with no clear standard that promotes inter-vendor inter-operability. Proprietary solutions range from sub-6 GHz non-line-of-sight (NLOS) to 70 GHz E-Band line-of-sight (LOS). At the lower frequency bands, deployment is easier because of the NLOS multi-path and longer propagation paths. However this comes at the cost of limited bandwidth in congested spectrum that must be shared with access links. At high frequency spectrum large swaths of bandwidth are available, but existing solutions do not provide adequate deployment solutions for small cells. InterDigital's "Millimeter Wave Hotspot (mmH) solutions provide technology components for a mmW air interface suitable for small cell backhaul. The aim of these solutions is to enable the deployment and cost advantages similar to sub-6 GHz NLOS backhaul systems while providing higher capacity using millimeter wave frequencies.

Both backhaul and access enhancements for mmW bands are needed, along with possible joint backhaul-access solutions. Small cell backhaul is a first step for mmH since throughput-enhanced access links will not work without a suitable backhaul. Several industry forums are already starting to address the wireless backhaul challenge using lower frequency bands, including the recently created 802.16 study group "r" which will look at Small Cell Backhaul enhancements. Using the mmW band provides a long term capacity solution.

In this whitepaper, we present a survey of the existing small cell backhaul landscape and investigate market requirements for the expected 5-year capacity growth. We describe how the small cell backhaul aspects of the mmH solutions can meet these requirements and unleash the abundant mmW spectrum for small cells and hotspots.

1 Landscape

Today there exist a broad range of wireless backhaul solutions which vary by spectrum, architecture topology and most importantly cost. In this section, we give an overview of existing backhaul architectures and spectrum, discuss the vendor landscape and growing interested in mmW technologies.

1.1 Taxonomy of Backhaul Solutions

Small-cell mobile backhaul transports traffic to an aggregation point in the same way that fiber or wireless backhaul in the macro-cell layer does. Like in a macrocell, small-cell backhauls span across wired and wireline options. The focus of this section is on wireless backhaul solutions. Fiber will make up only a minority of small-cell backhaul links since fiber is expensive both to install and to lease, if it is available at all. Also performance requirements for small-cell backhaul can be met by both fiber and wireless backhaul. Fiber availability, however, is crucial in small-cell deployments as this provides locations for traffic aggregation points in the wireless backhaul system.

Figure 1-1 shows a taxonomy of existing small cell backhaul solutions, along with mesh extensions that are part of InterDigital's mmH work. The wireless backhaul options can generally be broken into line-of-sight (LOS), where a direct path through the air is required between the transmitter and receiver, and non-line-of-sight (NLOS), where diffraction, transmission and reflections are sufficient for signal propagation from transmitter to receiver. Figure 1-2 depicts the typical deployments for LOS and NLOS options. In the following sections, comparisons of spectrum options and licensing, and network topologies is given for both NLOS and LOS solutions.

