The Role of Fixed Wireless Access Networks in the Deployment of Broadband Services and Competition in Local Telecommunications Markets

An Engineering, Economic, and Public Policy Analysis

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Abstract

Through the use of a forward-looking engineering-economic model, this paper analyzes the cost structure of broadband fixed wireless access (BFWA) networks and examines their economic viability by comparing the costs of implementing BFWA networks operating at 2.6 GHz MMDS frequencies with the costs of implementing Digital Subscriber Line (DSL) and cable modem/Hybrid Fiber Coax (cable) networks to provide voice over IP and broadband Internet access services to residential and small business customers. Detailed investment requirements are reported for the state of Delaware along with a series of sensitivity analyses on how network costs vary with population density, usage demand, available spectrum, choice of operating frequency, and technical characteristics of the underlying networks. Major findings include:

On average, costs of BFWA networks are higher than costs of DSL and cable networks. However, BFWA is more cost effective than DSL and cable for density areas of less than 100 lines/square mile. In low-density areas of less than 5 lines/square mile, BFWA is the only viable choice to provide broadband services as costs of DSL and cable networks are extremely high due to the high costs of local loop plant. Although it is unlikely that BFWA will be a third option for broadband services in high-density areas where both DSL and cable modem services are available, our results suggest that BFWA is a viable solution for medium-density areas where DSL and cable modem services may not be available due to distance limitations of DSL and lack of cable infrastructure.

Costs of BFWA networks are distance insensitive but more sensitive to subscriber usage demands than are the costs of DSL and cable networks. Second-generation OFDM systems using desktop CPE with integrated antenna lower overall costs by eliminating expensive rooftop antenna installation, despite the need for more base stations due to shorter reach.

If more spectrum become available, it can be used to lower the costs of urban wireless networks. However, in rural areas where systems are coverage, not capacity limited, more spectrum will not reduce network costs. What does help in rural areas is getting spectrum in the right band. Our results show that the use of 700 MHz UHF spectrum instead of MMDS further lowers costs especially in rural areas, because of the longer reach possible at 700 MHz.

Keywords: Broadband fixed wireless access, BFWA, broadband Internet access, voice over IP, MMDS, 700 MHz UHF spectrum, engineering-economic model.

1. Introduction

Recently the Federal Communications Commission (FCC) has moved to classify broadband Internet access as an information rather than telecommunications service, has declined to mandate open access over cable modem, and may extend that policy to DSL facilities. Some fear that as a result the current wireline facilities duopoly may result in a similar duopoly for Internet service. This outcome would be avoided if broadband fixed wireless access (BFWA) technologies emerge to enable additional facilities based competitors in broadband service markets. Service providers today are currently evaluating a new generation of BFWA systems that can operate in various frequency ranges and provide wireline equivalent services. To help better understand the economics of BFWA networks and their role in the deployment of broadband services and competition in local telecommunications markets, this paper analyzes the cost structure of BFWA networks and examines their economic viability by comparing the costs of implementing BFWA networks providing voice over IP and broadband Internet access services with the costs of providing comparable services using DSL and cable modem/HFC networks.

The deployment of BFWA networks in the last mile has been emerging to serve two classes of customers: 1) large corporate enterprises and 2) residential households and small businesses. Large corporate enterprises often use frequency bands above 11 GHz to set up a point-to-point BFWA system between their high-rise corporate offices. On the other hand, network operators, to serve residential and small business customers, typically deploy point-to-multipoint networks operating in frequency bands below 11 GHz. This research focuses on the residential and small business market because of its wide and as of yet unmet demand for broadband services. This demand presents an opportunity to explore the impact of BFWA technology on the deployment of broadband services and competition in local telecommunications markets.

The next section provides an overview of available spectrum and technology choices for BFWA deployment. Section 3 discusses research methodology and introduces the engineering-economic model developed to estimate the cost of implementing a BFWA network. Sections 4, 5, and 6 presents a case study of implementing BFWA networks to provide voice over IP and Internet access services to residential and small business customers across the entire state of Delaware. Detailed investment requirements and annualized cost per customer location are reported along with a series of sensitivity analyses on how network costs vary with population density, usage demand, available spectrum, choice of operating frequency, and technical characteristics of the underlying networks. Section 7 presents a cost comparison by density area of implementing BFWA, DSL, and cable modem/HFC networks to provide voice over IP and Internet access services. Lastly, Section 8 concludes the paper by providing policy implications of the research findings.

2. Overview of Available Spectrum and BFWA Technology

Broadband wireless access services being offered today operate at several frequency bands, both licensed and unlicensed (licensed-exempt). As shown in Table 1, more spectrum is available at higher frequency bands. However, the characteristics in terms of radio propagation, rain and snow fading, atmospheric attenuation, and complexity in RF equipment are quite different at different frequency bands. These traits make each frequency band suitable for different applications and customer markets. In general, digital microwave systems fall into two categories: systems operating at frequencies below 11 GHz and above 11 GHz. A system operating at a frequency below 11 GHz has a longer propagation distance (up to 30 miles). It is mildly affected by precipitation such as rain and snow. Frequencies below 11 GHz are generally not absorbed by objects in the environment. They tend to be reflected, resulting in extensive multipath[1]. On the other hand, multipath tends not to be an issue at frequencies above 11 GHz because most of the multipath energy is absorbed by the physical environment. However, it is more susceptible to signal fade due to rain and snow. Since propagation losses caused by atmospheric absorption are much higher, a system operating at frequencies above 11 GHz has a shorter coverage distance (usually less than 3 miles). The cost of RF equipment is also more expensive at higher frequency bands as it requires more expensive semiconductor technologies such as GaAs.

A number of standards committees are currently developing specifications for BFWA systems. These include the IEEE Wireless Metropolitan Area Networks (IEEE WirelessMAN), the European Telecommunications Standards Institute-Broadband Radio Access Networks (ETSI-BRAN), and the Broadband Wireless Internet Forum (BWIF). The IEEE WirelessMAN group has recently approved the 802.16 standard for BFWA systems above 11 GHz. However, at the time of this writing, there is no standard for systems below 11 GHz. The first-generation BFWA systems use either wireless LAN equipment operating over an extended range or a vendor proprietary cable modem derivative wireless system based on single-carrier-modulation technology.

[1] Multipath is the composition of a primary signal plus duplicate or echoed signals caused by reflections off objects between the transmitter and receiver.

Name	Type	Frequency	Bandwidth
Wireless Communications Service (WCS)	Licensed	698-746 MHz 746-794 MHz 2.305-2.310 GHz 2.31-2.32 GHz 3.65-3.7 GHz 4.94-4.99 GHz	48 MHz 48 MHz 5 MHz 10 MHz 50 MHz 50 MHz
Advanced Mobile & Fixed Communications Services (AMFCS or 3G)	Licensed	1.710-1.755 GHz 1.755-1.810 GHz 2.110-2.150 GHz	45 MHz 55 MHz 40 MHz
Multipoint Distribution Service (MDS) Multichannel Multipoint Distribution Service (MMDS)/Instructional TV Fixed Service (ITFS)	Licensed	2.160-2.165 GHz 2.500-2.690 GHz	5 MHz 190 MHz
Industrial Scientific and Medical (ISM)	Unlicensed	902-928 MHz 2.400-2.4835 GHz	26 MHz 83.5 MHz
Unlicensed National Information Infrastructure (U-NII)	Unlicensed	5.15-5.25 GHz 5.25-5.35 GHz 5.725-5.825 GHz	100 MHz 100 MHz 100 MHz
Multichannel Video Distribution& Data Service (MVDDS)	Licensed	12.2-12.7 GHz	500 MHz
Digital Electronic Message Service (DEMS)	Licensed	24.25-24.45 GHz 25.05-25.25 GHz	200 MHz 200 MHz
Local Multipoint Distribution Service (LMDS)	Licensed	27.5-28.35 GHz 29.1-29.25 GHz 31.0-31.3 GHz	850 MHz 150 MHz 300 MHz
39 GHz Wireless Services	Licensed	38.6-40 GHz	1400 MHz
Developing Millimeter Wave Systems	Unlicensed	57-64 GHz	7000 MHz

Table 1: Available Frequency Bands for Broadband Wireless Services in the United States, Adapted from (Kobb, 2001)

One of the major challenges faced by first-generation broadband fixed wireless service providers is to maintain service reliability in a non-line-of-sight environment due to multipath interference. This fundamental shortcoming in the first-generation single-carrier-based technology has slowed BFWA deployments since reliable services can only be provided in a few carefully selected markets with a clear-line-of-sight environment. OFDM is an emerging technology that offers a capability to overcome multipath without compromising the system’s spectral efficiency. Since transmission is carried over several narrow sub-carriers, which are less impacted by multipath, OFDM improves the system’s coverage and provides more robust performance in an obstructed non-line-of-sight environment. Another method of defeating multipath is antenna diversity. Techniques such as multiple-in/multiple-out (MIMO) and beam-forming antenna technologies have been integrated into some of the new generation BFWA equipment. Another emerging trend for the second-generation BFWA systems is the use of desktop CPE with integrated antenna. These user-self-installable indoor CPE units are very attractive for the service providers as they eliminate truck rolls and high installation costs of setting up outdoor antennae and equipment at the customer premises. See (Webb, 2001) for more information about BFWA technology choices.

3. Research Methodology and Engineering-Economic Model

A BFWA engineering-economic model was developed to estimate the cost of implementing a BFWA network to provide voice over Internet Protocol (VoIP) and broadband Internet access services. Following the forward-looking economic cost methodology, which is widely used to analyze business opportunities for new technologies and for new entrants – and selected by the FCC for determining cost-based access charges, pricing for interconnection, unbundled network elements, and universal service support levels – the BFWA model assumes a "greenfield" deployment where all construction takes place in an area where there is no pre-existing telecommunications infrastructure. A BFWA network must be built to provide voice over IP and broadband Internet access services to all residential and small business customers in the serving area.

Figure 1 shows the relationships among the various modules in the model. More detail can be found in (Wanichkorn, 2002).

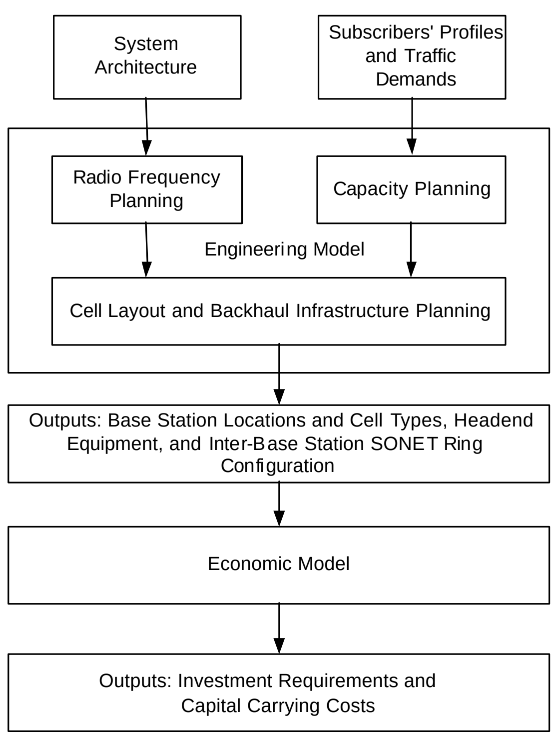


Figure 1: The BFWA Engineering-Economic Model Flow Diagram

System Architecture

By “system architecture”, we mean the technical characteristics of the system to be modeled, including information on the operating frequency, system configuration, underlying network technology, and equipment specifications. Assumptions on data rate and quality of service requirements, cell types (supercell and minicell), sectorization plan, cellularization and frequency reuse plan are addressed in this module.

A system based on first generation single-carrier technology using 2.6 GHz MMDS frequencies was chosen as an initial baseline system because it is among the most widely implemented BFWA systems to date. However, the model was programmed to be adaptable for systems using other technologies and operating frequency ranges. Table 2 outlines key parameters of the baseline system’s technology.

Parameters	Baseline Technology
PHY Layer Transmission	Single carrier with time domain decision feedback equalization
Duplexing	FDD with a 30 MHz guard band
Multiple Access	Downstream: Broadcast TDM Upstream: TDMA
Modulation	Downstream: selectable QPSK, 16QAM, 64QAM Upstream: selectable QPSK, 16QAM
MAC Layer Protocol	DOCSIS 1.1 based with wireless extension Embedded Voice over IP bandwidth provision
Security and Privacy	Packet data encryption and authentication using digital certificates

Table 2: Baseline Technology Parameters

Figure 2 shows a basic block diagram of the baseline BFWA system architecture. The customer premises equipment (CPE) hardware configuration consists of an outdoor antenna and transceiver assembly, an indoor integrated wireless modem/multi-terminal adapter unit, and a power supply. A coax line provides the DC and IF signal handling between the transceiver and indoor equipment. The wireless modem performs voice over IP and data to IF signal modulation and demodulation. The multi-terminal adaptor provides four RJ-11 ports for up to four telephone and fax lines, and one RJ-45 port for an Ethernet connection. Base station equipment consists of routers, wireless modem termination system (WMTS), transmitters, receivers, network management system, tower, and antennae.

