Analysis of Architectural Alternatives for Low Cost Infrastructure

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1. Executive Summary

1.1. Overview

The initial rollout of the WiMAX network is based on a traditional cellular type architecture that is characterized by the following:

- Three sector Cells with radius of 1-2 km, using a frequency reuse of 3.
- Macro Base Stations with RF output power of 43 dBm, with indoor radios and tower top LNAs. This is sufficient for first wall indoor penetration for a large percentage of the coverage area.
- High capacity backhaul, using a mixture of point to point wireless and wired technologies.

This architecture satisfies the requirements that it was designed for, which is to provide a carrier class, robust wireless infrastructure, that can be scaled to higher capacities by adding new carriers to existing cell sites. However it does come at a high initial cost of deployment. The objective of this study is to investigate alternative network architectures which may have lower deployment costs. In particular we analyze architectures based on pico-cell type base stations, that have lower RF output power, but are also cheaper to deploy. A critical aspect of pico-cell architectures is the network architecture used for backhaul, and the main thrust of this study is to analyze a few of these designs. In particular the following backhaul architectures are analyzed, in decreasing order of cost:

1. Point to Point backhaul to a central site
2. Mesh type backhauls, with multiple point to point backhaul links per node
3. Mesh type backhauls with a single point to multipoint backhaul link per node
4. Mesh type backhauls with a single radio per node, that is used for both backhaul as well as access

For each one of these architectures we will investigate both in-band as well as out of band approaches. In every case the access will be based on WiMAX technology, however the backhaul may be based on other technologies which may be better suited.

1.2. Conclusions

From the analysis in this document, the following conclusions can be drawn:

- Pico cells with 1 radio and in-band backhaul suffer a rapid decrease in capacity as more cells are added. They are suitable for temporary adhoc type networks, but not as a replacement for the macro infrastructure

- Pico cells with 2 radios, one used for access and the other for out of band backhaul, have greater capacity, but for the range of backhaul speeds that are available, the number of cells that can be supported from a single cell with a wired interface, is 2 or 3 at most. This also makes it un-suitable as a replacement for the macro infrastructure
- There are 2 architectures that can be used as a replacement for the macro infrastructure:

1. Mesh based backhaul with at least 3 out of band backhaul radios per node
2. Centralized point to point backhaul, with multiple links originating from a central point

For both these architectures, we need to do a cost analysis to compare it with the usual macro infrastructure, such as the following:

Given a certain coverage area:

- How many 3-sector macro cells are needed to cover that area?
- How many pico-cells are needed to cover that area?
- What is the cost of providing coverage using macro cells? For this we need the cost of the equipment + installation costs + cost of backhaul
- What band should be used to provide backhaul for pico cell options 1 and 2?
- What is the cost of providing coverage using pico cells using option 1? What is the threshold below which the pico BS (includes backhaul) cost needs to be, in order for it compete with the macro cost?
- What is the cost of providing coverage using pico cells using option 2? What is the threshold below which the pico BS (includes backhaul) cost needs to be, in order for it compete with the macro cost? What about the cost of the central controller?