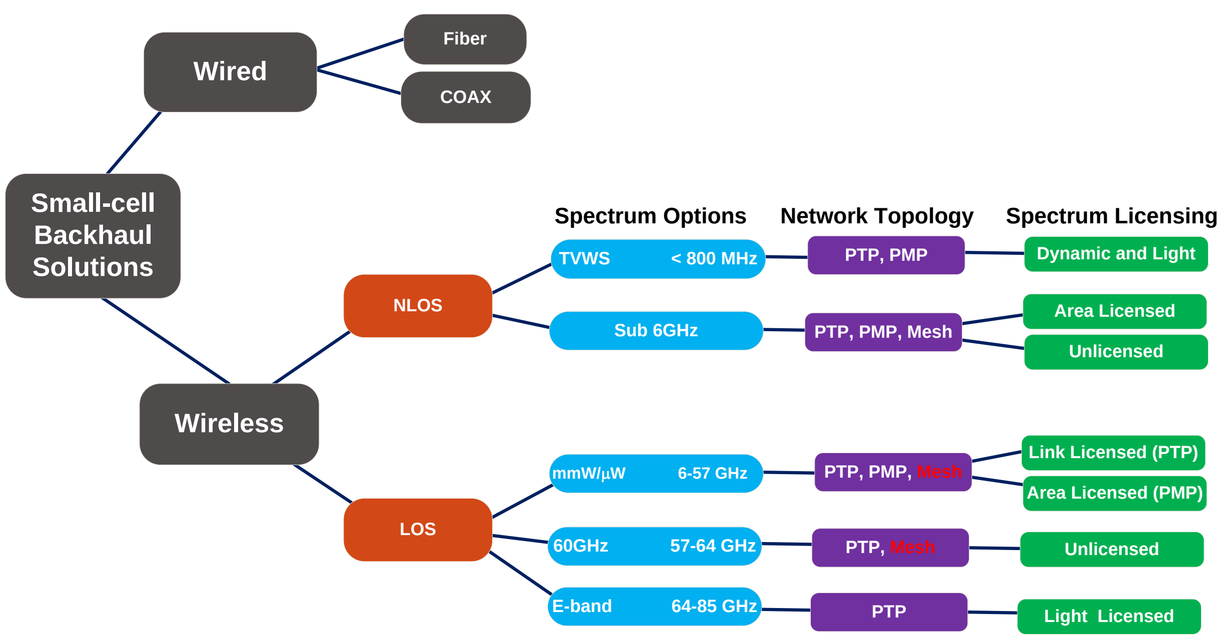

Figure 1-1 Taxonomy of Backhaul Solutions, with mmH additions in Red

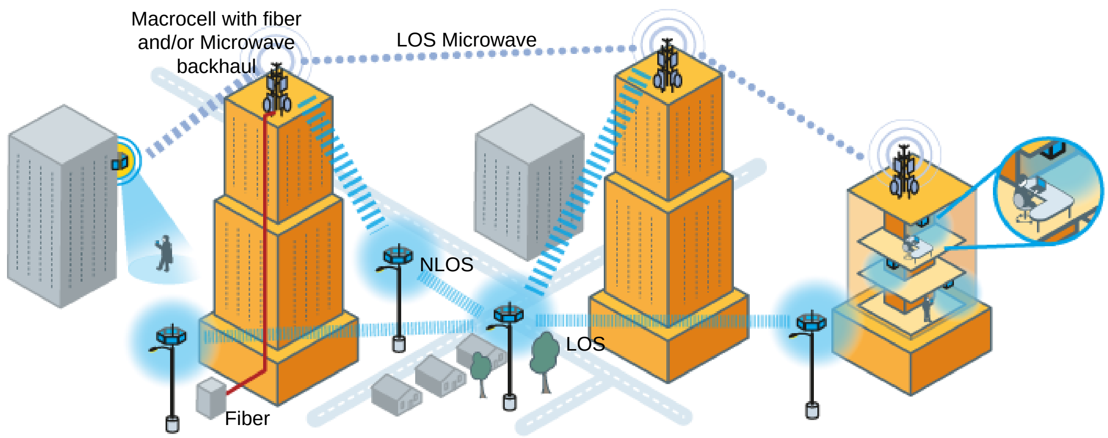

Figure 1-2 LOS vs. NLOS Typical Deployments

1.2 Network Topology Options

The connectivity between the small cells and the aggregation point could be based on point-to-point, point-to-multipoint, or mesh topologies. Relative to the entire backhaul transport network, tree and branch architectures are typically used, as show in Figure 1-3, but in this paper we focus on the "last mile" connectivity for small cells. In point-to-point (PTP) technologies, there is a dedicated RF channel per link between the hub or aggregation point and the end-point. Also the hub or aggregation point has a dedicated radio and antenna for each PTP link. In point-to-multipoint (PMP) technologies, RF is shared across all PMP links. Also the hub or aggregation point has a shared radio antenna that is used across all PMP links at the aggregation point. As a further option, instead of connecting every single small cell to the macro site chain, tree or mesh topologies can be used between the small cell sites to provide the required connectivity.

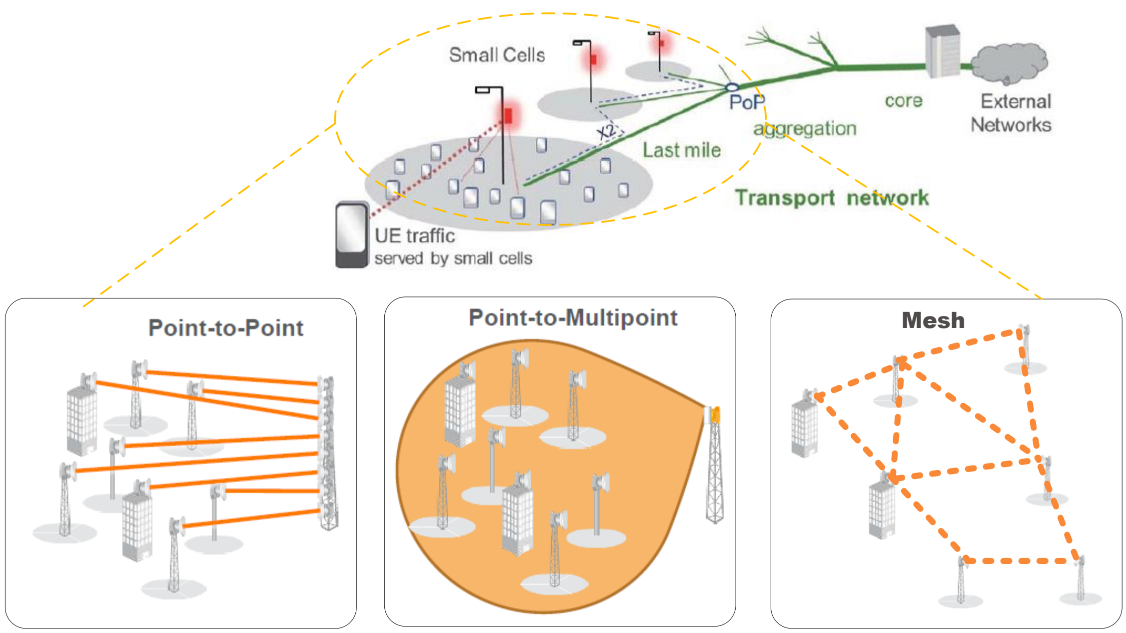

Figure 1-3 PTP, PMP and Mesh topologies (source: NGNM Small Cell Backhaul Requirements [3])

Near-LOS or even NLOS options can be considered when LOS solutions restrict backhaul coverage. There might be cases where specific small cell base stations cannot be directly connected to the macro cell site via a single wireless link because of physical obstructions, but can be reached via another small cell. In these cases more complex topologies like chains and mesh could be used. Such topologies would require the small cell backhaul solutions to support multiple wireless links as well as traffic aggregation. Connecting small cell base stations via chains or mesh may be an appropriate topology when they are installed on street furniture, e.g. lamp posts or other places where obstructions are common. In those cases it is sufficient that only one of the small cells is connected to the fiber network (e.g. via macro cell site) and further connectivity is provided among the small cell base stations themselves.

1.3 Existing Spectrum and Licensing Options

In this section we describe the spectrum options for small cell backhaul. Operators indicate an increasing focus on the sub 6 GHz and 60 GHz bands as the ones ideally suited to address small cells' specific requirements in a NLOS and LOS environment, respectively. The preference for licensed operation in the sub-6 GHz frequencies is intuitive since interference from other networks would be very difficult to manage, whereas in the 60 GHz band, interference without licensing is still quite manageable.

TVWS (< 800MHz): TVWS channels offer good propagation properties, both in range and throughput or around obstacles. TVWS spectrum is unpaired and its channels are 6/7/8 MHz wide depending on the country. In locations where TVWS channel availability is high, TVWS spectrum can provide wireless backhaul connections between small cells. The main risk with this spectrum is availability of TVWS channels and ability to provide guaranteed QoS requirements of small-cell backhaul.

Sub-6 GHz licensed: Sub-6 GHz gives operators the flexibility to reach locations that are not within LOS. PMP architecture is the most common, but PTP can also be used. The downsides that severely restrict adoption are that available bands in sub-6 GHz spectrum are scarce and expensive, and that they commonly come in narrow channels that have limited capacity, especially when used in a NLOS environment. The capacity limitations are compounded in a PMP architecture, where available capacity is shared among cells in the PMP network and frequency reuse is limited.

Sub-6 GHz unlicensed: In many areas, especially the dense urban areas that small cells target, interference in these intensely used bands is already high, thus discouraging further mobile operators from relying on these bands for backhaul. However, these bands offer a temporary or fallback solution to operators that do not have access to sub-6 GHz licensed spectrum and have small cells with NLOS.

Microwave PTP/PMP: Microwave is by far the spectrum most commonly used for cellular backhaul but has very strong competition in the small-cell market because it combines some of the disadvantages of other bands without providing a unique benefit. Unlike sub-6 GHz bands, microwave requires LOS, but does not offer benefits of 60 GHz or E-band, such as smaller antennas, more capacity, and lower spectrum costs. Since microwave links can reach more-distant locations, they can be used in rural small-cell deployments or other locations where the small cell is far from the aggregation point. For metropolitan locations, the longer radius can become a liability, because it decreases the ability to reuse spectrum. In some bands and countries, regulatory requirements result in antenna sizes that are too large for small cells.