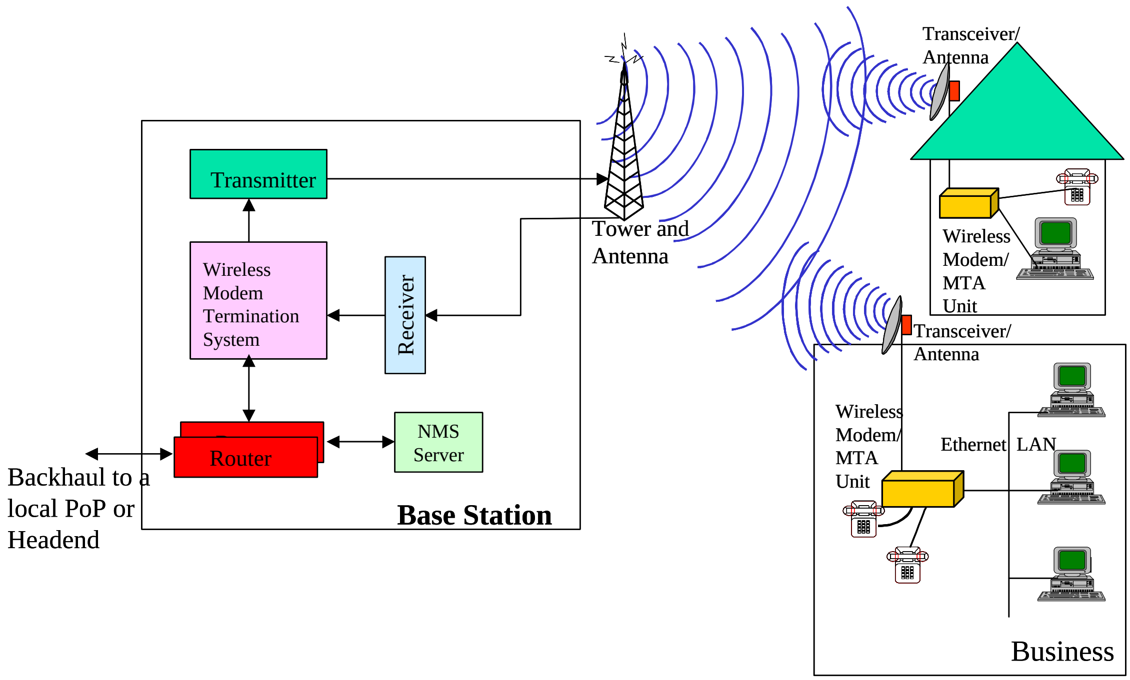


Figure 2: Broadband Fixed Wireless Access System Block Diagram

Both supercells and minicells are used to better provide capacity and coverage to the end users. The supercell architecture is designed for areas where subscribers are sparsely located or for an initial rollout of the system when the customer base is minimal and the traffic density is low. A high-power single transmitter site with an omni-directional antenna on a tall base station tower, approximately 400 feet, is used to provide complete coverage for the area. For MMDS services, the FCC allows up to 2000 Watts (63 dBm) EIRP for an omni-directional transmitter. Low order modulation schemes (16QAM for downstream and QPSK for upstream) are employed to better reach outlying subscribers. The minicell architecture covers a smaller service area but offers a higher cell capacity through sectored antennae as compared to the supercell architecture. Minicells provide services in a market where the potential subscriber base can support multiple cell sites and high aggregate throughput is demanded. Because of its small cell size, the base station tower is assumed significantly lower, approximately 150 feet, and the transmitter power level per sector is scaled back for a cellular architecture, in the range of approximately 1-100 Watts EIRP (30-50 dBm), so that the total transmitted EIRP per base station is within the FCC limit. High order modulation schemes (64QAM for downstream and 16QAM for upstream) are used to increase the cell capacity. Table 3 summarizes the design assumptions for the supercell and minicell architectures.

Cell Type	Supercell	Minicell
Cell Deployment	Single cell	Multiple cells with cellularization
Base Station Antenna Height	400 ft	150 ft
Transmitter Power Level	Up to 2000 Watts EIRP	1-100 Watts EIRP
Cell Sectorization and Antenna Pattern	non-sectored cell using omni-directional antennas	sectored cell using directional antennas
Modulation	Downstream: 16QAM Upstream: QPSK	Downstream: 64QAM Upstream: 16QAM

Table 3: Supercell and Minicell Design Assumptions

We have adopted a reuse plan proposed in (Roman, 1998) for the sectorized minicell architecture. This patented reuse plan offers a high bandwidth efficiency and allows for changes in the sector structure without the need to revisit the subscribers. The proposed reuse plan divides the available spectrum into two frequency groups. Each frequency group is used alternatively in each sector of a cell and cells are arranged in parallel strips of alternated polarity. Since one half of the spectrum is used in each sector, a 4-sectored cell provides a 200% increase in the cell capacity. Following the same argument, an 8-sectored cell and a 16-sectored cell provide 400% and 800% increased in the cell capacity, respectively. In a real implementation where demand is not homogenous, a mixture of differently sectorized cells can be deployed with a requirement that the distance ratio between co-channel interferer and cell size (D/R) ≥ 5 must be preserved. Consequently, carrier-to-interference characteristics remain the same. Figure 3 shows an example of a mixed deployment of differently sectorized cells.

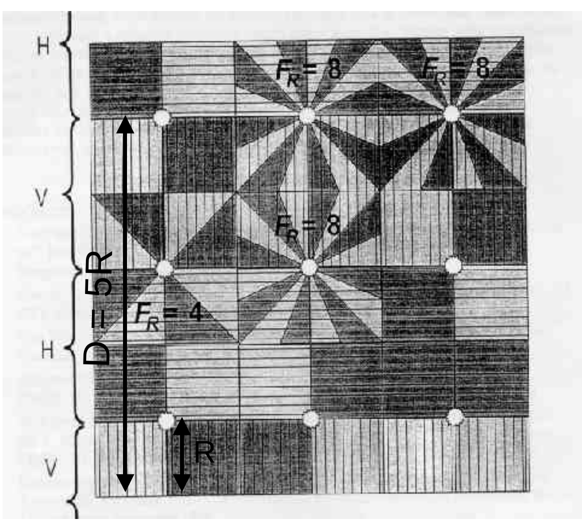


Figure 3: Example of a Mixed Deployment of Differently Sectorized Cells, Adapted from (Roman, 1998)

Radio Frequency Planning

The radio frequency planning module uses inputs from the system architecture module to estimate the capacity of various cell types to be employed in the network. The default scenario assumes 18 MHz (three 6 MHz channels) of spectrum are allocated for each downstream and upstream direction and different channels for unsectorized and sectorized cells, for a total of 72 MHz for the system. Table 4 summarizes the usable capacity for each cell type, assuming 80% bandwidth utilization, ¾ Forward Error Correction (FEC), and 20% overhead.

Cell Type	Omni-Directional Supercell	4-Sectored Minicell	8-Sectored Minicell	16-Sectored Minicell
Downstream:				
Channel bandwidth	18 MHz	18 MHz		
Downstream Modulation	16QAM	64QAM		
Modulation Efficiency (bits/s/Hz)	3.333	5		
Frequency Reuse	1	2	4	8
Downstream Capacity per Cell	**28.8 Mbps**	**86.4 Mbps**	**172.8 Mbps**	**345.6 Mbps**
Upstream:				
Channel Bandwidth	18 MHz	18 MHz		
Downstream Modulation	QPSK	16QAM		
Modulation Efficiency (bits/s/Hz)	1.667	3.333		
Frequency Reuse	1	2	4	8
Upstream Capacity per Cell	**14.4 Mbps**	**57.6 Mbps**	**115.2 Mbps**	**230.4 Mbps**

Table 4: Estimation of Cell Capacity

We use the Erceg propagation model (Erceg et al., 1999), which is proven to fit well with the measured results from MMDS network field trials in Dallas-Fort Worth, Texas and in Monmouth County, New Jersey (Erceg, 2001, Kim et al., 1999), and the Barnett and Vigants' fade margin model[2] (Barnett, 1972). Given the RF specifications of the base station and customer premises equipment, interference and link budget analyses are performed to determine coverage ranges of supercell and minicell as summarized in Table 5. Complete link budget calculations are provided in Appendix A.

[2] For a conservative design, we reason that at least 10dB of fade margin should be included in the path calculation. As such, a minimum required fade margin of 10 dB is applied if the predicted value based on the Barnett and Vigants' formula is lower than 10 dB.

Cell Architecture	Maximum Path Length (miles) for								
	Hot Humid Coastal Area			Inland Temperate Area			Very Dry Area		
	Smooth Terrain	Average Terrain	Rough Terrain	Smooth Terrain	Average Terrain	Rough Terrain	Smooth Terrain	Average Terrain	Rough Terrain
Supercell	9.0	8.5	5.3	12.0	9.5	5.3	12.6	10.2	5.3
Minicell	3.6	1.9	1.3	3.6	1.9	1.3	3.6	1.9	1.3

Table 5: Estimation of Cell Coverage Radius[3]

Subscribers' Profiles and Traffic Demands

This module contains inputs describing the subscribers' geographic locations and their usage demands. The HM5.0a database is used to provide information on telephone subscription throughout the United States. These data are granular to the "cluster" level, which is defined as the smallest grid of customer locations that are "close enough together to be efficiently engineered as a single telephone plant serving area" (HAI Consulting, 1998). The number of homes and businesses in each cluster, cluster area, relative distances from a cluster to its serving PSTN's central office, and the geographic locations of the central offices are extracted from the HM5.0a database. Based on these data, the geographic locations and spatial distribution of the subscribers are computed. Note that we assume broadband services provided by the modeled BFWA network are targeted only for small business customers since medium to large business enterprises can afford more sophisticated broadband access solutions, such as high-speed fiber networks. Because the number of firms from the HM5.0a cluster data includes firms of all sizes, an assumption needs to be made regarding the number of small firms located in each cluster. Based on the 1990 U.S. Census data, approximately 85% of firms in the U.S. are small firms assuming that a small firm is a firm with 1-9 employees (U.S. Census, 1990). Using these statistics, the number of small firms in each cluster is estimated. In rural areas where other types of wireline networks are not available, fixed wireless access might be the only choice for broadband services. Consequently, we assume that all firms located in any cluster with line density of less than 200 lines/square mile are small businesses and receive services from the modeled BFWA network.

The number of residential and business voice lines in each cluster and the corresponding busy hour CCS per line are taken from the HM5.0a database. Internet access demands in term of peak upstream and downstream traffic per customer location and the number of active customers during busy hours are user selectable. Table 6 summarizes data traffic parameters and default values.

[3] The maximum path length is computed iteratively by matching the allowable path loss, required fade margin, and path length until the three values are consistent. For the same type of terrain, the same coverage distance of a minicell is observed across all atmospheric categories because the same amount of

Parameters	Residential	Small Business
Average Downstream Data Rate	20 Kbps/location	80 Kbps/location
Average Upstream Data rate	2 Kbps/location	20 Kbps/location
Busy Hour Activity Ratio	30%	90%

Table 6: Data Traffic Parameters and Default Values

Capacity Planning

The capacity planning module estimates the amount of traffic which traverses the network during the peak busy hour. This information is used in the cell layout and backhaul infrastructure planning module to size the appropriate base station and headend equipment as well as the necessary backhaul infrastructure. Since a standards-based voice over IP solution for fixed wireless access does not exist today, we assume that the modeled system uses one of the existing voice over IP codecs. The default codec for the baseline system is assumed to be G736.32 with a packet size of 20 ms, and, as a result, the data rate required for a voice channel is 48 Kbps/channel. The busy hour voice traffic per line can be expressed as:

$$\textit{BH voice traffic (Kbps/line)} = \frac{\textit{(BH CCS/line)* (48 Kbps/voice channel)}}{\textit{(36 CCS /voice channel)}} \qquad (1)$$

and the total busy hour voice traffic in each direction can be computed as:

Total BH voice traffic (Kbps) =
*(Residential BH voice traffic in Kbps/line * No. of residential VoIP lines) +*
*(Business BH voice traffic in Kbps/line * No. of business VoIP lines)* (2)

The total busy hour data traffic in each direction can be computed as:

Total BH data traffic (Kbps) =
*(Residential data traffic in Kbps/location * No. of households * Residential BH activity ratio) + (Business data traffic in Kbps/location * No. of firms * Business BH activity ratio)* (3)

Required system capacity is determined by traffic during the peak busy hour. When this time occurs can vary based on the type of user. For the business user, busy hours are between 8AM and 9AM, and 4PM and 6PM (Cornelius, 1998). For the residential user, busy hours are between 5PM and 10PM (Morgan, 1998). We assume that the peak utilization interval occurs around 5PM to 6PM where the business and residential busy hours overlap and compute network capacity requirements based on total voice and data traffic expected during that peak interval. A growth margin of 5% is assumed for extra

10 dB fade margin is added to the calculation. Consequently, the distance is determined solely from the propagation loss. See Appendix A for details.

capacity for network growth or peak load management purposes. The amount of busy hour traffic expected from each cluster (cluster's capacity requirement) in each upstream/downstream direction can be expressed as:

Cluster's capacity requirement (Kbps) =
*(1 + Growth margin) * [Total BH voice traffic (Kbps) + Total BH data traffic (Kbps)]* (4)

Cell Layout and Backhaul Infrastructure Planning

The cell layout and backhaul infrastructure planning module contains the main algorithms implemented in the engineering model. Based on a greedy heuristic, a cell layout algorithm was developed to determine the number of base stations, their locations and cell types (supercell or minicell) such that all customers in the selected area are served with an adequate service level (i.e, justified capacity and coverage requirements)[4]. Once the cell site network is determined, the module makes use of the SONET ring layout algorithm from the HM5.0a model to construct a SONET ring infrastructure which interconnects the base stations and their serving headends as shown in Figure 4. Headends are assumed to be located at the same locations as the existing PSTN tandem offices listed in the HM5.0a database. The module then determines the necessary headend equipment needed to handle the traffic backhauled from the base stations, and the facilities needed to transport the traffic to the interexchange carriers' and Internet service providers' points of presence (IXCs' and ISPs' POPs).