2. Architectural Alternatives

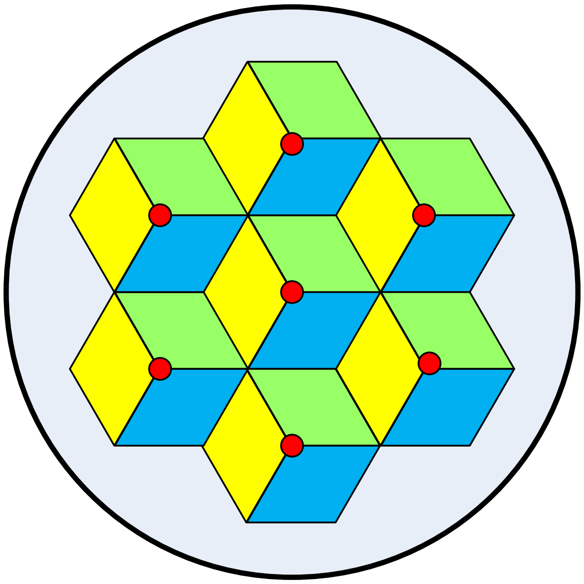


Figure 1a: Macro Cell Based Architecture

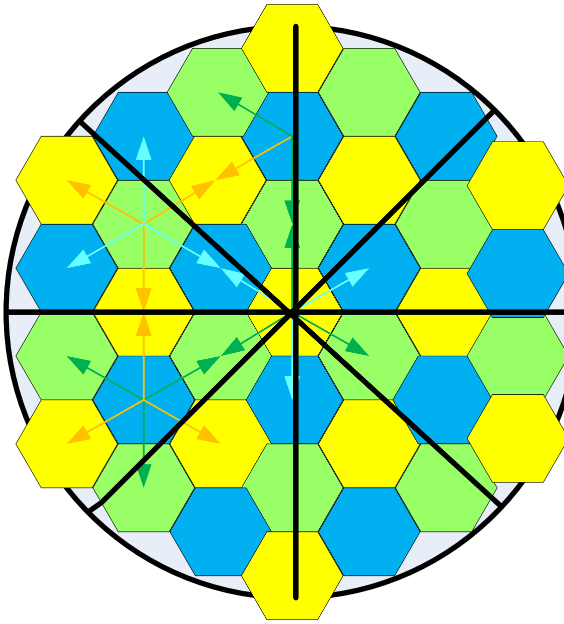


Figure 1b: Pico Cell Based Architecture

The initial deployment of the WiMAX network is based on the traditional Macro Cell Architecture shown in Figure 1a. The objective of this report is to investigate the technical and business feasibility of an alternative architecture based on pico cells, shown in Figure 1b. The main differences between these architectures is summarized in the Table below:

Macro Cells	Pico Cells
3 sector cells, with 40 dBm or more RF output power	Single sector cells (omni), with RF output power of 30 dBm or less
Typical cell radius is 1 km or more	Typical cell radius is 0.5 km or less

The benefits of using a pico cell based architecture are the following:

- Lower cost Base Stations
- Increase in network capacity: This is due to the fact that for the pico cell case, a larger fraction of the mobiles will be in higher modulation states as compared to the macro cell case.
- Better Coverage: It is easier to handle coverage holes using pico cells, especially in urban and dense urban areas

The main issue in deploying a pico cell based architecture is the cost of backhauling traffic. The question to be answered is the following: Is the cost savings from deploying smaller Base Stations enough to offset the increase in cost due to deploying a larger number of backhaul links? In this report we will investigate several different ways in which pico cells can be backhauled:

1. Wireless Point to Point backhaul to central hub, in a star type architecture
2. Wireless Mesh based backhaul
3. Broadband over Power Lines (BPL) based backhaul

We enumerate and analyze, from both technical and business point of view, these different backhaul alternatives. For each case we do the following:

- Document the capacity limits of the backhaul architecture (number of cells that can be backhauled using a single wired point of presence).
- Tally the total cost of supporting all the required infrastructure elements.

We will consider the case where the total coverage area is 40 sq km (radius of 3.6 km).

- Using macro cells of 1 km radius, a total of 13 cells are required.
- Using pico cells of 0.5 km radius, a total of 51 cells are required.

2.1. Point to Point Backhaul from a Central Hub

2.1.1. Out of Band Link

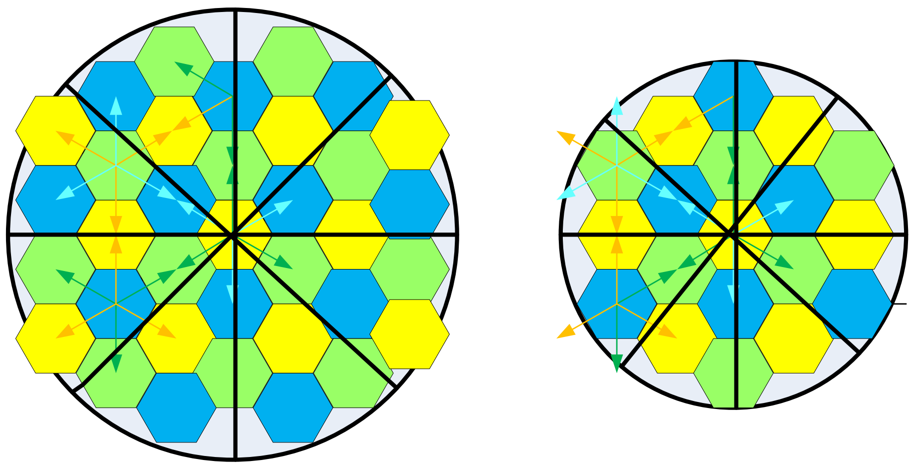


Figure 1

This section covers the case when the pico-cells are backhauled back to the central site, using common carrier channels. Hence each pico-cell site has two radios, one for access and the other for point to point backhaul. The requirements for the point to point backhaul links include the following:

- Backhaul capacity of 15 mbps in each direction
- Link distance of 4 km
- The central hub should be capable of supporting 30 or more point to point links, in a zoning friendly manner

2.1.2. In Band Link

This section covers the case when the pico-cells are backhauled back to the central site, using the same channel that they use for access. Hence thisarchitecture requires a single radio per pico-cell site.

2.2. Mesh Based Backhaul

2.2.1. Mesh Backhaul Based on a Single Radio per Node

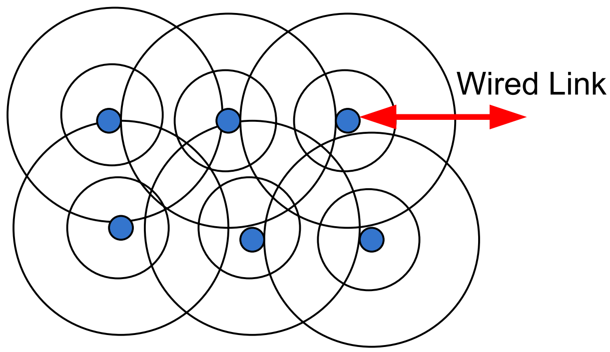


Figure 2

This architecture requires a single radio per pico-cell site, that is used for both backhaul and access. This main application for this design is for low cost and low power adhoc networks that can be quickly set up and torn down, or for low density broadband access in rural areas.

Today this application is served by WiFi mesh networks from companies such as Tropos Networks. For the WiFi case, restricting each node to a single radio also restricts them to using a single WiFi channel, that is used for access as well as for backhaul. Hence each packet is transmitted twice before it exits a cell: Once from the client device to the mesh node serving the cell, and then from the serving mesh node to some neighboring mesh node. Given the contention based nature of the CSMA/CA protocol that is used in WiFi, this behavior leads to rapid decrease in effective user throughput with increasing number of cells.

For the case of WiMAX based single radio mesh networks, it is possible to improve performance over WiFi mesh by exploiting the following properties of the WiMAX protocol:

- Even with a single channel, it is possible to partition the available spectrum into multiple non-overlapping portions, by using the frequency division property of OFDMA. Hence by allocating separate sub-channels to access and backhaul, it is possible to reduce the interference within a cell
- OFDMA supports the PUSC permutation scheme, that can be used to randomize the sub-carriers being used by neighboring cells, thus reducing interference.
- WiMAX supports HARQ based re-transmissions that are much more efficient and faster than the WiFi ARQ mechanism in recovering from link errors
- The WiMAX MAC protocol is based on reservation based data access, unlike the WiFi MAC which is a pure contention based protocol. This makes WiMAX more efficient in handling data, especially at higher loads.

Assuming that there are N cells in the mesh each with a capacity of C bps, it can be shown that the best case per cell capacity is upper bounded by (C/N), as follows: Assuming that the per cell capacity is X bps, the boundary cell that is connected to the wireline network has to handle a total of (N – 1)X bps coming from the (N – 1) other cells in the mesh + X bps that are generated locally in the boundary cell. Since

$(N – 1)X + X = C$, it follows that $X = C/N$ bps

Note that this analysis was highly simplified and assumed perfect co-ordination between cells resulting in optimum utilization of the available bandwidth. For WiFi meshes this assumption is clearly not satisfies due to the contention based nature of the MAC protocol, and in practice the capacity of single cell in WiFi meshes is closer to $C/2^N$ bps. For the case of WiMAX meshes, we can make use of the properties of the WiMAX protocol enumerated above, to design the network so that its capacity achieves the C/N capacity limit for a N node mesh network. These capacity limits also lead to the conclusion that it does not make sense to set up a single radio mesh network with a large number of cells, and typical networks should not have more than 5-10 cells per wired node.