60 GHz: This is the unlicensed band that has attracted the highest interest among operators and backhaul vendors. The atmospheric and oxygen attenuation that makes the 60 GHz band not well suited to covering long-distance links is beneficial in a small-cell environment, where short range translates into less interference among adjacent links and, hence, greater spectrum reuse. The high frequency also allows for smaller antennas, which are a requirement for small-cell installations. However, LOS requirements make it difficult to integrate the backhaul module within the small cell but relay links may be used to overcome LOS limitations. There are no channelization or antenna design requirements which increases the flexibility of solutions in this band, making it possible to reduce the antenna size and widen the beam width.

E-band: Licenses in this band are inexpensive, but in most countries it is subject to tight regulations dictating specific antenna designs and channelization, which result in bigger antennas compared to the 60 GHz band. Regulatory changes are expected to remove these constraints in some markets, and will increase the attractiveness of this band for small-cell backhaul. In some countries, including the US, links are licensed and registered in a database, which means interference can be more effectively avoided or managed, thus protecting the operator's investment in the backhaul equipment.

1.4 Current Vendor Solutions

The small-cell backhaul market is evolving quickly, and its players are still finding their position within the small-cell ecosystem. Figure 1-4 illustrates the approximate industry coverage of small cell backhaul solutions, categorized by spectrum band. Currently there are no mesh or PMP solutions available in the mmW frequencies. This is the gap that InterDigital's small-cell backhaul solution addresses.

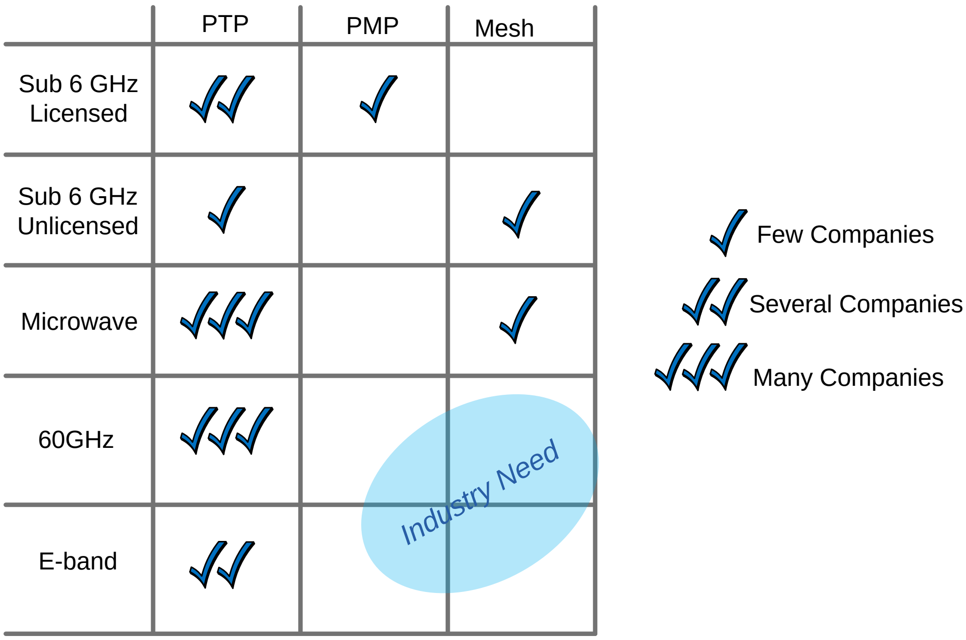

Figure 1-4 Industry Coverage of Small Cell Backhaul Solutions

In the market today, mesh solutions in the unlicensed sub-6 GHz band exist that use 802.11n with likely migration to 802.11ac. (e.g., Ruckus Wireless and Ubiquiti). These solutions initially address the early demand for small-cell backhaul in a cost-effective way, but could face tremendous challenges in the future when spectrum becomes more crowded and interference must be managed. While 802.11ac promises significant data rate improvements over 802.11n using 80 MHz and 160 MHz channels, compared to 40 MHz in 802.11n, it operates in the same 5 GHz band and does not introduce any new spectrum. The 802.11ac standard extends 802.11n peak rates by using a 256-QAM modulation scheme. However, the channel conditions required to make use of 256-QAM are unlikely to be viable for the typical length of backhaul links. Most operators approach the license-exempt sub-6 GHz market with extreme caution. The combination of licenses-exempt operations and good NLOS propagation make the potential for interference high thus making performance and throughput difficult to guarantee in the unlicensed sub-6 GHz bands.

1.5 Growing Interest in mmW

PTP microwave and millimeter wave systems have been used for over two decades for high capacity macrocell backhauling. These systems have typically operated in licensed bands, assume LOS availability, and are optimized for high capacity long ranges (e.g. a few miles). The wireless industry is beginning to recognize the symbiotic relationship between higher frequency and smaller cell solutions as a means to address the data capacity crisis. In Table 1-1, we trace some of the leading industry events foretelling the coming mmW solutions for next generation networks. In the year 2012, we have seen an explosion of interest in mmW that is spawning many new activities.

Table 1-1 Key Events Foretelling Advances in mmW Backhaul

	Event	Date	Objective	Significance
Pre-2012	Wireless HD (802.15.3c based)	2006 - present	Defines short-range (10m) wireless interchange of high-definition multimedia data between audio-visual devices in the 60 GHz unlicensed band	First commercial products for mmW data streaming connectivity
Pre-2012	WiGiG (802.11ad)	2009 - present	Defines transmission of audio, video, and data in the millimeter wave frequency band operating in both LOS and NLOS environments.	Being adopted by chipset vendors for high volume commercial uses
Pre-2012	Millimeter Wave Mobile Broadband (MMB)	June 2011	Samsung IEEE Communications Magazine [4] article on demonstrating feasibility of mmW to achieve gigabit-per-second data rates at a distance up to 1 km in an urban mobile environment.	Targeted towards LTE integration. Effort backed by field measurements
2012	IWPC Mobile Gigabit Working Group (MoGIG)	Jan 2012 - present	Focused on studying the use cases, physical layer feasibility, and architectures for seamless integration and application of millimeter wave and terahertz frequencies into existing cellular and HetNet infrastructure [5].	Industry group to discuss feasibility of mmW architectures
2012	WiGiG Backhaul	May 23, 2012	Press Interview with WiGiG president [6], "The WiGig Alliance is pushing Wireless Gigabit technology beyond its initial mission of providing multi-gigabit connections between devices and into the world of small cells as a short-range backhaul solution"	Indication of extending existing mmW standards toward backhaul concepts
2012	3GPP Release 12+ Planning	June 2012	Member companies presented views on technology to be considered for Release 12 and beyond.	Several companies noted mmW for cellular should be considered by R13 or beyond
2012	National Science Foundation (NSF) AIR Project	July 2012 - present	"The 5G project will develop smarter and far less expensive wireless infrastructure by means of smaller, lighter electrically steerable directional antennas using the millimeter-wave spectrum, where huge amounts of BW is readily available. It will also help develop smaller, smarter cells with devices that cooperate rather than compete for spectrum"[7].	5G mmW solutions for cellular systems
2013	"MUSIC" Multistream Wireless Backhaul	Start January 2013	Demonstrate increasing the data rates in small cell backhauling scenarios despite the increased path loss at higher frequencies (> 10 GHz). The properties of wireless backhaul channels (LOS and NLOS) will be investigated and specific attention is paid to multiple antennas [8].	European project under CELTIC program with $8M funding

2 Market Requirements

In this section we look at the market requirements for small cell backhaul including cost, range (inter-site distance), latency, and data rate. These requirements will drive the technical direction of the backhaul solution for the mmH solutions.