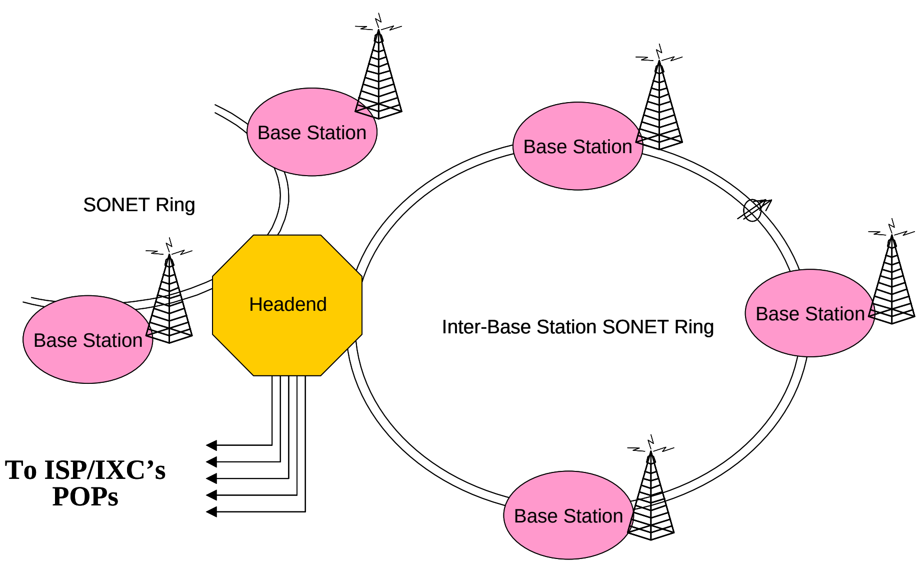


Figure 4: Inter-Base Station SONET Ring Architecture

[4] Coverage is calculated based on cell radius without regard to topological variations that might limit line-of-sight. A detailed case study for a 110 square mile area centered on Eugene, Oregon showed that cell overlap typically results in comprehensive coverage, despite intervening hills and valleys.

Figure 5 shows the basic elements of the headend office equipment consisting of add drop multiplexers (ADMs), routers, Ethernet switches, a VoIP soft switch, a network management system, and a backup power supply. The regional headend office also houses other network equipment that can be shared among base stations such as servers for IP services, caches, and firewalls. The model assumes that the inter-base station SONET rings use OC-48 circuits and each OC-48 circuit in a ring requires two strands of fiber (assuming no use of Dense Wavelength Division Multiplexing, DWDM). The OC-48 circuits are further divided into DS-3 channels which can be individually allocated to establish transport links between base stations and the headend office. There are five ISP/IXCs' POPs connected to each headend office via a point-to-point fiber link. Each link is assumed to be a half a mile long and requires four strands of fiber per link for redundancy.

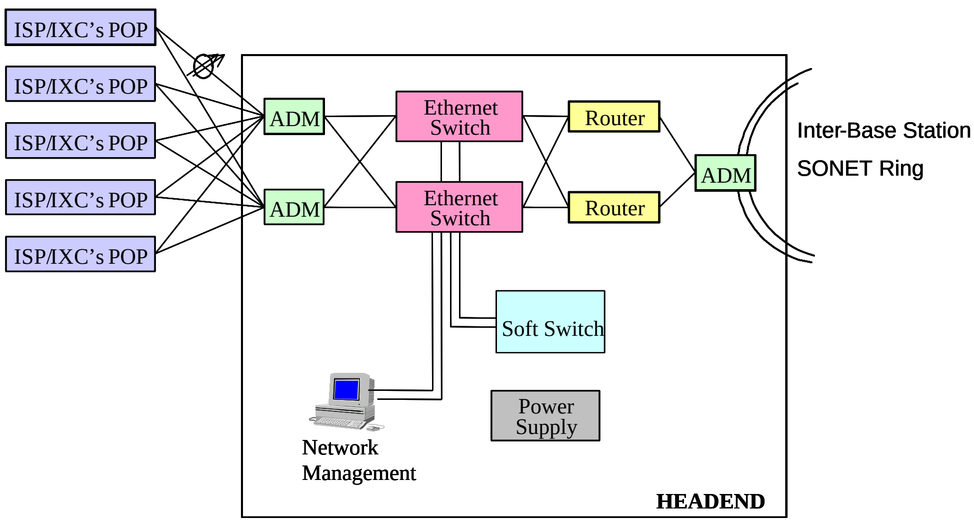


Figure 5: Basic Elements of Headend Office Equipment

Economic Model

Based on the cell site structure, headend facilities, and SONET ring infrastructure from the engineering model, the economic model computes the investments and forward-looking capital carrying costs required to build the projected BFWA network. It then produces reports showing investment requirements and annualized cost per customer location by type of network component and by density area. The economic model requires a number of user inputs about equipment and installation costs, expected service life of the component, and annualized cost factor. These inputs and their corresponding default values are provided in Appendix B. Note that capital carrying costs include only the costs of the network infrastructure. Other costs such as spectrum acquisition, network maintenance, operation and support, advertising, marketing, and other costs of running a company are not included in the model.

4. Economic Analysis of First-Generation Broadband Fixed Wireless Access Networks

The state of Delaware was chosen as a representative state to show results of the engineering-economic model. Table 7 shows the characteristics of the service area in terms of the number of clusters, cluster area, and the number of voice lines and customer locations categorized by density area. Care must be taken when classifying clusters into a density range. An outlier consisting of an isolated home with one voice line in an area of 0.001 square mile would fall into a density range of 1000 lines per square mile or 1000 locations per square mile if the cluster density is simply computed based on the number of lines or locations divided by the cluster area. This could be misleading since a density area of 1000 lines (or locations) per square mile implies that the cluster is located in a medium- to high-density area, while in reality it is a small isolated home in a field. We adopted the methodology used in the HM5.0 model, which classifies clusters based on the telephone line density of the census block group (CBG) containing the cluster.

Density Range (lines/square mile)	Subscriber and Area Information					
	Residential Voice Lines	Business Voice Lines	Households	Small Firms	Clusters (Main and Outlier)	Cluster Area (square miles)
<5	544	65	501	16	10	37
5-100	53,865	8,191	49,296	2,048	180	1,241
100-200	24,687	3,709	22,702	927	48	237
200-650	46,062	13,104	41,617	3,276	81	176
650-850	9,448	3,393	8,646	848	18	21
850-2250	91,189	29,934	82,260	7,483	158	96
2250-5000	41,348	13,906	37,636	3,477	68	22
5000-10000	36,398	14,372	33,046	3,593	62	14
>10000	20,748	12,876	19,196	3,219	48	4
Total	**324,289**	**99,550**	**294,900**	**24,887**	**673**	**1,848**

Table 7: Characteristics of the Service Area in Delaware

Figure 6 shows the spatial distribution of clusters in Delaware. Generally, clusters in a density range of more than 100 lines per square mile are near big cities, like Wilmington and Dover, while low-density clusters are sparsely distributed over the entire state. The computed cell site configuration consists of 77 omni-directional supercell base stations, 33 four-sectored minicell base stations, 9 eight-sectored minicell base stations, and 5 sixteen-sectored minicell base stations, for a total of 124 base stations (Figure 7).

All clusters with density less than 5 lines per square mile are served by omni-directional supercell base stations while clusters in other density ranges are served by a mix of supercell and minicell base stations (Figure 8). High-density areas are more likely to be capacity limited, requiring multisector minicells. Figure 9 shows results of the model generated SONET ring layout for inter-base station and backhaul transmissions to the headend office. The configuration consists of three rings directly connected to the headend, and six stand-alone rings which are connected to each other via ring connectors between the two nearest base stations of the two adjacent rings.

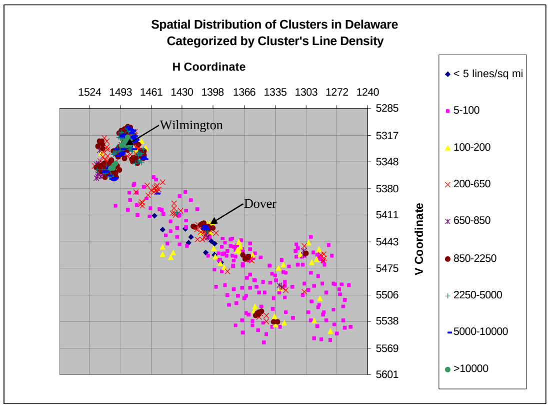


Figure 6: Spatial Distribution of Clusters

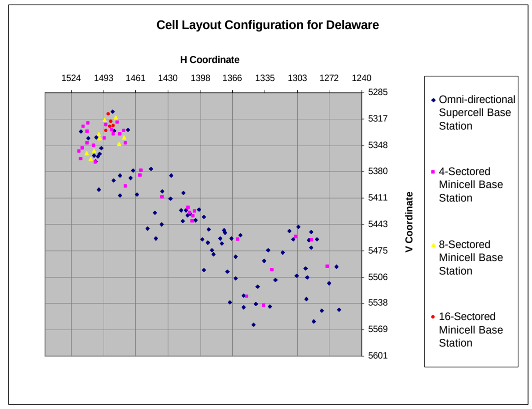


Figure 7: Cell Layout Configuration

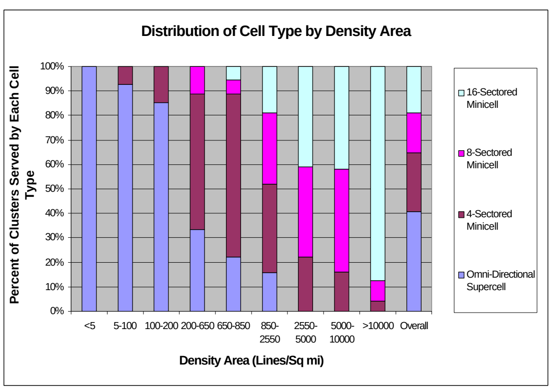


Figure 8: Distribution of Cell Type by Density Area

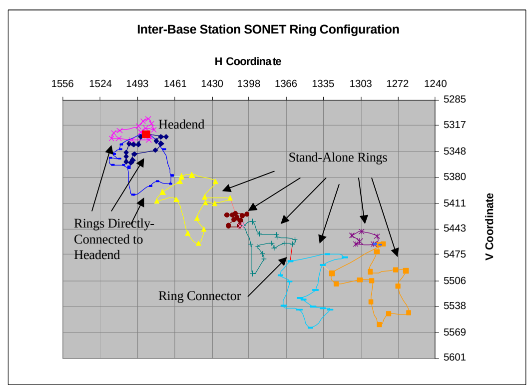


Figure 9: SONET Ring Configuration

Figure 10 shows initial capital investments required to construct the projected BFWA network. For presentation purposes, various cost components are grouped into five categories by equipment type as shown in the figure. Initial investments include equipment and installation costs of network infrastructure. Results show that CPE costs dominate all costs and account for 55% of total investment. Costs of base station radio and network electronics contribute approximately 29% to total investment. Next are costs of cell site building and land, which account for 12% of total costs. SONET ring costs are 3%. Lastly, costs of headend facilities account for approximately 1%.

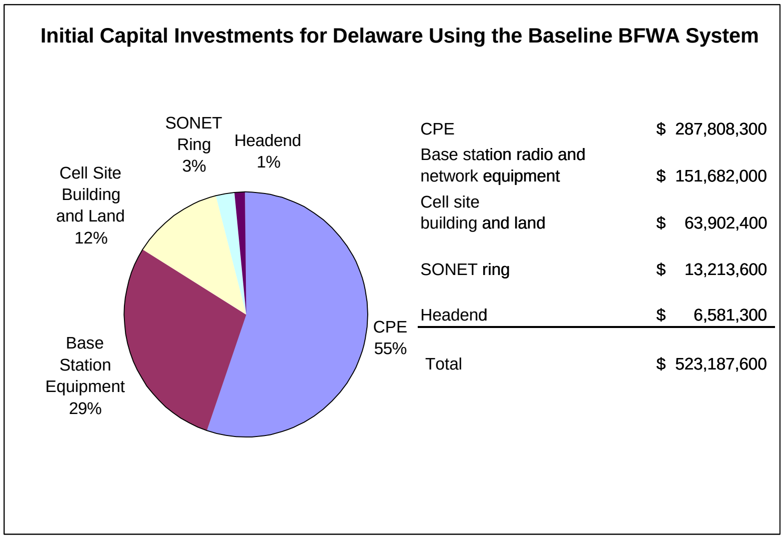
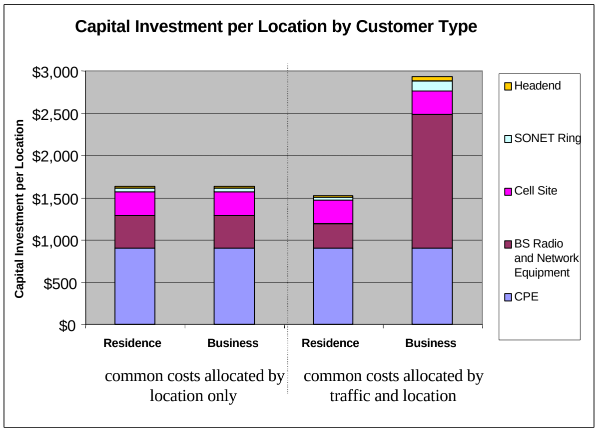


Figure 10: Estimated Initial Capital Investments for Delaware using the Baseline Single-Carrier BFWA System operating at MMDS Frequencies

Telecommunications network investment costs are often presented in terms of investment per subscriber. Since all network elements except CPE are shared among many subscribers, these shared costs must be allocated. The simplest approach is to allocate these shared costs equally among all locations. A more sophisticated approach might recognize that some shared equipment is sized based on network traffic, and allocate costs according to each location's share of total traffic. Table 8 suggests one way to allocate costs which attempts to take into account traffic as well as locations. If costs are allocated strictly by location, businesses and residences have similar costs per subscriber location (Figure 11). However, if costs are allocated by traffic, as in Table 8, then investment per business location would appear to be higher, reflecting the higher levels of traffic generated by businesses as compared to a residence. In this paper, we take the simple approach of allocating all shared costs by location only.