We now describe the protocol that should be used to support single radio WiMAX meshes starting with the simplest case of a network of linear cells.

2.2.1.1. Linear Single Radio Mesh Network

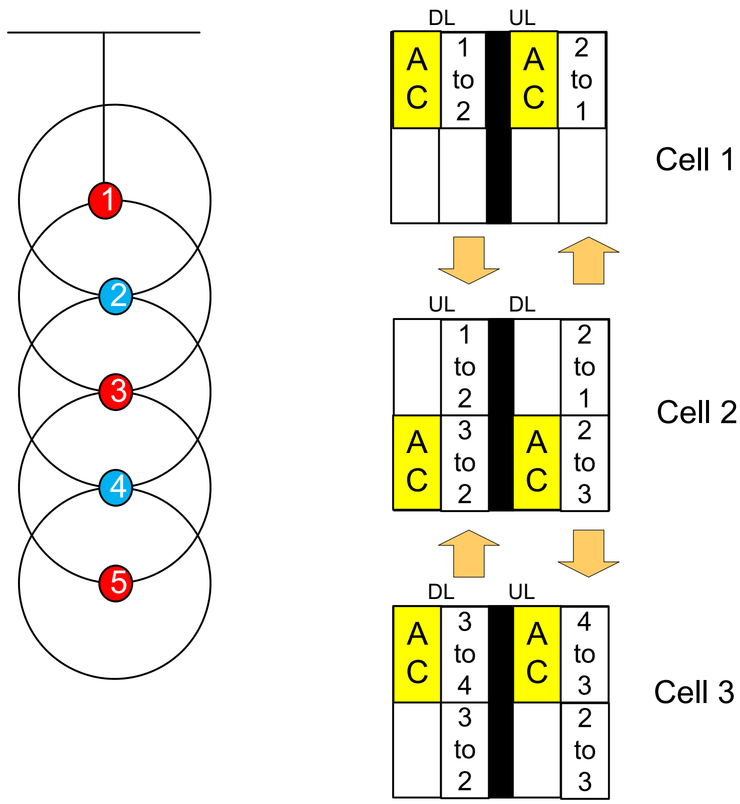


Fig 3: Frame Structure in the Linear Single Radio Mesh Network

The linear single radio mesh design for WiMAX networks is illustrated in Figure 3. It operates as follows:

- The TDD frames at each node are synchronized with each other, and split between the downlink and the uplink in the ratio 1:1.
- The nodes are numbered sequentially from 1 to N. All the odd numbered nodes are put into Group 1 and all the even numbered nodes are put into Group 2. All the nodes in a group transmit (and receive) at the same time. The DL portion of the frame in Group 1 nodes overlaps with the UL portion of the frame in Group 2 nodes and vice versa.
- The DL (and UL) portion of each frame is divided into 2 parts: Part 1 (in yellow) is devoted to access, while part 2 is dedicated to backhaul. This division is made along the time axis.
- The backhaul portion of the frame (both UL and DL), is also divided into 2 parts. One of the parts is used for backhauling traffic to (from) the cell on the left, while the other part is used for the cell on the right. This division is made along the frequency axis.
- The data portion of the frame may also be divided into two parts, such that all the nodes in Group 1 use one of the parts, while the nodes in Group 2 use the other part.

- The backhaul portion of the frame should use the AMC permutation, since it has lower PHY overhead. The frequency diversity that the PUSC permutation provides is not needed for backhaul since the nodes are stationary.
- The DL (and UL) frame should be divided between the backhaul and access portions in the ratio of
  BH:AC = N -1 : 1

2.2.1.2. Single Radio Mesh Networks of the Tree Type

In this section we describe the operation of single radio mesh networks in which more than one node falls within the range of another node. We will consider the simplest case in which 2 nodes are within range, in this section. This results in a tree type topology for the network.