2.1 Total Cost of Ownership

When considering the total cost of ownership for backhaul systems, numerous publications [9][10][11][12] converge around the position that point to point systems (PTP) do not make financial sense with increasing small cell density. Instead, business case studies are suggesting that point to multipoint (PMP) systems are at a financial advantage. Additionally, these studies commonly point out that fiber is generally more expensive than wireless because of the high cost of laying the fiber. Hence, fiber solutions may not be suitable for the small cell business case, and even if deployed with sufficient density, there may not be sufficient access to it. Existing fiber deployments may not be made available to all small cell operators due to competitive business positions.

From the various references mentioned above, the general consensus is that PMP systems have lower TCO than PTP systems because of the following:

- Where licensing is required, spectrum is licensed by region in frequencies typically used by PMP systems whereas spectrum is typically licensed per link in frequencies typically used by PTP systems. Therefore, PMP licensing costs do not increase with growing cell densities.
- By the very nature of LOS propagation, PTP systems are more difficult to plan and install, thus driving up deployment cost.
- PTP systems require more equipment. For example, when each link is added to the system, a highly directional antenna and transceiver is added to each end of the link regardless of what equipment is already present.

The difference in TCO between NLOS and LOS options for PMP systems is driven by equipment and installation costs. Based on today's technology being evaluated in these studies, PMP-LOS systems require costly installation to point antennas in the correct direction and generally require installations at both ends of the link. PMP-NLOS systems on the other hand benefit from propagation characteristics making locating sites, positioning and installation easier. Additionally, the cost of PMP-NLOS systems can be nearly 35% less than PMP LOS systems [10].

Spectrum cost is not seen as a driver for small cell backhaul as long as spectrum above 3 GHz is assumed and that per-link pricing is avoided. In a whitepaper from BlinQ Networks [11], it is shown that the spectrum license costs per MHz-pops[1] in the 3.5 GHz band are one to two orders of magnitude lower than spectrum costs at the recent 700 MHz and 800 MHz auctions. Additionally, in a study from Sezna Fili Consulting [10], the comparison between license and licensed-exempt spectrum costs shows that spectrum cost is not a significant driver of TCO.

Therefore from a TCO point of view, the key attributes for cost effective small cell backhaul are

- Easy of deployment, such as that offered by NLOS systems
- Use PMP configurations to lower per link costs
- Avoid per-link spectrum licensing.
- Avoid fiber because of high leasing and installation costs

InterDigital's mmH small cell backhaul will enable the deployment and cost advantages of sub-6 GHz PMP-NLOS backhaul systems while providing higher capacity using millimeter wave frequencies. Not mentioned in any referenced TCO analysis reports, as these reports are focused in near term, is the limited spectrum available at sub-6 GHz and how that may affect the business case 5 years from now. It can be anticipated that sub-6 GHz spectrum will be demanded for additional access links, thereby creating a demand at higher frequency spectrum for solutions providing similar advantages to those of sub-6 GHz spectrum. Beamforming for phased array antennas will provide the "ease of deployment" that exists with current sub-6 GHz NLOS backhaul systems. Lower modulation and coding schemes coupled with higher gain antennas will overcome propagation issues. Finally, the 60 GHz band will be explored first, where a license free deployment is available and radio equipment is becoming commoditized.

2.2 Inter-Site Distance Between Small Cells

The inter-site distance is an especially important market requirement driving technical considerations for mmW use in small cells. Range is a technology challenge at the mmW frequencies due to higher path loss and less multipath opportunities compared to sub-6 GHz systems. But even for these sub-6 GHz systems, inter-site distances are becoming smaller, driven by the limited spectrum and need for more spatial reuse. In this section we give a survey of inter-site distance expectations for small cells based on systems being deployed with lower sub-6 GHz considerations. Our view is mmW use in small cells is expected to gain traction through providing high throughput wireless backhaul sub-6 GHz small cells. Eventually mmW access links will be added as well to greatly increase capacity of small cell systems. **Viewpoints on small cell range and inter-site distances are generally consistent in a nominal 50 – 200m range** [10] [11] [13].

[1] "MHz-pops" is defined as the product derived from multiplying the number of megahertz associated with a license by the population of the license's service area.)

2.3 Backhaul Data Rate Requirements

In this section we address the anticipated growth in data rate for wireless backhaul over the next five years. As discussed in Section 2.1, cost effective deployment of small cells requires wireless backhaul solutions instead of additional fiber PoP installations and leasing. Recognizing this, we assume that additional fiber will generally not be installed and that wireless backhaul will aggregate the data flows of multiple small cells to/from the fiber PoP at current PoP densities. There are various topologies that can be deployed in a given small cell cluster, such as star and mesh, as shown in Figure 2-1, but all of these require backhaul to the fiber PoP. Therefore the cumulative backhaul data rates to the final hop (or aggregator node at the fiber PoP) must grow with additional small cell densification. This is driven by the increase in areal capacity demand, i.e., more cells are added as demand increases. In other words, if the PoP density (PoP/km^2) is fixed and the areal capacity (Gbps/km^2) is increasing, then the aggregated data flow to the aggregation node must grow with areal capacity demand.

This results in the realization that capacity for the small cell backhaul radio link must follow the cellular capacity growth projections of roughly 78% CAGR [14], or 18x increase over 5 years.