Equipment and Network Infrastructure	Percent of Costs Allocated Based on			
	Location Connected	Upstream Traffic	Down-stream Traffic	VoIP Lines
CPE	100%	0%	0%	0%
Base station equipment	0%	50%	50%	0%
Cell site building and land	100%	0%	0%	0%
Headend equipment except soft switches	0%	0%	100%	0%
Headend soft switches	0%	0%	0%	100%
Headend building and land	100%	0%	0%	0%
Links to ISP/IXCs' POPs and SONET Rings	0%	0%	100%	0%

Table 8: Sample Cost Allocation Criteria by Traffic and Location



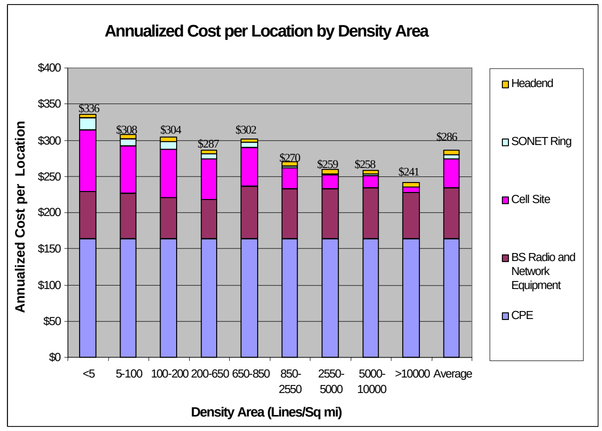


Figure 11: Capital Investment per Location

Figure 12: Annualized Cost per Location by Density Area

The initial capital investment for each network element is converted into a flow of annualized costs over its economic life. These annualized costs offer a useful way to determine revenues that the network operator must receive in order to pay for initial investments. Figure 12 shows annualized cost per subscriber location by density area. Based on these results, total costs per location vary from $336/year to $241/year from low- to high-density areas. The average value across all density ranges is $286 per location. Except for the density range of 650-850 lines per square mile, annualized costs per location show a decreasing trend from the lowest to the highest density range. At this particular density, omni-directional base stations are capacity limited and the more costly sectored base stations are not fully utilized, resulting in a higher base station equipment cost per location for this density range.

CPE and headend costs are the same across all density zones as the same type of CPE is used at each customer location and the cost of the one headend facility is shared equally among all customers. Cost of SONET rings per location declines from low- to high-density ranges. The model computes cost of SONET rings between each pair of adjacent base stations and allocates cost of that portion of the rings equally to each customer served by these two base stations. Since the cost of SONET rings is directly proportional to the ring distance and the ring distance is longer in low-density areas, cost of SONET rings per location is then higher in the low-density areas. Costs of cell site per location (including land and building costs) decrease from low- to high-density areas. Although land costs are higher in the high-density range, cost per location is still lower because more customers share the cost of each site. Conversely, cost of base station equipment per location is higher in the high-density areas. This is because there are more business locations in those areas. As a result, average traffic per location is higher in the high-density areas. Since base station equipment is sized by the amount of traffic expected in the service area, higher traffic per location translates to higher cost of base station equipment.

Sensitivity Analysis

The flexibility of the engineering-economic model allows us to examine the effect of changes in model inputs on total costs. This section examines the impact of changes in traffic demands, available spectrum, and network equipment costs on the model results.

Figures 13 and 14 respectively show the effects of changes in data and voice traffic assumptions on costs. Results show that costs are quite sensitive to traffic assumptions. Total costs per location increase approximately 17%, 34%, 50%, and up to 67% when data traffic per location increases two, three, four, and five times the default values of 20 Kbps downstream and 2 Kbps upstream per household and 80 Kbps downstream and 20 Kbps upstream per business location. Total costs per location increase 12%, 30%, and 45% when average busy hour CCS per voice line are double, triple, and four times the default values (3.87 CCS/residential voice line and 5.50 CCS/business voice line for Delaware). While CPE costs remain constant, costs of other network components are higher as traffic increases because more network capacity is needed to handle the higher traffic volume – for example, additional sectors must be added per base station. In an area where a sixteen-sectored cell has already been deployed, a new cell site must be added. Network electronics at the headend and SONET ring capacity have to be resized to accommodate the additional traffic, resulting in an increase in their costs per location.

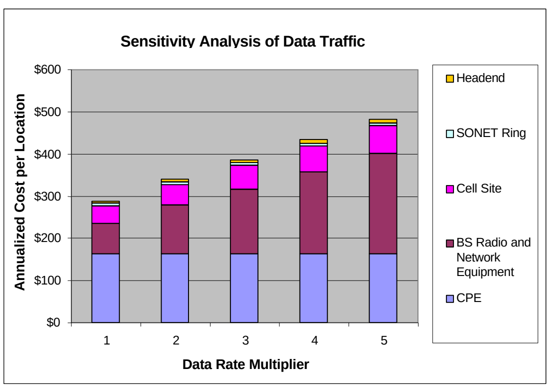


Figure 13: Sensitivity Analysis of Data Traffic

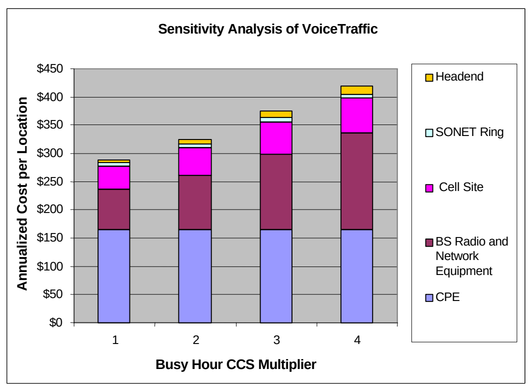


Figure 14: Sensitivity Analysis of Voice Traffic

Figure 15 examines the effect of changes in the ratio of downstream and upstream data traffic on costs, e.g. if traffic becomes more symmetry. A slight increase in costs of base station equipment and cell sites implies that only a few additional sectors and cell sites have to be added to the original design to handle the changes in upstream traffic volumes. Most cell sites in the original layout are downstream traffic limited; i.e. there is surplus upstream traffic capacity to accommodate an increase in upstream traffic volume.

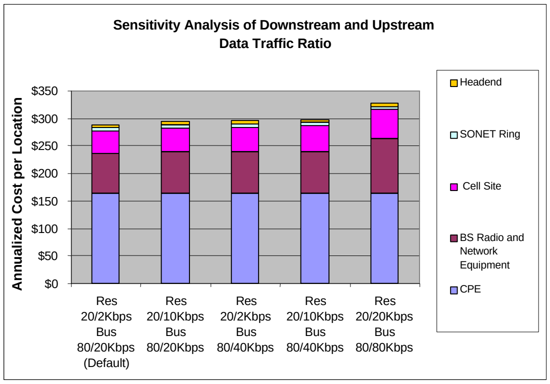


Figure 15: Sensitivity Analysis of Downstream and Upstream Traffic Ratio

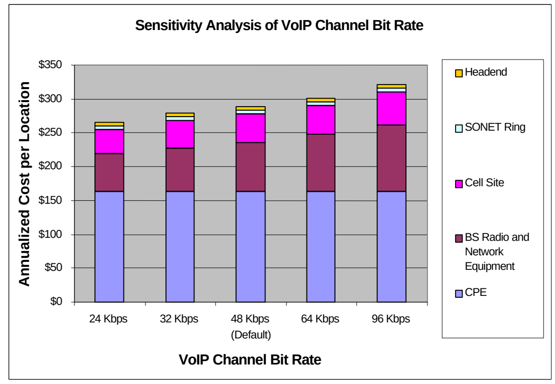


Figure 16: Sensitivity Analysis of VoIP Channel Bit Rate

Another parameter that has an impact on network traffic is VoIP channel bit rate as it determines the amount of bandwidth usage per voice channel. The baseline system assumes G736.32 VoIP codec with a packet size of 20 ms, resulting in an estimated data rate of 48 Kbps per voice channel. Figure 16 shows changes in costs as VoIP channel bit rate changes from 24 Kbps to 96 Kbps per voice channel. Our results suggest an average of 0.2% increase in cost per location for every one Kbps increase per voice channel.

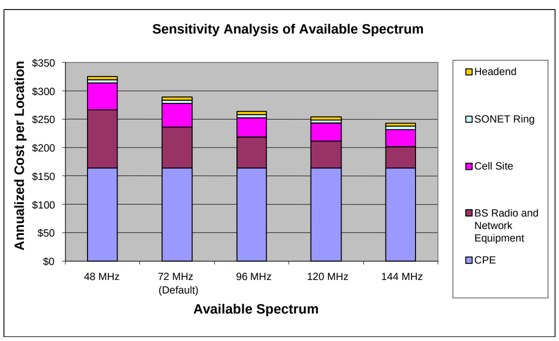


Figure 17: Sensitivity Analysis of Available Spectrum

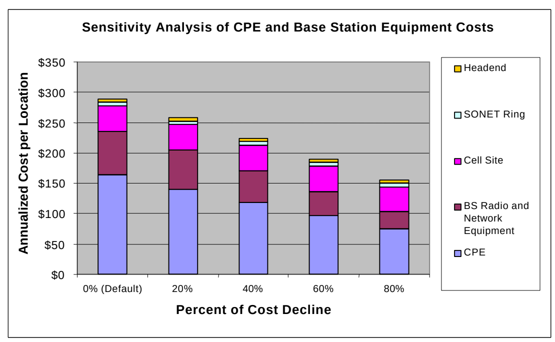


Figure 18: Sensitivity Analysis of CPE and Base Station Equipment Costs

Figure 17 shows annualized cost per location as a function of available spectrum. The first bar in the figure corresponds to a band plan where two 6MHz channels (12 MHz) are allocated in each direction with different channels for sectorized and unsectorized cells, for a total of 48 MHz for the system. In the same manner, the second, third, fourth and fifth bars, respectively, represent plans with 3, 4, 5 and 6 channels allocated in each direction with a total of 72 MHz, 96MHz, 120 MHz and 144 MHz for the system. Results show that an increase in available spectrum from 48 MHz to 144 MHz reduces total cost per location down from $325 to $222, a 32% reduction. On average, each additional 6MHz channel allocated in each direction (total of 4 channels or 24 MHz for both sectorized and unsectorized cells) reduces cost per location by approximately 8%. It is important to note that this number should be viewed as a lower bound (maximum saving) since we assume that costs of base station equipment remain unchanged as we increase the number of channels per cell. Depending upon the system design, adding more channels typically requires modifications in base station electronics, such as additional WMTS cards, or higher router capacity, which could lead to an increase in equipment cost. Broadband fixed wireless access is a relatively new technology. Costs of CPE and base station equipment should decline in the future due to improved electronics and higher volumes of production. A sensitivity analysis was performed to see the effect of a cost decline in CPE (not including installation and backup batteries) and base station radio and network electronics (not including ADMs, transmission lines, antennae, towers, and backup power supplies) on total cost per location. Figure 18 shows changes in annualized cost per location as costs of CPE and base station radio and network electronics decreases 20% to 80% from the default values. On average, a 10% decrease in costs of CPE and base station electronics lowers total cost per location by approximately 7%. Thus BFWA technology stands to benefit greatly from Moore’s Law.

5. Economic Implications of Moving CPE antenna from Outdoor to Indoor and the Use of OFDM Technology in Second-Generation BFWA Systems

Second-generation OFDM technology provides approximately 9 dB additional carrier-to-interference ratio, all other factors held constant. This additional margin can be used in one of two ways: 1) to allow the use of CPE with an indoor antenna; or 2) to support a longer maximum cell radius when an outdoor antenna is used. We compare both of these alternatives to our baseline case for the state of Delaware.

The configuration of the OFDM-based CPE with outdoor antenna is assumed similar to the one used in the baseline scenario. For the CPE with indoor antenna, we assume a low power indoor CPE equipped with an integrated transceiver, wireless modem, MTA, and a broad beam-low gain antenna. To improve the reach, a lower modulation scheme is typically used as it provides an additional signal margin to compensate for a wall/window penetration loss. For indoor CPE, we assume 16QAM is used in the downstream transmission and QPSK is used in the upstream direction for both supercell and minicell architectures. We also assume that the indoor CPE is placed on a windowsill and the penetration loss through a window is 8 dB (Rappaport, 1996, Nextnet Wireless, 2002).