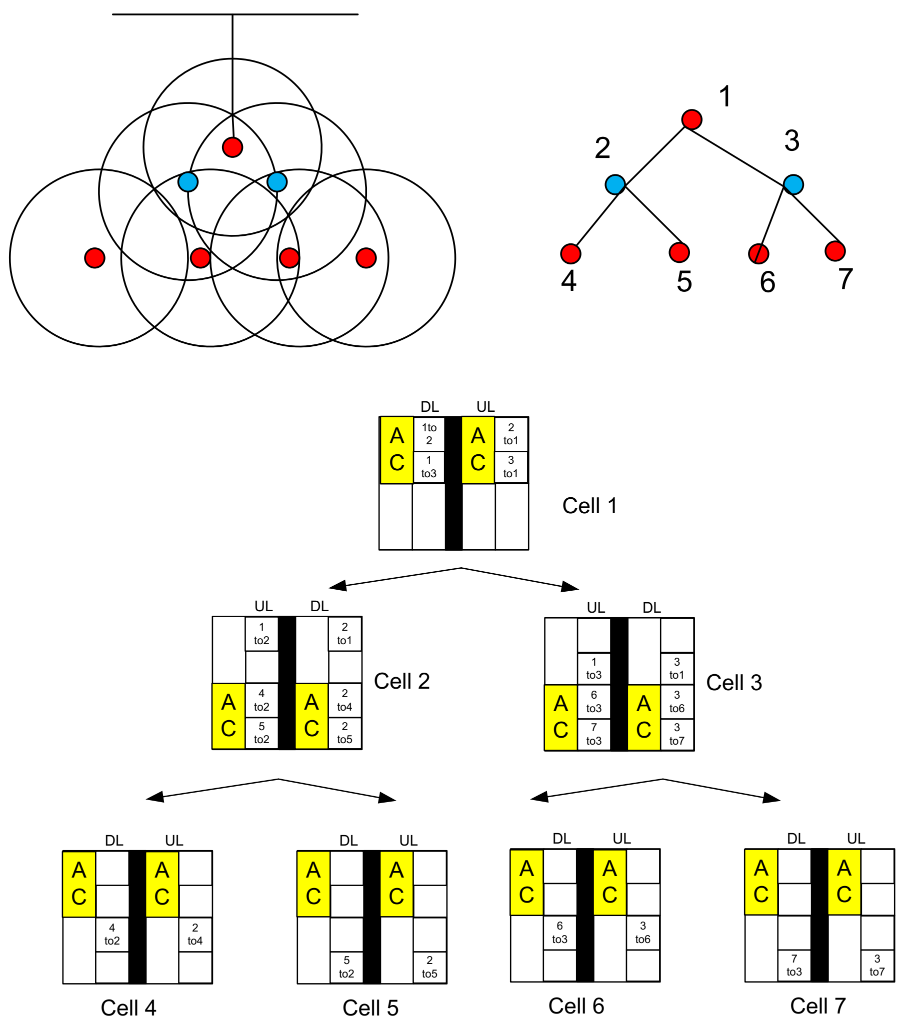


Figure 4: Tree type mesh networks

The tree type single radio mesh design for WiMAX networks is illustrated in Figure 4. It operates as follows:

- The TDD frames at each node are synchronized with each other, and split between the downlink and the uplink in the ratio 1:1.
- The nodes are numbered sequentially from 1 to N and divided into Group 1 and Group 2. The DL portion of the frame in Group 1 nodes overlaps with the UL portion of the frame in Group 2 nodes and vice versa. In the tree type topology, if a node is in Group 1 (Group 2), then its children nodes will be in Group 2 (Group 1). We will assume that the root node of the tree is in Group 1.

- The DL (and UL) portion of each frame is divided into 2 parts: Part 1 (in yellow) is devoted to access, while part 2 is dedicated to backhaul. This division is made along the time axis.
- The backhaul portion of the frame (both UL and DL), is divided into 4 parts along the frequency axis. These parts are used for backhaul transport to the neighboring nodes, using a pattern that is illustrated in the above figure.
- The backhaul portion of the frame should use the AMC permutation, since it has lower PHY overhead. The frequency diversity that the PUSC permutation provides is not needed for backhaul since the nodes are stationary.
- The DL (and UL) frame should be divided between the backhaul and access portions in the ratio of
  BH:AC = N -1 : 1