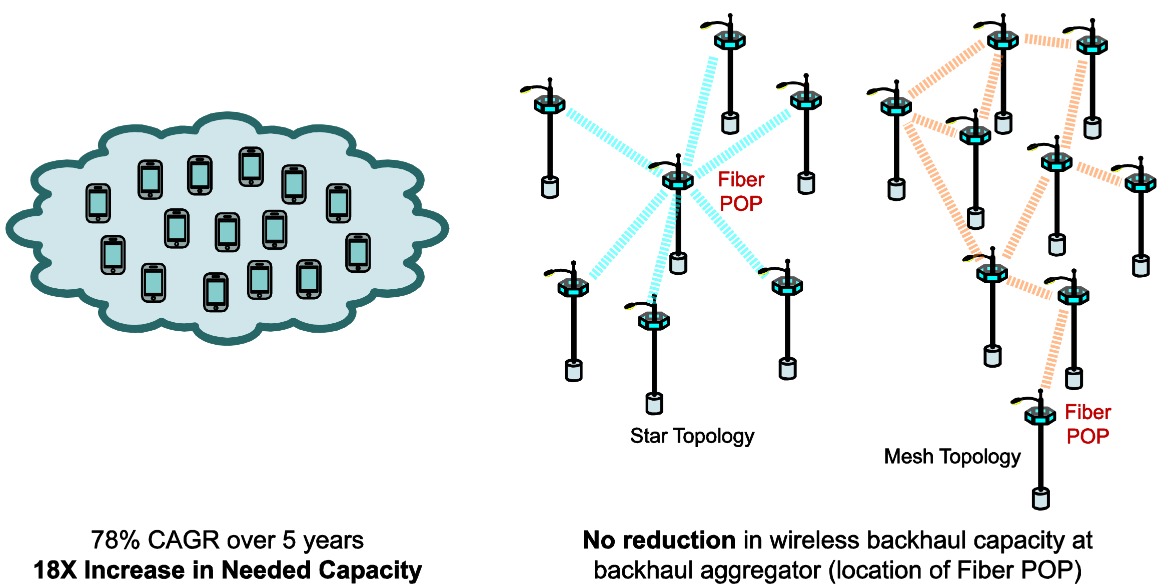

Figure 2-1 Small Cell Wireless Backhaul Capacity Growth

Today's small cell backhaul requirements can vary widely depending on assumptions such as whether multi-technology is considered (Wi-Fi, HSPA, LTE), the bandwidth available at each node, and the degree of MIMO techniques that are assumed. Nevertheless, various reports lead to a similar thinking that approximately 35 Mbps of average backhaul capacity is right for today's small cell deployment activities for downlink [10][15]. **We therefore conclude that over the next 5 years, will we see wireless backhaul follow the mobile data CAGR curve, demanding nearly 1 Gbps for downlink.** Even though uplink data rates typically trail downlink, we propose using similar data rate requirements for uplink. Some macro cells today require near this level of wireless backhaul as pointed out in [10], and for this reason tower mounted point-to-point solutions exist in the market. However, small cell solutions will require more cost effective point to multi-point solutions capable of the 1 Gbps rate.

2.4 Traffic Classes and Latency

In this section we investigate and recommend latency requirements for the next generation small cell backhaul. Latency is a key metric that affects the Quality of Experience (QoE) of end to end services. Small cell systems with wireless backhaul will add another communication link to the end-to-end system, and therefore the impact of additional latency on the end-to-end delay requirements must be understood.

One way to evaluate the required latency for the next generation of small cell backhaul is to consider the requirements of both the most stringent scenarios and the most likely scenarios. 3GPP TS 23.203 [16] gives a table of packet delay budgets for each of the standardized QoS Class Identifier (QCI) classes, where the delay is measured from the UE to the packet gateway (PGW). We extract the latency requirement by service class and compare them to the CAGR of traffic, show in Table 2-1. A key take away from this is that video and TCP traffic (email, web browsing, etc.) will out-pace gaming where latency requirements are most critical. Nevertheless, a healthy growth rate of 63% CAGR for gaming, where delay requirements are most stringent, is still expected.

Table 2-1 Latency for various service classes

Service	CAGR 2011-2016 [17][17]	Packet Delay that applies to Radio Interface (round trip)[2] [16]
Voice (VoIP)	19%	160 ms
Gaming	63%	60 ms
Live Video	90% (Live & buffered combined)	260 ms
Buffered Video		560 ms
TCP Traffic	85%	560 ms

Another source for small cell backhaul latency requirements is the recently complete NGNM report [3]. The recommendation for the overall backhaul delay budget from that study is:

> "The overall backhaul delay budget in one direction from small cell connection point to the core network equipment **SHOULD NOT** exceed 20ms, for 98% packets for high priority Classes of Service or in uncongested conditions. We note that the backhaul latency MUST fit into the operator's overall E2E latency budget for the service(s) being offered."

In order to estimate the required latency of the small cell backhaul segment, we first take the most stringent requirement from the 3GPP latency of Table 2-1. The 60 ms latency for gaming represents the round trip delay from the user equipment to the core network. A typical value achievable over these delay segments may be 40 ms when air interface conditions are good, resulting in fewer retransmissions. This results in typically 20 ms margin being available for the additional latency that a small cell backhaul would incur.

As a secondary analysis, we can take the NGNM requirement of 20 ms which includes the delay from the small cell backhaul as well as the backhaul from the RAN to the core network. This backhaul from the RAN to the core network can typically be 10 ms, resulting in only an additional 10 ms remaining for small cell backhaul.

While this analysis can upper bound the allowable small cell latency to between 10 and 20 ms, it should be recognized that small cell backhaul will be an additional segment added to existing networks that are currently optimized for end-to-end delay in a proprietary manner that may not follow the 3GPP guidelines. It is quite conceivable that any additional delay could be significant from cost-performance trade space for an operator. Therefore, **the recommendation here is to keep the small cell backhaul delay as low as possible and under 10 ms round trip, or 5 ms one way**.

[2] Note: From the table in TS23.203, 20 ms is assumed for the one way delay between the packet gateway and the radio base station segment. Therefore 20 ms is subtracted from the table in TS 23.203 to reproduce only the delay applicable to the radio interface. Additionally, TS23.203 gives one way delay and values are doubled for the round trip delays shown here

3 InterDigital's mmW Small Cell Backhaul Solution

In this section we describe our Small Cell mmW Backhaul solution and its feasibility based on the market requirements described in the section above.

3.1 Millimeter Wave Directional Mesh Small Cell Backhaul Concept

Mesh backhaul is a valuable feature to consider for the small-cell backhaul architecture in order to increase the deployment options and flexibility where wired backhaul can be scarce or cost prohibitive. The backhaul links among small-cell nodes form a multi-hop mesh network (as depicted in Figure 3-1) so that long backhaul links are not required (thus reducing CAPEX), and increasing backhaul reliability by providing multiple routes.