Table 9 summarizes cell layout results for Delaware for the three comparing scenarios, which are: scenario 1) single-carrier-based system using CPE with outdoor antenna, scenario 2) OFDM-based system using CPE with outdoor antenna, and scenario 3) OFDM-based system using CPE with indoor antenna. A complete link budget analysis is provided in Appendix A. The cell coverage radii are based on the values for average terrain and inland temperate areas. Comparing scenarios 1 and 2 where both use CPE with outdoor antennae, the OFDM-based system offers a substantial increase in cell coverage radius while maintaining cell capacities. As a result, the total number of base stations required can be reduced from 124 to 85 base stations. When moving the CPE antenna from outdoor to indoor (scenario 2 vs. scenario 3), the total number of base stations increases from 85 to 161 base stations. This is because of the lower cell capacities and the smaller cell coverage radii of scenario 3 as compared to scenario 2. The capacity of a minicell is compromised because a lower modulation scheme with lower spectral efficiency is used. Compared to the outdoor CPE scenario, the capacity of minicells is reduced by approximately 33% in the downstream direction and by 50% in the upstream direction and the cell coverage radius is reduced by approximately 50%. Note that if a higher modulation scheme (64QAM downstream/16QAM upstream) was used in order to maintain capacity per sector, cell coverage radius would be reduced by 75%, an additional 25% reduction compared to the lower modulation scheme scenario.

Cell Layout Assumptions and Results	**Single-Carrier BFWA System**	**OFDM-Based BFWA System**	
	Outdoor CPE	**Outdoor CPE**	**Indoor CPE**
Cell Coverage Radii:			
- supercell radius	9.5 miles	13 miles	5.1 miles
- minicell radius	1.9 miles	3.1 miles	1.5 miles
Cell Capacity: (Downstream/Upstream)			
- omni-directional supercell	28.8/14.4 Mbps		28.8/14.4 Mbps
- 4 –sectored minicell	86.4/57.6 Mbps		57.5/28.8 Mbps
- 8- sectored minicell	172.8/115.2 Mbps		115.2/57.6 Mbps
- 16-sectored minicell	345.6/230.4 Mbps		230.4/115.2 Mbps
No. of Base Stations:			
- Omni-directional supercell	77	50	110
- 4-sectored minicell	33	16	23
- 8-sectored minicell	9	9	19
- 16-sectored minicell	5	10	9
Total	124	85	161

Table 9: Comparison of Cell Layout Results for Delaware

Table 10 shows initial capital investments for the three scenarios. For Delaware, the lowest investment is observed when using the OFDM-based system with indoor CPE (scenario 3). For the same outdoor CPE configuration, using the OFDM-based system instead of the single-carrier-based system leads to a 7% saving in total investment. This saving is a result of lower costs of base station equipment, cell sites, and SONET rings since fewer numbers of base stations are required in the network. For the same OFDM-based system, the use of indoor CPE instead of outdoor CPE leads to a 40% saving in CPE costs due to the elimination of installation expense. However, total investment is reduced by less than 1%, due to a 57% increase in base station, cell site, and SONET ring costs since more base stations are needed in the network. It is important to note that we assume an average cost to install outdoor CPE of $250 per location. Although our results suggest less than 1% saving in total investments from using user-self-installable indoor CPE instead of outdoor CPE, a greater saving can be expected if a higher installation cost is assumed, as moving the CPE antenna from outdoor to indoor completely eliminates this high installation cost. Conversely, if installation is significantly less than $250, the savings from indoor CPE may not outweigh the higher base station costs.

Network Component	Initial Capital Investment (Percent of Total Investment)		
	Single-Carrier BFWA System	OFDM-Based BFWA System	
	Outdoor CPE	Outdoor CPE	Indoor CPE
CPE	$287,808,300 (55%)	$287,808,300 (59%)	$175,882,900 (36%)
Base station radio and network equipment	$151,682,000 (29%)	$134,837,200 (28%)	$206,220,000 (43%)
Cell site building and land	$63,902,400 (12%)	$45,983,600 (9%)	$81,804,700 (17%)
SONET ring	$13,213,600 (3%)	$12,185,200 (3%)	$15,861,200 (3%)
Headend facilities	$6,581,300 (1%)	$6,581,300 (1%)	$6,581,300 (1%)
Total Capital Investment	**$523,188,100**	**$487,395,600**	**$486,350,100**

Table 10: Comparison of Initial Capital Investment between Single Carrier-Based and OFDM-Based BFWA Systems operating at MMDS Frequencies

Figures 19 and 20 show annualized costs per location by density range for scenarios 2 and 3 (See Figure 12 for results of scenario 1). All three show costs declining from low to high density areas. Comparing scenario 1 (Figure 12) with scenario 2 (Figure 19), annualized costs per location for the single-carrier-based system are higher than for OFDM at all density ranges except the highest density range of more than 10,000 lines per square mile. Looking at each cost component for each density range, costs of CPE and headend per location are the same for both scenarios while costs of base station radio and network electronics equipment, cell sites, and SONET rings are higher for the single-carrier-based system. At the highest density range cells are capacity limited not coverage limited. Thus, the extra reach of OFDM is of no benefit, and thus costs for single-carrier and OFDM with outdoor CPE are the same.

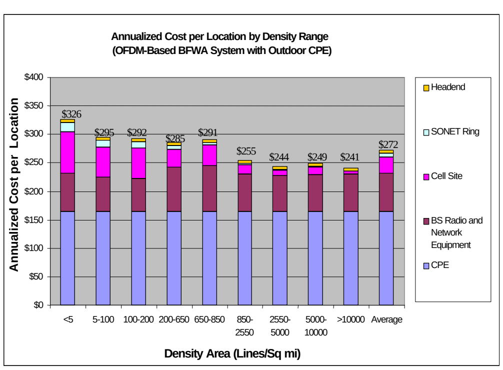


Figure 19: Annualized Cost per Location by Density Range for the OFDM-Based System using CPE with Outdoor Antenna

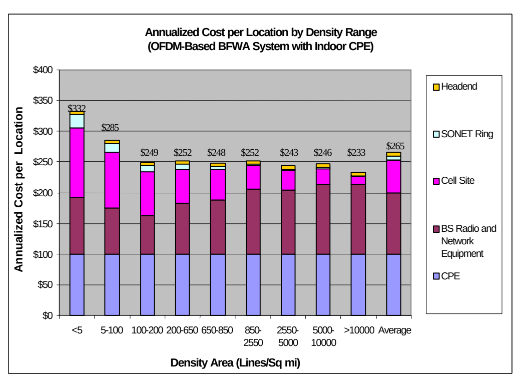


Figure 20: Annualized Cost per Location by Density Range for the OFDM-Based System using CPE with Indoor Antenna

Comparing scenario 2 (Figure 19) with scenario 3 (Figure 20), annualized costs per location are lower when using indoor CPE at almost all density ranges except the lowest density range of less than 5 lines per square mile. Since more base stations and cell sites are needed when using indoor CPE, higher costs of base station equipment, cell sites, and SONET rings are expected. While a reduction in CPE costs can justify the higher costs of base station equipment, cell sites, and SONET rings in other density areas, it is not high enough to justify those costs in the lowest density area of less than 5 lines per square mile. As a result, total cost per location for this range increases when using indoor CPE instead of outdoor CPE. This result implies that in the low-density areas or areas where cells are coverage-limited, using indoor CPE instead of outdoor CPE in order to save installation costs may not be a cost-effective solution, as doing so requires more cells to cover the service area and the resulting higher base stations and cell sites costs outweigh the savings from eliminating CPE installation costs.

6. Using the 700 MHz UHF Spectrum to Provide Broadband Fixed Wireless Access Services

The FCC has recently identified several additional spectrum bands for the use of advanced wireless systems. Among these bands is a portion of the 700 MHz UHF spectrum, currently used for television broadcast but subject to return for reauction by 2006. Spectrum in this frequency range offers several advantages over higher frequencies such as ISM, MMDS and UNII bands currently used to implement broadband fixed wireless access services. These include a much longer propagation range, ability to penetrate walls, and low susceptibility to rain and snow fading.

The previous sections provide economic analyses of using the 2.6 GHz MMDS spectrum to implement a BFWA network. To examine how choice of operating frequency affects the cost structure of a BFWA network, this section presents a cost comparison of using the 700 MHz UHF spectrum vs. the 2.6 GHz MMDS spectrum. Following the methodology used in the previous section, three BFWA system scenarios are included in the analysis: single-carrier, OFDM with outdoor CPE and OFDM with indoor CPE. Two changes were made to the radio frequency planning module to capture propagation characteristics of the 700 MHz spectrum: 1) using the Hata Model instead of the Erceg model to estimate propagation losses and 2) modifying fade margin requirements to the appropriate values for the 700 MHz spectrum. Other model assumptions about traffic demand, equipment specification, cell design structure, available spectrum, frequency reuse plan, and network equipment costs are assumed to be the same and independent of the operating frequencies.

Table 11 shows cell layout results of the three BFWA systems operating at MMDS or 700 MHz frequencies. While both systems operating at either MMDS or 700 MHz frequencies offer the same cell capacities, cell coverage radii of the systems operating at 700 MHz frequencies are more than 100% larger than of comparable systems operating at MMDS frequencies. As a result, the required number of base stations is reduced by more than half when using the 700 MHz spectrum to provide service. While the number of unsectored supercell, 4-sectored minicell, and 8-sectored minicell base stations decreases, the number of 16-sectored minicell base stations increases when using the 700 MHz spectrum. The longer reach at 700 MHz increases the required capacity to serve the larger coverage area, thus requiring more 16-sectored minicells.

Cell Layout Assumptions and Results	Single-Carrier BFWA System	OFDM-Based BFWA System	
	Outdoor CPE	Outdoor CPE	Indoor CPE
Cell Coverage Radii: (MMDS/700 MHz)			
- supercell radius	9.5/20 miles	13/27 miles	5.1/13.2 miles
- minicell radius	1.9/5.7 miles	3.1/7.5 miles	1.5/4.4 miles
Cell Capacity: (Downstream/Upstream)			
- omni-directional supercell	28.8/14.4 Mbps		28.8/14.4 Mbps
- 4 –sectored minicell	86.4/57.6 Mbps		57.5/28.8 Mbps
- 8- sectored minicell	172.8/115.2 Mbps		115.2/57.6 Mbps
- 16-sectored minicell	345.6/230.4 Mbps		230.4/115.2 Mbps
No. of Base Stations: (MMDS/700 MHz)			
- Omni-directional supercell	77/17	50/3	110/33
- 4-sectored minicell	33/15	16/5	23/11
- 8-sectored minicell	9/3	9/7	19/7
- 16-sectored minicell	5/15	10/14	9/21
Total	124/50	85/29	161/72

Table 11: Comparison of Cell Layout Assumptions and Results for Delaware between Systems operating at 2.6 GHz MMDS and 700 MHz Frequencies

Table 12 summarizes initial capital investments required to implement BFWA networks operating at 700 MHz frequencies for our three scenarios. The numbers in the parenthesis show the savings projected when using the 700 MHz spectrum instead of the MMDS spectrum to implement the networks. These savings are obtained by subtracting the investments shown in Table 12 from the investments estimated for the comparable systems operating at MMDS frequencies shown in Table 10. Two significant findings emerge from these results. First, the OFDM-based BFWA system using CPE with indoor antenna is the most cost-effective solution. Second, for the same type of base station and customer premises equipment, the systems operating at 700 MHz frequencies have total investment cost approximately 13% to 17% less than the systems operating at MMDS frequencies. The savings result from the lower costs of base station equipment, cell sites, and SONET rings. The highest savings are in the costs of cell sites, as the systems operating at 700 MHz frequencies require approximately half the number of cell sites to cover the service area. This directly translates to approximately 50% savings in costs of cell site buildings and land. The savings in base station equipment, approximately 20%, result mostly from lower costs of common equipment at the base station (i.e., network monitoring, backup equipment, tower, and ADM). And lastly, approximately 2% savings in SONET ring costs result from shorter total ring distances among base stations.

Network Component	Initial Capital Investment (Saving from Choosing 700 MHz over MMDS Frequencies)		
	Single-Carrier System	OFDM-Based System	
	Outdoor CPE	Outdoor CPE	Indoor CPE
CPE	$287,808,300 ($0)	$287,808,300 ($0)	$175,882,900 ($0)
Base station radio and network equipment	$122,285,700 ($29,396,300, 19%)	$103,841,600 ($30,995,600, 23%)	$169,266,500 ($36,953,500, 18%)
Cell site building and land	$30,189,700 ($33,712,700, 53%)	$20,160,900 ($25,822,700, 56%)	$41,859,200 ($39,945,500, 49%)
SONET ring	$9,067,900 ($4,145,700, 2%)	$7,545,800 ($4,639,400, 2%)	$10,411,600 ($5,449,600, 2%)
Headend facilities	$6,581,300 ($0)	$6,581,300 ($0)	$6,581,300 ($0)
Total Capital Investment	**$455,932,900 ($67,225,200, 13%)**	**$425,937,900 ($61,457,700, 13%)**	**$404,001,500 ($82,348,600, 17%)**

Table 12: Initial Capital Investment of BFWA Systems operating at 700 MHz Frequencies and Savings over BFWA Systems operating at MMDS Frequencies

Figure 21 compares and contrasts annualized costs per location of BFWA systems operating at MMDS and UHF frequencies. Total costs per location vary from $225 to $286 where the lowest cost corresponds to an OFDM-based system with indoor CPE operating at 700 MHz and the highest cost is for the single-carrier-based system with outdoor CPE operating at MMDS frequencies. As shown in Figure 22, total savings of $30 to $40 in annualized costs per location are expected when choosing the 700 MHz spectrum over the MMDS spectrum to provide service. Costs of CPE and headend facilities are independent of operating frequency, resulting in no saving in these two network components. The highest savings from choosing 700 MHz over MMDS spectrum are realized when using the OFDM-based system with indoor antenna, which results in the greatest reduction in the number of cell sites.