2.2.2. Out of Band Backhaul Based on Two Radios per Node

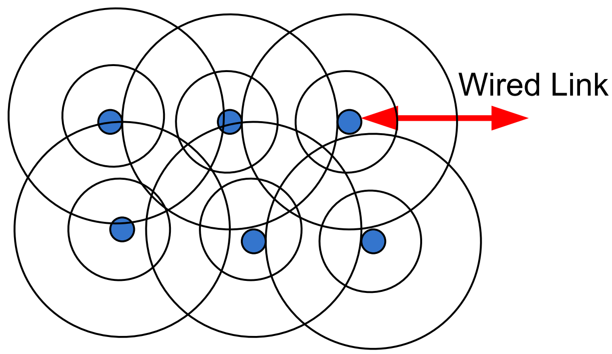


Figure 5: Out of Band Backhaul based on Shared Backhaul Links

This architecture is based on 2 radios per pico-cell site, one for access and the other for backhaul. All the backhaul radios operate in the point to multi-point mode, and use the same channel, so that they can communicate with each other. The access radios may use different channels to reduce inter-cell interference.

In this case, we have the option of using radio technologies other than WiMAX, for the backhaul links. A commonly used option is 802.11a, which runs in the license exempt 5.8 GHz band, and provides about 20 mbps of useful capacity per link. WiMAX based backhaul options include 802.16d and 802.16e. As in the single radio case, the sub-channelization feature in 802.16d and 802.16e can be used to eliminate the contention between neighboring cells, thus improving throughput in comparison to 802.11a.

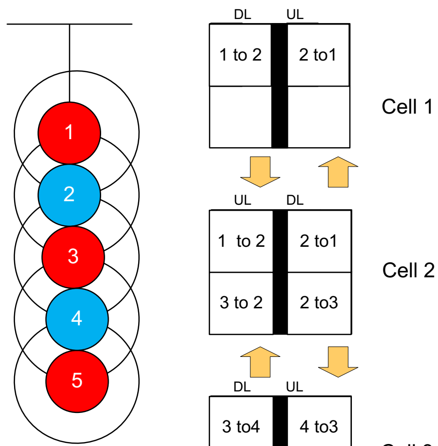
For the case of 802.16e based backhaul, the frame structures shown in Figure 3 (for a linear topology) and Figure 4 (for a tree topology) apply, the only difference being that the space in the frame set aside for access is no longer needed, so that the entire frame is devoted to doing backhaul. This is illustrated in Figure 6a for the linear case.

The capacity of this type of network is upper bounded by the capacity of the backhaul links. Define the following:

C: Traffic generated in each access node (up+down)
B: Backhaul capacity per node (up + down)

We illustrate the capacity calculation for the simple case of the linear network, as illustrated in Figure 6b. The resulting load on the backhaul links is shown, where X = C/2. The most heavily loaded backhaul link belongs to node 2, and equals 7C. Hence the capacity per node is given by (B/7). For the more general case of N nodes arranged linearly, it can be shown that the node capacity is given by

$$\frac{B}{2N-3}.$$



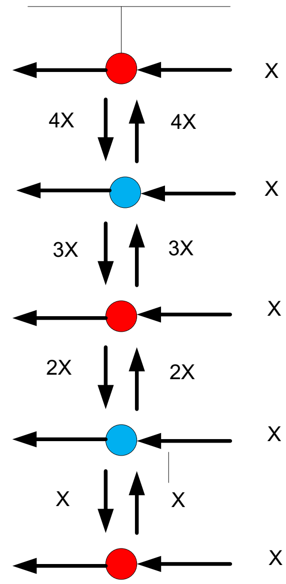


Figure 6a: Backhaul Frame Structure for the Out of Band case (Linear Network)

Figure 6b: Capacity Analysis

If we invert the capacity formula, so that

$$N = \frac{1}{2} * \left(\frac{B}{C} + 3\right)$$

The interpretation of this equation is that if the backhaul capacity is fixed at B, and the node access capacity is fixed C, then N is the largest number of nodes that can be added to the network, without degrading the per node access capacity. Once the number of nodes exceeds N, the node access capacity falls below C, due to the lack of backhaul bandwidth.

Note that the size of the regions devoted to backhaul can be varied from node to node, such that relative size increases as we move towards the node that is connected to the wired backhaul. For example in node 2, the ratio of the size of the backhaul region devoted to traffic going to node 1 to the size of the backhaul region devoted to traffic going to node 3 is 4:3 (N-1:N-2 for the N node case). This ratio can be calculated similarly for the other nodes.