The InterDigital Millimeter Wave small-cell backhaul solution is an intelligent directional-mesh operating in mmW frequencies (e.g., 60 GHz or E-band) and provides high performance, reliability and redundancy required for carrier-grade backhaul. Utilizing novel methods for automatic long-range discovery and leveraging electrically steerable antenna arrays, each node establishes optimal paths to its neighbors using self-configuration techniques. When link congestion or deteriorating RF conditions occur, new paths are determined based on QoS requirements such as latency, throughput and packet-error rate and the mesh self-tunes itself to achieve optimal performance. The self-tuning process occurs in real-time and without need for human intervention. Full-duplex operation for dedicated backhaul links that can transmit and receive simultaneously is achieved by providing enough separation between transmit and receive antennas.

In order to achieve maximum throughput and minimal latency for this mesh network, a fully scheduled, synchronized and time-division multiplex (TDM) based multi-hop directional-mesh MAC is developed. Electrically steerable antenna arrays enable fast TDM operation thus reducing the need for multiple baseband and RF processing chains for each individual link. While operation at mmW frequencies provides some immunity against interference, automatic interference management techniques overcome any overlap in directional beams and external interference.

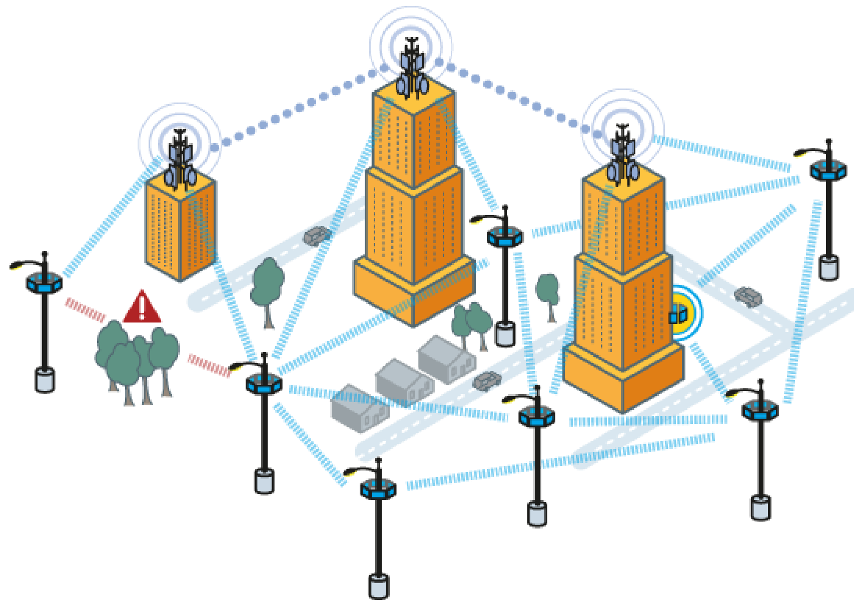

Figure 3-1 mmH multi-hop directional mesh small-cell backhaul

3.2 Range and Data Rate

While the availability of fiber and areal capacity demands will be correlated (i.e., there will be more fiber in areas of higher areal capacity demand) the number of cells that will need to be supported per fiber PoP could vary substantially. This could be driven not only by availability of fiber, but also by the fees charged. Assuming 802.11ad is used as a baseline backhaul technology, we can set some bounds on the number of cells that could be supported per fiber and inter-site distances (ISDs) that could be supported.

The Single Carrier (SC) PHY in 802.11ad is a likely candidate PHY for early deployments. The highest data rate for the SC PHY is ~4.6 Gbps. In a dense network where the ISD is small enough to achieve this link data rate and full duplex operation is assumed, the bottleneck link data rate must support the aggregated data rate of all the other cells in backhaul network. As an example, if we provision for a busy time traffic rate of 200 Mbps in UL and DL per cell, the largest number of cells that can be supported by a single fiber PoP is about 12. Of course, this was assuming the ISD was small enough to support the 4.6 Gbps data rate. The ISD that is small enough to support these rates depends on the antenna capabilities and desired robustness to the environment, for example, rain.

For the assumptions given in Table 3-1, the range of each modulation coding set (MCS) and corresponding data rate is given in Table 3-2 for antenna array sizes of N = 25, 49, and 81 elements. The estimates of the ranges are based on simulations done by 802.11ad wherein the required antenna port power for each MCS in additive white Gaussian noise (AWGN) was determined by simulation for a given packet error rate (typically 1**%). With an array size of 25 elements (e.g., a 5x5 array), an inter-site distance of ~60 m can be supported,** which roughly corresponds to the maximum cell densities discussed by some operators. A 60 m ISD with a peak hour cell throughput of 200 Mbps represents about 56 Gbps/km^2 of areal capacity, which is a very high density and may serve, for example, a very dense urban or stadium deployment. Antennas of this size are not expected to be cost prohibitive. As an example, large arrays are already used in WirelessHD consumer electronics.

For N = 81 elements (e.g., a 9x9 array), an ISD of 150 m can be supported at the highest rate and corresponds to an areal capacity of about 8.8 Gbps/km^2 which may be more typical for earlier deployment and address a larger market.

Note that the range estimates have included losses due to a heavy rainfall of 25 mm/hr which has a likelihood of less than 0.05% in the New York region. These ranges are therefore considered rather conservative, that is, 99.95% of the time the peak MCS should be supported. An operator would usually look for higher robustness, but since our system employs adaptive coding and modulation with many MCSs, plus the redundancy provided by the mesh architecture, the system does not fail in the other 0.05% of the time. It may simply operate at a lower MSC on the same link or redirect traffic to another link. Note further that only the links supporting the aggregated traffic need to support the largest data rates, so node spacing away from the fiber PoP could possibly be larger if permitted by the access network capacity demands.

Table 3-1 MCS range estimation assumptions

Parameter	Value	Comments
Channel BW and MCS	1.76, MCS 1-12	802.11ad channel, SC PHY
Transmit power	10 dBm	10 dBm for world-wide. US can use 26 dBm
Antenna Gain (Tx and Rx)	7 dBi + 10*log(N)	7 dBi from element gain. N = number of elements. Limit N such that EIRP<40 dBm
Noise figure (NF)	7 dB	
Other impairments	8 dB	Implementation losses
O_2 (and other gasses) losses	13 dB/km	Specific to 60 GHz band at sea level
Rainfall losses	10 dB/km	~25 mm/hr

Table 3-2 Link ranges as a function of MCS and antenna array size

MCS Index	PHY Data Rate* (Mbps)	Modulation Type	Required Antenna port power (dBm) for NF + other = 15 dB	Inter-site distances (m) for Tx power =10 dBm and N elements per antenna		
				N = 25	N = 49	N = 81
0	Control only		-78	415	557	675
1	385	BPSK+Rep	-68	220	326	420
2	770	BPSK	-66	189	287	375
3	962.5	BPSK	-65	175	268	354
4	1155	BPSK	-64	162	251	333
5	1251.25	BPSK	-62	137	217	294
6	1540	QPSK	-63	149	234	313
7	1925	QPSK	-62	137	217	294
8	2310	QPSK	-61	126	202	275
9	2505.5	QPSK	-59	106	173	240
10	3080	16-QAM	-55	73	124	178
11	3850	16-QAM	-54	66	114	164
12	4620	16-QAM	-53	60	104	152