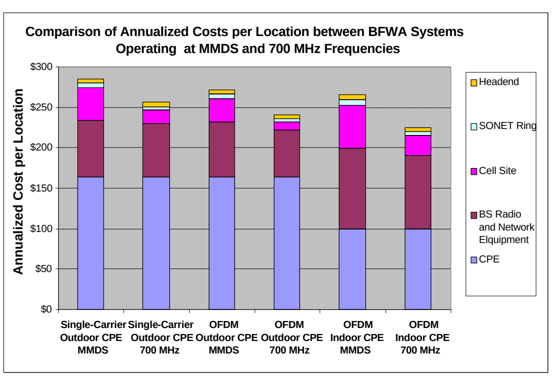


Figure 21: Comparison of Annualized Costs per Location between BFWA Systems Operating at MMDS and 700 MHz Frequencies

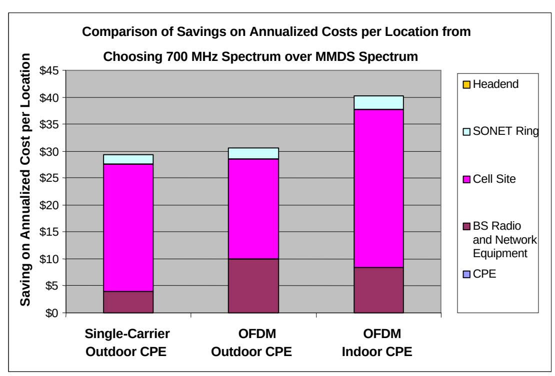


Figure 22: Savings on Annualized Costs per Location from Choosing 700 MHz over MMDS Spectrum

Table 13 contrasts annualized costs per location of BFWA systems operating at MMDS and 700 MHz frequencies by density area. For all six scenarios, costs per location show a declining trend from low-to high-density areas. OFDM dominates single-carrier at both MMDS and UHF frequencies. An OFDM-based system using CPE with indoor antenna is the most cost effective choice for medium- to high-density areas where as the OFDM-based system using CPE with outdoor antenna is a better solution for low-density areas.

Density Range (lines/ square mile)	Choices of Frequency, Technology, and CPE					
	MMDS			700 MHz		
	SC Outdoor	OFDM Outdoor	OFDM Indoor	SC Outdoor	OFDM Outdoor	OFDM Indoor
<5	$336	$326	$332	$315	**$250***	$267
5-100	$308	$295	$285	$295	**$248***	$254
100-200	$304	$292	$249	$263	$247	**$230***
200-650	$287	$285	$252	$261	$242	**$233***
650-850	$302	$291	$248	$252	$237	**$227***
850-2250	$270	$255	$252	$247	$236	**$217***
2250-5000	$259	$244	$243	$234	$238	**$212***
5000-10000	$258	$249	$246	$244	$242	**$207***
>10000	$241	$241	$233	$241	$241	**$214***
Average	**$286**	**$272**	**$265**	**$256**	**$241**	**$225***

Table 13: Comparison of Annualized Costs per Location by Density Range between BFWA Systems Operating at MMDS and 700 MHz Frequencies (* indicates the lowest cost among all six scenarios)

7. Cost Comparison of BFWA, DSL, and Cable Modem/HFC Networks

The section explores the economic viability of broadband fixed wireless access networks by comparing the costs of implementing BFWA networks with the costs of implementing DSL and cable modem/HFC (cable) networks to provide voice over IP and Internet access services. The costs of implementing DSL and cable networks were estimated using DSL and HFC models which were developed on the same basis as the BFWA model (Fryxell, 2002). The outside plant of the DSL network follows current architectures of telephone networks, with copper pairs connecting customer premises to the Central Office (CO) or to a Remote Terminal (RT) such as Digital Loop Carrier (DLC) systems. RTs are used in neighborhoods where distance limitations or economic considerations do not make it appropriate to have copper lines all the way from the customer premises to the CO. The DSL model assumes a maximum copper length of 12,000 feet. In this mixed copper/fiber configuration, the RT houses DSLAMs which provide the interface between the fiber and copper segments of the local loop. The outside plant of the cable network has three main sections: fiber feeder, distribution, and drop. Fiber optic cables connect a distribution hub to optical nodes located in neighborhoods. Optical nodes are the interface between the fiber feeder and the coaxial cable. This coaxial part can be further divided into distribution and drop. The distribution takes the network to the street just outside customer premises while the drop connects the distribution to each individual customer. The HFC model assumes a limit of 500 customer locations passed per optical node. The RF spectrum has a single 30Mbps (6MHz) downstream data channel and four 5Mbps (3.2 MHz) upstream data channels. More detail on the DSL and HFC models can be found at (Fryxell, 2002, Fryxell et al., 2000).

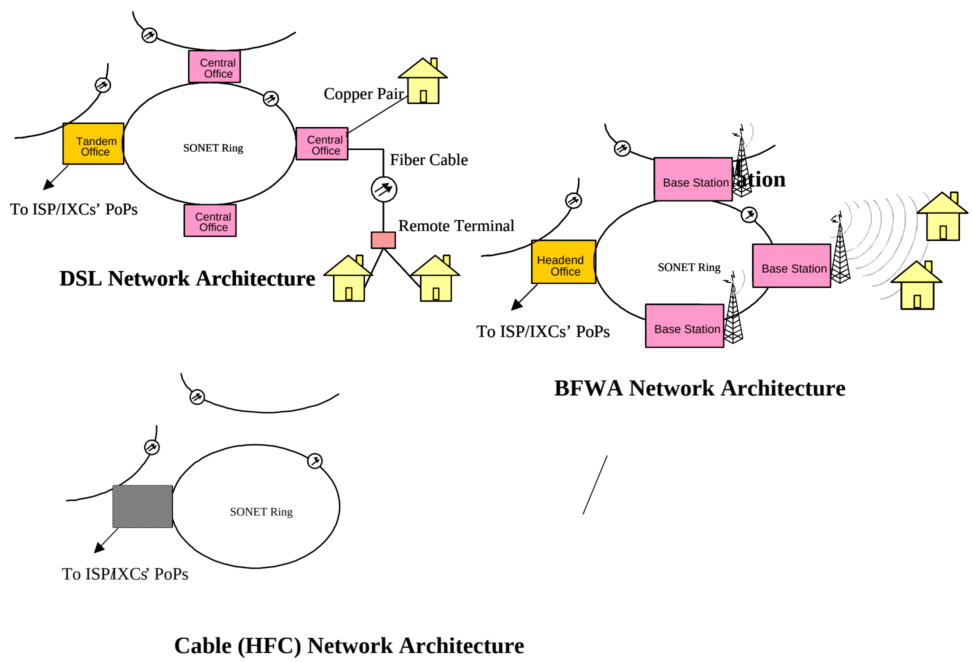


Figure 23: Comparison of BFWA, DSL, and HFC/Cable Modem Network Architectures

Assuming the same usage patterns as described in Section 3, Figures 24 and 25, respectively, show annualized costs per location of implementing DSL and cable networks to provide voice over IP and Internet access services to all residential and small business customers in the entire state of Delaware. Unlike BFWA networks, costs of DSL and cable networks are quite sensitive to subscriber density. Costs of DSL networks vary from $707 to $181 per location while costs of cable networks vary from $646 to $110 per location from low- to high-density areas. CPE and local loop plant dominate costs in both architectures. On average, CPE and local loop plant account for more than 80% of tatal cost. CPE is 44% in the cable architecture while in the DSL architecture CPE is the same dollar value but accounts for only 27% of total network costs. This is because of the high cost of DSLAMs at the remote terminal which accounts for almost 38% of the DSL network costs. Offices and office equipment account for 11% for cable and 13% for DSL. Lastly, SONET ring interoffice facilities are approximately 2-3% of total costs.

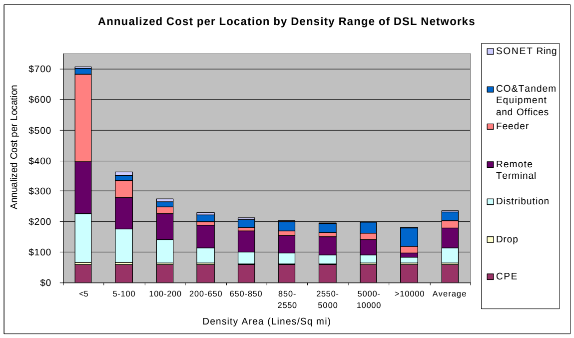


Figure 24: Annualized Cost per Location by Density Range of DSL Networks

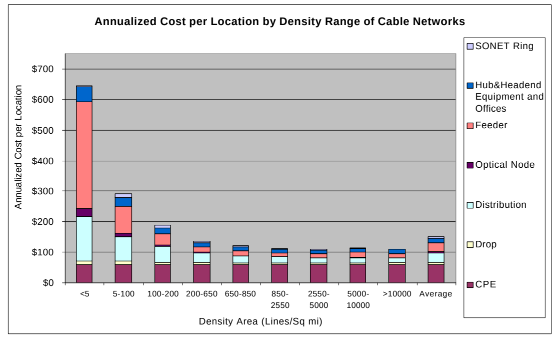


Figure 25: Annualized Cost per Location by Density Range of Cable Networks

Cable is more cost effective than DSL across all density ranges. The cable advantage is relatively small for the low-density areas, where the dominant term is the feeder and the potential for sharing in the cable architecture is not fully realized. This difference grows to its maximum value in the medium-density areas and then decreases slightly in the high-density areas. This last effect is actually related to the distance between the cluster and the local office and only indirectly related to density zones as the highest density zones are associated with shorter distances to the local office and therefore most of the loops are entirely copper. The concentration of DSLAMs in the local office leads to savings associated with cheaper equipment, larger scale and higher fill rates (Fryxell, 2002).

Density Range (line/square mile)	Annualized Cost per Location		
	BFWA	DSL	Cable
0-5	**$250-$336***	$707	$646
5-100	**$248-$308***	$364	$292
100-200	$230-$304	$274	**$189***
200-650	$233-$287	$228	**$136***
650-850	$227-$302	$212	**$121***
850-2250	$217-$270	$202	**$113***
2250-5000	$212-$259	$195	**$109***
5000-10000	$207-$258	$199	**$114***
>10000	$214-$241	$181	**$110***
Average	**$225-$286**	**$236**	**$151***

Table 14: Comparison of Annualized Costs per Location by Density Range of BFWA, DSL, and Cable Networks (* indicates the most cost effective solution)

Table 14 compares and contrasts annualized costs per locations of BFWA, DSL, and cable networks. Based on a state-wide average cost per location, cable is the most cost-effective solution among the three networks. However, results by density area show that BFWA is cheaper than cable and DSL in areas where line density is less than 100 lines per square mile. This is mainly due to the fact that costs of cable and DSL networks are directly proportional to loop lengths while costs of BFWA are not. As shown in Figures 24 and 25, feeder costs of cable and DSL increase tremendously at these low-density areas where loop lengths are long, resulting in much higher total costs.

Costs of BFWA networks shown in Table 14 do not include spectrum costs. To examine whether spectrum costs will change our findings, we estimated spectrum costs as shown in Table 15. Based on costs of PCS spectrum and the number of customer locations (households and small businesses) obtained from the HM5.0a database, spectrum costs are approximately $0.75-$3/MHz/location. The modeled BFWA networks require 72 MHz of spectrum. Based on these data, spectrum investments are estimated to be $54-$216/location. Assuming an infinite life time of spectrum, annualized costs of spectrum incurred by the BFWA operators are simply the interest payments on spectrum investments. For a 10% cost of capital, spectrum costs are approximately $5.4-$21.6/location/year.

Frequency Band	Total Bandwidth	Net Bids (million)	Auction Date	Customer Locations (million)	Cost/MHz/ Location
PCS A&B Block	60 MHz	$7,019	March 1995	111.87	$1.04
PCS C Block	30 MHz	$10,071	May 1996	111.87	$3.00
PCS D, E&F Block	30 MHz	$2,517	January 1997	111.87	$0.75

Table 15: Estimation of Spectrum Cost

Results of the engineering-economic models suggest that operators of BFWA networks can afford to pay a maximum of $396/location/year for the cost of spectrum to be breakeven with costs of cable networks in areas with line density of less than 5 lines/square mile. Similarly, the breakeven spectrum cost for areas with line density of 5-100 lines/square mile is $44/location/year. Assuming that the value of MMDS and 700 MHz spectrum is comparable to the value of PCS spectrum estimated above, we found that including spectrum costs should not substantially change our findings. Even if spectrum costs are twice the values we estimated, BFWA will still be the most cost effective solution for these low-density areas.

8. Policy Implications and Conclusions

Competition in broadband services: Despite the promise of broadband satellite or Fiber to the Home (FTTH), currently DSL, cable modem, and broadband fixed wireless are the only three viable choices for broadband services in the residential and small business market. DSL and cable modem enjoy a considerable advance in terms of deployment while broadband fixed wireless has started to emerge. Analyses shown in this paper suggest that among the three technology choices, broadband fixed wireless access is the most cost effective solution to provide broadband services in low-density areas (<100 lines/square miles). Indeed, in rural areas where customers are sparsely located (<5 lines/square mile), fixed wireless is the only viable choice to provide broadband services as costs of DSL and cable networks are extremely high due to the high costs of local loop plant. As a result, it is unlikely that DSL and cable operators will extend their broadband services to those high cost areas. While we cannot count on fixed wireless to be a third option to provide broadband services in high-density areas where both DSL and cable modem services are available, our results suggest that fixed wireless is a viable solution for medium-density areas where DSL and cable modem services may not be available due to distance limitations of DSL and lack of cable infrastructure.