Assume the following capacities for various access and backhaul technologies:

Access Technology	**C (mbps)**
802.16e (5 MHz)	7 mbps
802.16e (10 MHz)	14 mbps

Table 1

Backhaul Technology	**B (mbps)**
802.11a (20 MHz)	20 mbps
802.16d (10 MHz)	25 mbps

802.16e (10 MHz)	14 mbps

Table 2

In the Table 3 we provide estimates for number of cells that can be backhauled without reduction in cell capacity, using various types of backhaul, for 5 MHz and 10 MHz 802.16e cells:

Access Technology	**Backhaul Technology**	**N**
802.16e (5 MHz)	802.11a (20 MHz)	3
	802.16d (10 MHz)	3
	802.16e (10 MHz)	2
802.16e (10 MHz)	802.11a (20 MHz)	2
	802.16d (10 MHz)	2
	802.16e (10 MHz)	2

Table 3

From Table 3 we can reach the following conclusions: If we are interested in providing a backhaul architecture that does not lead to a reduction cell capacity, then the 2 radio point to multipoint type design does not work very well, since it can backhaul only 2 or 3 cells at most, before the access capacity exceeds the backhaul capacity. However this architectures does perform better than the 1 radio architecture, in which the per cell capacity decreases by 1/N with increasing number of cells.

2.2.3. Out of Band Backhaul Based on Three or More Radios per Node

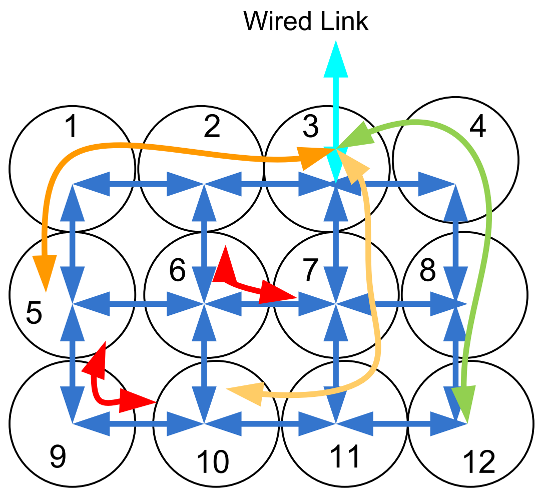


Figure 7

This architecture requires multiple backhaul radios per pico-cell site, 4 in the example in figure 7. These are also accompanied by directional antennae, so that it is possible to establish a 2 dimensional backhaul grid as shown. The capacity of this type of mesh network is limited by the product of the number of backhaul interfaces and the per link backhaul bandwidth at the gateway node, and can be computed as follows:

Define the following:
C: Access capacity per node (up + down)
B: Backhaul capacity per link (up + down)
M: Number of backhaul links at the gateway node

Then total backhaul capacity at the gateway node is given by MB. Hence total number of cell N, that can be supported without causing throughput reduction, is given by:

$N = (MB/C) + 1$

Once the number of nodes exceeds N, the throughput per nodes drops below C. In order to realize the maximum throughput, the node traffic needs to carefully routed through the mesh in order to distribute equally among the backhaul links at the gateway. An example of this is shown in Figure 7, where B = 20 mbps, C = 5 mbps and M = 3, so that N = (3*20/5) + 1 = 13. Nodes 1, 2 and 5 routed through the gateway link on the left, nodes 10, 11 and 7 are routed through the gateway link at the bottom and nodes 12, 8 and 4 are routed through the gateway link on the right. Nodes 9 and 6 split up their traffic equally among their neighboring nodes as shown.

Access Technology	Backhaul Technology M = 3	N
802.16e (5 MHz)	802.11a (20 MHz)	9
	802.16d (10 MHz)	11

	802.16e (10 MHz)	7
802.16e (10 MHz)	802.11a (20 MHz)	5
	802.16d (10 MHz)	6
	802.16e (10 MHz)	4

Table 4

Table 4 computes the number of nodes that can be supported, with M = 3, for the access and backhaul technologies and speeds enumerated in Tables 1 and 2.