**PHY data rate includes12.5% overhead for a guard interval.*

3.3 Latency of Mesh Backhaul

Latency is a key factor for the viability of the wireless multi-hop mesh-network as described in section 3.1. The processing delays at each hop and link-layer contention (access to the medium) are the key contributing factors to latency. Link-layer contention in multi-hop wireless networks causes packets to drop at the first sign of network overload. This contention also increases as the load increases, ultimately resulting in saturating the network. In the proposed backhaul system a strict bound on latency is achieved by limiting the number of hops and providing fully scheduled medium access. The latter is accomplished by a fully distributed directional multi-hop mesh customized for mmW frequencies. Joint scheduling and routing algorithms operating at layer 2 ensure that latency and QoS requirements are acheived, and that data is re-routed based on link-metrics that are updated in real-time. Operating at layer 2 allows for low-latency switching which keeps overall latency and overhead to a minimum, and improves multi-hop performance.

3.4 Cost of Small Cell Backhaul Solution

The cost of the mmH solution will depend on overall market uptake of mmW devices. Qualitatively, several high level design choices point to a reasonable expectation for a cost competitive solution:

- Use of unlicensed or low-license fee spectrum (e.g., 60 GHz)
- Reuse of technology being commercially commoditized (e.g., 802.11ad)
- Use of beam-steering antennas to support self-configuration (reduced deployment costs)

3.5 The mmW Small Cell Backhaul Solution Value Proposition

Considering the market requirements and current backhaul offerings in the market today, there is clearly a technology gap that needs to be filled before the mmW small cell value proposition can be fully realized. Spurred on by the consumer electronics market, phased arrays antenna technologies and costs are rapidly decreasing and can be leveraged for the backhaul market. Building on 802.11ad technology also leverages an existing standard, but that standard was conceived with very short range communications in mind (~10 m). Enhancing the 802.11ad specification to support longer mmW link distances, directional mesh networking, QoS driven low latency, and new interference management is required.

Value Proposition

InterDigital's backhaul solution brings together all the key features operators are looking for in a small cell backhaul.

- **Access to 6 GHz of bandwidth – No License Required:** Each channel is ~2GHz. Three channels available in most of the world.
- **Noise Limited Operation – Better than having a licensed sub-6 GHz band:** Highly directional antennas, nulling, and atmospheric losses imply low interference.
- **No New Fiber:** Existing fiber PoP density is sufficient. Small cells grow out from existing eNode B locations.
- **Flexible topology:** Directional multi-hop mesh eliminates the need for direct (and longer) links between small-cells and aggregation point/macro-cell. Provides flexibility in topology by using LOS links to immediate small-cell neighbors instead of LOS requirement to the aggregation point.
- **Scalability:** New small-cell nodes can be added with minimal backhaul planning.
- **Flexible and Auto-configuration:** Electrically steerable antennas allow auto discovery and creation of new links and nodes.
- **Low Cost Sites and Installation:** Less than ½ hr installation time on street furniture with minimally trained installer.
- **Built-in Robustness:** Redundancy through mesh, which also provides load balancing and deployment flexibility.
- **Distributed directional-mesh MAC:** A fully distributed scheduled, multi-hop and TDM based directional mesh MAC to ensures fast scheduling and minimal queuing delay.
- **Full-Duplex:** Full-duplex operation achieved by spatial separation of Tx and Rx.

- **Low-latency:** Layer 2 forwarding/routing coupled with joint scheduling and routing allow for a low-latency mesh-backhaul.
- **Low Cost Nodes:** Leveraging the consumer electronics market for antennas, radios, and baseband processing.
- **Single baseband and RF processing chain:** Avoids multiple baseband and RF processing chains (as used in traditional-mesh) by using electronically steerable antennas and TDM-based MAC to develop a low-cost solution.
- **Integrated Access Link/Backhaul Hardware:** Flexibility to provide integrated backhaul module to be added to small-cell enclosure; enabled by electronically steerable antenna and automatic discovery.

4 Millimeter Wave Technology and Small Cells – A Broader View

The small cell community has made it clear that backhaul is the number one challenge, and that wireless solutions will be the most cost effective. To that end, this white paper has focused on the advantages of mmW technology as a cost effective, high performance small cell backhaul solution. But looking forward, the areal capacity that mmW can support makes it a promising approach for access links to and from the mobile terminals, as well as the backhaul. InterDigital's vision for future wireless networks seamlessly integrates mmW into the overall system.

Figure 4-1 shows a forward looking system architecture where a mmW base station (mB) supports both access and backhaul connections. The mB integrates other small cell access technologies such as LTE or 802.11. The left side of the diagram shows an 802.11 hotspot deployment, while the right side shows a cellular architecture. These two approaches may be combined with proper mobility and interconnection approaches. LTE, using the eNB shown in the figure, provides a macro-cellular overlay while mmW and other hotspot technologies provide the ultra-high capacity small cells. The mmW backhaul interconnects the mBs, eventually reaching a mmW basestation aggregation point (mBA), for a connection to the core network.