Subsidies to rural and high-cost areas: To date, universal service subsidies to rural and high-cost areas only include voice service with a small share being allocated to subsidize Internet access in schools. Several proposals under consideration by Congress would have the universal service fund be extended to broadband Internet access for households in high-cost areas. An important issue raised by broadband service providers offering integrated voice and data services is how to select the architecture to subsidize and how to determine the amount of universal service funding necessary. Our results suggest that broadband fixed wireless is the most effective technology to provide voice over IP and broadband Internet access services in rural and high-cost areas, and therefore should be qualified to receive universal service subsidies and used as a basis to determine the amount of funding required.

Spectrum management issues: Spectrum is a crucial element in the implementation of wireless networks. If more spectrum become available, it can be used to lower the costs of urban wireless networks. However, in rural areas where systems are coverage, not capacity limited, more spectrum will not reduce network costs. What does help in rural areas is getting spectrum in the right band. As shown in Section 6, having 700 MHz spectrum for fixed broadband wireless in rural areas does save money in comparison with 2.6 GHz spectrum (MMDS band), because of the longer reach possible at 700 MHz.

Provision of video services: Comparing cable, DSL, and broadband fixed wireless architectures, only cable can offer video-on-demand services at reasonable prices and without requiring major changes in the design of the network. Technically, switched video services can be provided over DSL networks but not yet economically. BFWA systems (and DSL) may be complemented by Direct Broadcast Satellite (DBS) for multichannel video delivery. Additional MMDS channels can supplement DBS for near-video-on-demand services, but significant use of BFWA for digital streamed video would greatly increase peak hour traffic and raise traffic sensitive costs correspondingly.

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Appendix A. Link Budget Analyses

Supercell link budgets for the baseline single-carrier-based system operating at MMDS frequencies using CPE with outdoor antenna

Description	Hot Humid Coastal Area			Inland Temperate Area			Very Dry Area		
	Smooth Terrain	Average Terrain	Rough Terrain	Smooth Terrain	Average Terrain	Rough Terrain	Smooth Terrain	Average Terrain	Rough Terrain
Downstream: 16QAM									
Transmitter power (dBm)	47.0	47.0	47.0	47.0	47.0	47.0	47.0	47.0	47.0
Transmission loss (dB)	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0
Antenna gain (dBi)	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0
Transmitter EIRP (dBm)	63.0	63.0	63.0	63.0	63.0	63.0	63.0	63.0	63.0
Receiver sensitivity (dBm)	-83.0	-83.0	-83.0	-83.0	-83.0	-83.0	-83.0	-83.0	-83.0
Fade margin (dB)	19.8	13.0	10.0	20.0	11.4	10.0	18.0	10.0	10.0
Req. received signal dBm)	-63.2	-70.0	-73.0	-63.0	-71.6	-73.0	-65.0	-73.0	-73.0
CPE antenna gain (dBi)	23.0	23.0	23.0	23.0	23.0	23.0	23.0	23.0	23.0
Propagation loss (dB)	146.4	156.0	159.0	149.0	157.6	159.0	151.0	159.0	159.0
Max path length (miles)	**9.0**	**8.5**	**5.3**	**12.0**	**9.5**	**5.3**	**12.6**	**10.2**	**5.3**
Thermal noise (dBm)	-106.2	-106.2	-106.2	-106.2	-106.2	-106.2	-106.2	-106.2	-106.2
Receiver noise figure (dB)	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Co-channel interferer (dBm)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$C/(I+N_0)$ at perimeter (dB)	38.0	31.2	28.2	38.2	29.6	28.2	36.2	28.2	28.2
Req. C/I for 10^{-6} BER (dB)	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0
C/I margin (dB)	**20.0**	**13.2**	**10.2**	**20.2**	**11.6**	**10.2**	**18.2**	**10.2**	**10.2**
Upstream: QPSK									
Transceiver power (dBm)	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0
Antenna gain (dBi)	23.0	23.0	23.0	23.0	23.0	23.0	23.0	23.0	23.0
Transceiver EIRP (dBm)	38.0	38.0	38.0	38.0	38.0	38.0	38.0	38.0	38.0
Max path length (miles)	9.0	8.5	5.3	12.0	9.5	5.3	12.6	10.2	5.3
Path loss (dB)	146.4	156.0	159.0	149.0	157.6	159.0	151.0	159.0	159.0
Receiver antenna gain (dBi)	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0
LNA gain (dB)	28.0	28.0	28.0	28.0	28.0	28.0	28.0	28.0	28.0
Transmission line loss (dB)	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0
Net received signal (dBm)	-64.4	-74.0	-77.0	-67.0	-75.6	-77.0	-69.0	-77.0	-77.0
Receiver sensitivity (dBm)	-87.0	-87.0	-87.0	-87.0	-87.0	-87.0	-87.0	-87.0	-87.0
Fade margin (dB)	19.8	13.0	10.0	20.0	11.4	10.0	18.0	10.0	10.0
Req. received signal (dBm)	-67.2	-74.0	-77.0	-67.0	-75.6	-77.0	-69.0	-77.0	-77.0
Thermal noise (dBm)	-106.2	-106.2	-106.2	-106.2	-106.2	-106.2	-106.2	-106.2	-106.2
Receiver noise figure (dB)	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
Co-channel interferer (dBm)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$C/(I+N_0)$ at perimeter (dB)	32.0	25.2	22.2	32.2	23.6	22.2	30.2	22.2	22.2
Req. C/I for 10^{-6} BER (dB)	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0
C/I margin (dB)	**18.0**	**11.2**	**8.2**	**18.2**	**9.6**	**8.2**	**16.2**	**8.2**	**8.2**

Minicell link budgets for the baseline single-carrier-based system operating at MMDS frequencies using CPE with outdoor antenna

Description	Hot Humid Coastal Area			Inland Temperate Area			Very Dry Area		
	Smooth Terrain	Average Terrain	Rough Terrain	Smooth Terrain	Average Terrain	Rough Terrain	Smooth Terrain	Average Terrain	Rough Terrain
Downstream: 64QAM									
Transmitter power (dBm)	34.0	34.0	34.0	34.0	34.0	34.0	34.0	34.0	34.0
Transmission loss (dB)	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0
Antenna gain (dBi)	23.0	23.0	23.0	23.0	23.0	23.0	23.0	23.0	23.0
Transmitter EIRP (dBm)	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0
Receiver sensitivity (dBm)	-77.0	-77.0	-77.0	-77.0	-77.0	-77.0	-77.0	-77.0	-77.0
Fade margin (dB)	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Req. received signal dBm)	-67.0	-67.0	-67.0	-67.0	-67.0	-67.0	-67.0	-67.0	-67.0
CPE antenna gain (dBi)	23.0	23.0	23.0	23.0	23.0	23.0	23.0	23.0	23.0
Propagation loss (dB)	145.0	145.0	145.0	145.0	145.0	145.0	145.0	145.0	145.0
Max path length (miles)	**3.6**	**1.9**	**1.3**	**3.6**	**1.9**	**1.3**	**3.6**	**1.9**	**1.3**
Thermal noise (dBm)	-106.2	-106.2	-106.2	-106.2	-106.2	-106.2	-106.2	-106.2	-106.2
Receiver noise figure (dB)	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Co-channel interferer (dBm)	7.4	5.6	2.7	7.4	5.6	2.7	7.4	5.6	2.7
$C/(I+N_0)$ at perimeter (dB)	26.8	28.6	31.5	26.8	28.6	31.5	26.8	28.6	31.5
Req. C/I for 10^{-6} BER (dB)	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0
C/I margin (dB)	**2.8**	**4.6**	**7.5**	**2.8**	**4.6**	**7.5**	**2.8**	**4.6**	**7.5**
Upstream: 16QAM									
Transceiver power (dBm)	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0
Antenna gain (dBi)	23.0	23.0	23.0	23.0	23.0	23.0	23.0	23.0	23.0
Transceiver EIRP (dBm)	38.0	38.0	38.0	38.0	38.0	38.0	38.0	38.0	38.0
Max path length (miles)	3.6	1.9	1.3	3.6	1.9	1.3	3.6	1.9	1.3
Path loss (dB)	145.0	145.0	145.0	145.0	145.0	145.0	145.0	145.0	145.0
Receiver antenna gain (dBi)	23.0	23.0	23.0	23.0	23.0	23.0	23.0	23.0	23.0
LNA gain (dB)	28.0	28.0	28.0	28.0	28.0	28.0	28.0	28.0	28.0
Transmission line loss (dB)	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0
Net received signal (dBm)	-58.0	-58.0	-58.0	-58.0	-58.0	-58.0	-58.0	-58.0	-58.0
Receiver sensitivity (dBm)	-83.0	-83.0	-83.0	-83.0	-83.0	-83.0	-83.0	-83.0	-83.0
Fade margin (dB)	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Req. received signal (dBm)	-73.0	-73.0	-73.0	-73.0	-73.0	-73.0	-73.0	-73.0	-73.0
Thermal noise level (dBm)	-106.2	-106.2	-106.2	-106.2	-106.2	-106.2	-106.2	-106.2	-106.2
Receiver noise figure (dB)	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
Co-channel interferer (dBm)	7.4	5.6	2.7	7.4	5.6	2.7	7.4	5.6	2.7
$C/(I+N_0)$ at perimeter (dB)	18.8	20.6	23.5	18.8	20.6	23.5	18.8	20.6	23.5
Req. C/I for 10^{-6} BER (dB)	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0
C/I margin (dB)	**0.8**	**2.6**	**5.5**	**0.8**	**2.6**	**5.5**	**0.8**	**2.6**	**5.5**

Supercell link budgets for the OFDM-based BFWA system operating at MMDS frequencies using CPE with outdoor antenna

Description	Hot Humid Coastal Area			Inland Temperate Area			Very Dry Area		
	Smooth Terrain	Average Terrain	Rough Terrain	Smooth Terrain	Average Terrain	Rough Terrain	Smooth Terrain	Average Terrain	Rough Terrain
Downstream: 16QAM									
Transmitter power (dBm)	47.0	47.0	47.0	47.0	47.0	47.0	47.0	47.0	47.0
Transmission loss (dB)	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0
Antenna gain (dBi)	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0
Transmitter EIRP (dBm)	63.0	63.0	63.0	63.0	63.0	63.0	63.0	63.0	63.0
Receiver sensitivity (dBm)	-92.0	-92.0	-92.0	-92.0	-92.0	-92.0	-92.0	-92.0	-92.0
Fade margin (dB)	25.5	17.5	10.0	24.0	15.5	10.0	22.5	14.0	10.0
Req. received signal dBm)	-66.5	-74.5	-82.0	-68.0	-76.5	-82.0	-69.5	-78.0	-82.0
CPE antenna gain (dBi)	23.0	23.0	23.0	23.0	23.0	23.0	23.0	23.0	23.0
Propagation loss (dB)	152.5	160.5	168.0	154.0	162.5	168.0	155.5	164.0	168.0
Max path length (miles)	**14.0**	**12.0**	**9.0**	**16.0**	**13.0**	**9.0**	**17.5**	**14.5**	**9.0**
Thermal noise (dBm)	-106.2	-106.2	-106.2	-106.2	-106.2	-106.2	-106.2	-106.2	-106.2
Receiver noise figure (dB)	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Co-channel interferer (dBm)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$C/(I+N_0)$ at perimeter (dB)	34.7	26.7	19.2	33.2	24.7	19.2	31.7	23.2	19.2
Req. C/I for 10^{-6} BER (dB)	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0
C/I margin (dB)	**25.7**	**17.7**	**10.2**	**24.2**	**15.7**	**10.2**	**22.7**	**14.2**	**10.2**
Upstream: QPSK									
Transceiver power (dBm)	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0
Antenna gain (dBi)	23.0	23.0	23.0	23.0	23.0	23.0	23.0	23.0	23.0
Transceiver EIRP (dBm)	38.0	38.0	38.0	38.0	38.0	38.0	38.0	38.0	38.0
Max path length (miles)	14.0	12.0	9.0	16.0	13.0	9.0	17.5	14.5	9.0
Path loss (dB)	152.5	160.5	168.0	154.0	162.5	168.0	155.5	164.0	168.0
Receiver antenna gain (dBi)	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0
LNA gain (dB)	28.0	28.0	28.0	28.0	28.0	28.0	28.0	28.0	28.0
Transmission line loss (dB)	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0
Net received signal (dBm)	-70.5	-78.5	-86.0	-72.0	-80.5	-86.0	-73.5	-82.0	-86.0
Receiver sensitivity (dBm)	-96.0	-96.0	-96.0	-96.0	-96.0	-96.0	-96.0	-96.0	-96.0
Fade margin (dB)	25.5	17.5	10.0	24.0	15.5	10.0	22.5	14.0	10.0
Req. received signal (dBm)	-70.5	-78.5	-86.0	-72.0	-80.5	-86.0	-73.5	-82.0	-86.0
Thermal noise (dBm)	-106.2	-106.2	-106.2	-106.2	-106.2	-106.2	-106.2	-106.2	-106.2
Receiver noise figure (dB)	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
Co-channel interferer (dBm)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$C/(I+N_0)$ at perimeter (dB)	28.7	20.7	13.2	27.2	18.7	13.2	25.7	17.2	13.2
Req. C/I for 10^{-6} BER (dB)	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
C/I margin (dB)	**23.7**	**15.7**	**8.2**	**22.2**	**13.7**	**8.2**	**20.7**	**12.2**	**8.2**