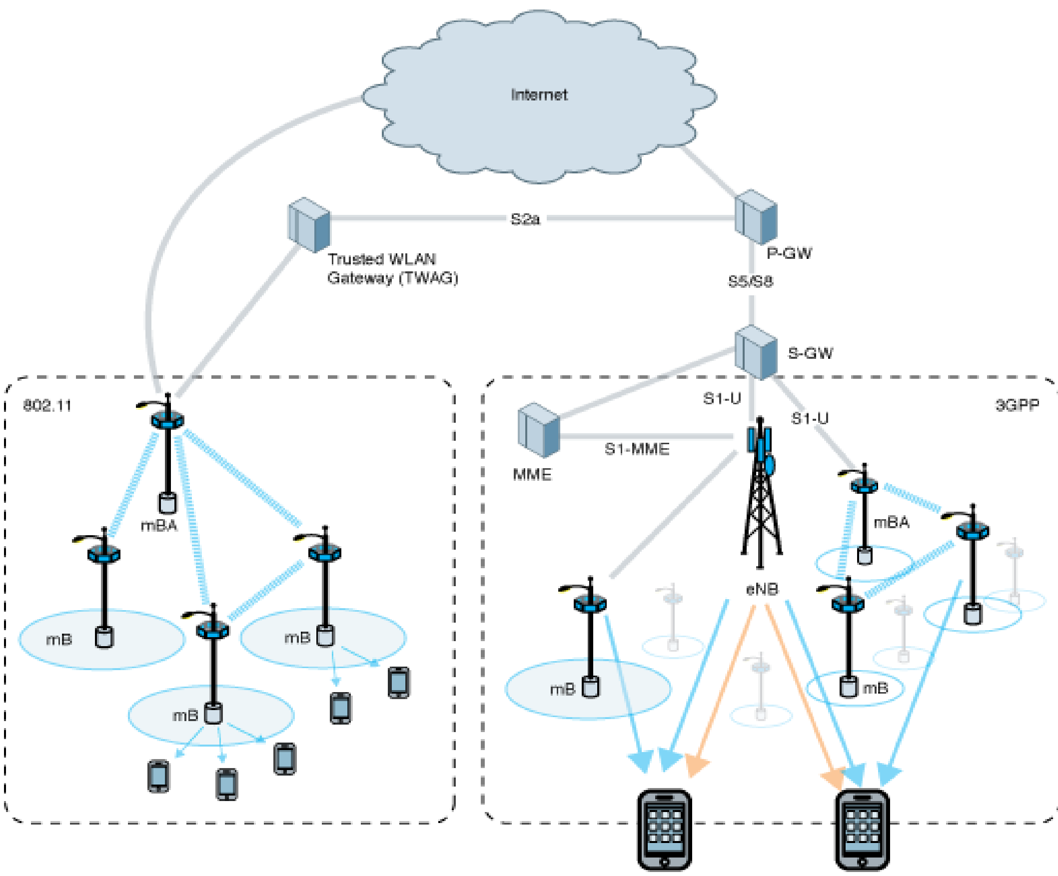

Figure 4-1 mmH Tiered Architecture

IEEE 802.11, through the framework of 802.11ad, 802.11aj, and WiGiG, already has addressed a mmW air interface. Those initiatives provide a starting point for a mmW backhaul, and may also provide a roadmap towards a mmW access link. On the other hand, within 3GPP the “Release 12 and Beyond” planning workshop in June 2012 included contributions from several companies that proposed mmW as a longer term solution to meet capacity needs. Whether the path forward is via 802.11, 3GPP, a combination of the two, or an entirely new direction, evolving mmW technology is a promising solution for both the access and backhaul to meet the anticipated data capacity crunch.

5 Conclusions

The advent of dense small cell deployments will require a cost effective backhaul solution that can provide spectrum relief for an 18x growth in capacity over the next 5 years, and far more in the next 10 years if the 78% CAGR continues. High costs of fiber and the need for flexible deployment options make wireless solutions very attractive for operators, however, many existing wireless backhaul solutions have architectures and spectrum allocations that are optimized for macro cells, and their cost effectiveness does not scale for the small cell business case. Existing point-to-point solutions that use mmW have costs that scale per link, rather than per cell, which becomes prohibitive with interconnected small cells. Existing non-line-of-sight point-to-multipoint solutions operate at lower frequencies where spectrum is limited and interference is a challenge. With a mmW point-to-multipoint backhaul using electrically steerable antennas, we can enable the deployment and cost advantages of sub-6 GHz point-to-multipoint non-line-of-sight backhaul systems while providing higher capacity using millimeter wave frequencies.

InterDigital's Millimeter Wave Hotspot (mmH) solutions solve the long term capacity growth problems beginning with backhaul for the small cell, and later introducing mmW access link technology. Backhaul solutions will require up to 1 Gbps data links in small cell clusters. Spacing between these cells will range from 50 to 200 meters. Our analyses demonstrate the feasibility of supporting these ranges with electrically steerable phased array antennas that provide low cost flexible mesh connectivity. Latency is kept to approximately 5 ms for high priority traffic so as not to exhaust the delay budget of existing networks. A small cell mesh backhaul using mmW bands will result in a scalable and cost effective solution for long term growth of very high capacity small cells.

6 References

[1] Cisco Visual Networking Index. [Online]. http://newsroom.cisco.com/press-release-content?articleId=668380

[2] T. Parker. (2012, September) FierceBroadbandWireless. [Online]. http://www.fiercebroadbandwireless.com/story/abi-ofdm-non-line-sight-dominate-small-cell-backhaul-2017/2012-09-12?utm_medium=nl&utm_source=internal

[3] NGNM Alliance. Small Cell Backhaul Requirements. [Online]. http://www.ngmn.org/fileadmin/user_upload/Downloads/Technical/NGMN_Whitepaper_Small_Cell_Backhaul_Requirements.pdf

[4] Zhouyue Pi and Farooq Khan, "An Introduction to Millimeter-Wave Mobile Broadband Systems," 2011.

[5] IWPC. [Online]. http://www.iwpc.org/WorkingGroups.aspx

[6] (2012, May) Fierce Broadband Wireless. [Online]. http://www.fiercebroadbandwireless.com/story/wigig-touted-small-cell-backhaul-play/2012-05-23

[7] (2012, July) NYU POLY. [Online]. http://www.poly.edu/press-release/2012/07/19/searching-1000-times-capacity-4g-wireless

[8] CELTIC Initiative. [Online]. http://www.celtic-initiative.org/Projects/Celtic-Plus-Projects/2012/MUSIC/music-default.asp

[9] Informa Telecoms and Media, "Last Mile Backhaul Options for West European Mobile Operators". Informa Telecoms and Media," 2010.

[10] M. Paolini, "Backhaul for Small Cells," 2012.

[11] F. Rayal. (August 21, 2012) Small Cell Wireless Backhaul Business Case. [Online]. http://www.blinqnetworks.com/media/uploads/resources/BLiNQ_Networks_-_Small_Cell_Wireless_Backhaul_Business_Case.pdf

[12] R. Schwartz and M. Johansson, "Rethinking Small Cell Backhaul," July 2012.

[13] Cambridge Broadband Networks. (2012, February) Examing Small Cell Backhaull Requirements. [Online]. http://cbnl.com/sites/all/files/userfiles/files/Examining%20small%20cell%20backhaul%20requirements%20webinar%2015%20Feb%202012_0.pdf

[14] "Microwave Backhaul and Issues for Small Cell Architectures," Second Quarter 2012.

[15] "Guidelines for LTE Backhaul Traffic Estimation," 3 July 2011.

[16] 3GPP. (2012, September) LTE; Policy and Charging Control Architecture. [Online]. ftp://ftp.3gpp.org/Specs/latest/Rel-11/23_series/23203-b70.zip

[17] Cisco. (2012, May) Cisco Visual Networking Index: forcast and Methodology, 2011-2016. [Online]. http://www.cisco.com/en/US/solutions/collateral/ns341/ns525/ns537/ns705/ns827/white_paper_c11-481360.pdf

[18] John Naylon. (2012, Feb) www.cbnl.com.