Minicell link budgets for the OFDM-based BFWA system operating at MMDS frequencies using CPE with outdoor antenna

Description	Hot Humid Coastal Area			Inland Temperate Area			Very Dry Area		
	Smooth Terrain	**Average Terrain**	**Rough Terrain**	**Smooth Terrain**	**Average Terrain**	**Rough Terrain**	**Smooth Terrain**	**Average Terrain**	**Rough Terrain**
Downstream: 64 QAM									
Transmitter power (dBm)	34.0	34.0	34.0	34.0	34.0	34.0	34.0	34.0	34.0
Transmission loss (dB)	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0
Antenna gain (dBi)	23.0	23.0	23.0	23.0	23.0	23.0	23.0	23.0	23.0
Transmitter EIRP (dBm)	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0
Receiver sensitivity (dBm)	-86.0	-86.0	-86.0	-86.0	-86.0	-86.0	-86.0	-86.0	-86.0
Fade margin (dB)	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Req. received signal dBm)	-76.0	-76.0	-76.0	-76.0	-76.0	-76.0	-76.0	-76.0	-76.0
CPE antenna gain (dBi)	23.0	23.0	23.0	23.0	23.0	23.0	23.0	23.0	23.0
Propagation loss (dB)	154.0	154.0	154.0	154.0	154.0	154.0	154.0	154.0	154.0
Max path length (miles)	**6.0**	**3.0**	**2.0**	**6.0**	**3.0**	**2.0**	**6.0**	**3.0**	**2.0**
Thermal noise (dBm)	-106.2	-106.2	-106.2	-106.2	-106.2	-106.2	-106.2	-106.2	-106.2
Receiver noise figure (dB)	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Co-channel interferer (dBm)	7.4	5.6	2.7	7.4	5.6	2.7	7.4	5.6	2.7
$C/(I+N_0)$ at perimeter (dB)	17.8	19.6	22.5	17.8	19.6	22.5	17.8	19.6	22.5
Req. C/I for 10^{-6} BER (dB)	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0
C/I margin (dB)	**2.8**	**4.6**	**7.5**	**2.8**	**4.6**	**7.5**	**2.8**	**4.6**	**7.5**
Upstream: 16QAM									
Transceiver power (dBm)	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0
Antenna gain (dBi)	23.0	23.0	23.0	23.0	23.0	23.0	23.0	23.0	23.0
Transceiver EIRP (dBm)	38.0	38.0	38.0	38.0	38.0	38.0	38.0	38.0	38.0
Max path length (miles)	6.0	3.0	2.0	6.0	3.0	2.0	6.0	3.0	2.0
Path loss (dB)	154.0	154.0	154.0	154.0	154.0	154.0	154.0	154.0	154.0
Receiver antenna gain (dBi)	23.0	23.0	23.0	23.0	23.0	23.0	23.0	23.0	23.0
LNA gain (dB)	28.0	28.0	28.0	28.0	28.0	28.0	28.0	28.0	28.0
Transmission line loss (dB)	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0
Net received signal (dBm)	-67.0	-67.0	-67.0	-67.0	-67.0	-67.0	-67.0	-67.0	-67.0
Receiver sensitivity (dBm)	-92.0	-92.0	-92.0	-92.0	-92.0	-92.0	-92.0	-92.0	-92.0
Fade margin (dB)	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Req. received signal (dBm)	-82.0	-82.0	-82.0	-82.0	-82.0	-82.0	-82.0	-82.0	-82.0
Thermal noise (dBm)	-106.2	-106.2	-106.2	-106.2	-106.2	-106.2	-106.2	-106.2	-106.2
Receiver noise figure (dB)	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
Co-channel interferer (dBm)	7.4	5.6	2.7	7.4	5.6	2.7	7.4	5.6	2.7
$C/(I+N_0)$ at perimeter (dB)	9.8	11.6	14.5	9.8	11.6	14.5	9.8	11.6	14.5
Req. C/I for 10^{-6} BER (dB)	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0
C/I margin (dB)	**0.8**	**2.6**	**5.5**	**0.8**	**2.6**	**5.5**	**0.8**	**2.6**	**5.5**

Supercell link budgets for the OFDM-based BFWA system operating at MMDS frequencies using CPE with indoor antenna

Description	Hot Humid Coastal Area			Inland Temperate Area			Very Dry Area		
	Smooth Terrain	Average Terrain	Rough Terrain	Smooth Terrain	Average Terrain	Rough Terrain	Smooth Terrain	Average Terrain	Rough Terrain
Downstream: 16QAM									
Transmitter power (dBm)	47.0	47.0	47.0	47.0	47.0	47.0	47.0	47.0	47.0
Transmission loss (dB)	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0
Antenna gain (dBi)	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0
Transmitter EIRP (dBm)	63.0	63.0	63.0	63.0	63.0	63.0	63.0	63.0	63.0
Receiver sensitivity (dBm)	-92.0	-92.0	-92.0	-92.0	-92.0	-92.0	-92.0	-92.0	-92.0
Fade margin (dB)	16.5	10.0	10.0	14.5	10.0	10.0	13.5	10.0	10.0
Req. received signal dBm)	-75.5	-82.0	-82.0	-77.5	-82.0	-82.0	-78.5	-82.0	-82.0
CPE antenna gain (dBi)	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
Window penetration loss (dB)	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
Propagation loss (dB)	142.5	149.0	149.0	144.5	149.0	149.0	145.5	149.0	149.0
Max path length (miles)	**7.0**	**5.1**	**2.8**	**7.9**	**5.1**	**2.8**	**8.5**	**5.1**	**2.8**
Thermal noise (dBm)	-106.2	-106.2	-106.2	-106.2	-106.2	-106.2	-106.2	-106.2	-106.2
Receiver noise figure (dB)	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Co-channel interferer (dBm)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$C/(I+N_0)$ at perimeter (dB)	25.7	19.2	19.2	23.7	19.2	19.2	22.7	19.2	19.2
Req. C/I for 10^{-6} BER (dB)	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0
C/I margin (dB)	**16.7**	**10.2**	**10.2**	**14.7**	**10.2**	**10.2**	**13.7**	**10.2**	**10.2**
Upstream: QPSK									
Transceiver power (dBm)	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Antenna gain (dBi)	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
Transceiver EIRP (dBm)	22.0	22.0	22.0	22.0	22.0	22.0	22.0	22.0	22.0
Max path length (miles)	7.0	5.1	2.8	7.9	5.1	2.8	8.5	5.1	2.8
Window penetration loss (dB)	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
Path loss (dB)	142.5	149.0	149.0	144.5	149.0	149.0	145.5	149.0	149.0
Receiver antenna gain (dBi)	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0
LNA gain (dB)	28.0	28.0	28.0	28.0	28.0	28.0	28.0	28.0	28.0
Transmission line loss (dB)	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0
Net received signal (dBm)	-76.5	-83.0	-83.0	-78.5	-83.0	-83.0	-79.5	-83.0	-83.0
Receiver sensitivity (dBm)	-96.0	-96.0	-96.0	-96.0	-96.0	-96.0	-96.0	-96.0	-96.0
Fade margin (dB)	16.5	10.0	10.0	14.5	10.0	10.0	13.5	10.0	10.0
Req. received signal (dBm)	-79.5	-86.0	-86.0	-81.5	-86.0	-86.0	-82.5	-86.0	-86.0
Thermal noise (dBm)	-106.2	-106.2	-106.2	-106.2	-106.2	-106.2	-106.2	-106.2	-106.2
Receiver noise figure (dB)	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
Co-channel interferer (dBm)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$C/(I+N_0)$ at perimeter (dB)	19.7	16.2	16.2	20.7	16.2	16.2	19.7	16.2	16.2
Req. C/I for 10^{-6} BER (dB)	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
C/I margin (dB)	**14.7**	**11.2**	**11.2**	**15.7**	**11.2**	**11.2**	**14.7**	**11.2**	**11.2**

Minicell link budgets for the OFDM-based BFWA system operating at MMDS frequencies using CPE with indoor antenna

Description	Hot Humid Coastal Area			Inland Temperate Area			Very Dry Area		
	Smooth Terrain	Average Terrain	Rough Terrain	Smooth Terrain	Average Terrain	Rough Terrain	Smooth Terrain	Average Terrain	Rough Terrain
Downstream: 16QAM									
Transmitter power (dBm)	34.0	34.0	34.0	34.0	34.0	34.0	34.0	34.0	34.0
Transmission loss (dB)	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0
Antenna gain (dBi)	23.0	23.0	23.0	23.0	23.0	23.0	23.0	23.0	23.0
Transmitter EIRP (dBm)	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0
Receiver sensitivity (dBm)	-92.0	-92.0	-92.0	-92.0	-92.0	-92.0	-92.0	-92.0	-92.0
Fade margin (dB)	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Req. received signal dBm)	-82.0	-82.0	-82.0	-82.0	-82.0	-82.0	-82.0	-82.0	-82.0
CPE antenna gain (dBi)	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
Window penetration loss (dB)	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
Propagation loss (dB)	141.0	141.0	141.0	141.0	141.0	141.0	141.0	141.0	141.0
Max path length (miles)	**2.8**	**1.5**	**1.0**	**2.8**	**1.5**	**1.0**	**2.8**	**1.5**	**1.0**
Thermal noise (dBm)	-106.2	-106.2	-106.2	-106.2	-106.2	-106.2	-106.2	-106.2	-106.2
Receiver noise figure (dB)	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Co-channel interferer (dBm)	7.4	5.6	2.7	7.4	5.6	2.7	7.4	5.6	2.7
$C/(I+N_0)$ at perimeter (dB)	11.8	13.6	16.5	11.8	13.6	16.5	11.8	13.6	16.5
Req. C/I for 10^{-6} BER (dB)	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0
C/I margin (dB)	**2.8**	**4.6**	**7.5**	**2.8**	**4.6**	**7.5**	**2.8**	**4.6**	**7.5**
Upstream: QPSK									
Transceiver power (dBm)	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Antenna gain (dBi)	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
Transceiver EIRP (dBm)	22.0	22.0	22.0	22.0	22.0	22.0	22.0	22.0	22.0
Max path length (miles)	2.8	1.5	1.0	2.8	1.5	1.0	2.8	1.5	1.0
Window penetration loss (dB)	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
Path loss (dB)	141.0	141.0	141.0	141.0	141.0	141.0	141.0	141.0	141.0
Receiver antenna gain (dBi)	23.0	23.0	23.0	23.0	23.0	23.0	23.0	23.0	23.0
LNA gain (dB)	28.0	28.0	28.0	28.0	28.0	28.0	28.0	28.0	28.0
Transmission line loss (dB)	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0
Net received signal (dBm)	-70.0	-70.0	-70.0	-70.0	-70.0	-70.0	-70.0	-70.0	-70.0
Receiver sensitivity (dBm)	-96.0	-96.0	-96.0	-96.0	-96.0	-96.0	-96.0	-96.0	-96.0
Fade margin (dB)	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Req. received signal (dBm)	-86.0	-86.0	-86.0	-86.0	-86.0	-86.0	-86.0	-86.0	-86.0
Thermal noise (dBm)	-106.2	-106.2	-106.2	-106.2	-106.2	-106.2	-106.2	-106.2	-106.2
Receiver noise figure (dB)	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
Co-channel interferer (dBm)	7.4	5.6	2.7	7.4	5.6	2.7	7.4	5.6	2.7
$C/(I+N_0)$ at perimeter (dB)	5.8	7.6	10.5	5.8	7.6	10.5	5.8	7.6	10.5
Req. C/I for 10^{-6} BER (dB)	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
C/I margin (dB)	**0.8**	**2.6**	**5.5**	**0.8**	**2.6**	**5.5**	**0.8**	**2.6**	**5.5**

Link budgets for the single-carrier-based BFWA System operating at 700 MHz frequencies using CPE with outdoor antenna

Description	Supercell (16QAM-Downstream/QPSK-Upstream)			Minicell (64QAM-Downstream/16QAM-Upstream)		
	Hot Humid Avg Terrain	Inland Avg Terrain	Dry Area Avg Terrain	Hot Humid Avg Terrain	Inland Avg Terrain	Dry Area Avg Terrain
Downstream:						
Transmitter power (dBm)	47.0	47.0	47.0	34.0	34.0	34.0
Transmission loss (dB)	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0
Antenna gain (dBi)	18.0	18.0	18.0	23.0	23.0	23.0
Transmitter EIRP (dBm)	63.0	63.0	63.0	55.0	55.0	55.0
Receiver sensitivity (dBm)	-83.0	-83.0	-83.0	-77.0	-77.0	-77.0
Fade margin (dB)	16.7	15.0	13.7	10.0	10.0	10.0
Req. received signal dBm)	-66.3	-68.0	-69.3	-67.0	-67.0	-67.0
CPE antenna gain (dBi)	23.0	23.0	23.0	23.0	23.0	23.0
Wall penetration loss (dB)	0.0	0.0	0.0	0.0	0.0	0.0
Propagation loss (dB)	152.3	154.0	155.3	145.0	145.0	145.0
Max path length (miles)	**17.5**	**20.0**	**22.0**	**5.7**	**5.7**	**5.7**
Thermal noise (dBm)	-106.2	-106.2	-106.2	-106.2	-106.2	-106.2
Receiver noise figure (dB)	5.0	5.0	5.0	5.0	5.0	5.0
Co-channel interferer (dBm)	0.0	0.0	0.0	6.2	6.2	6.2
$C/(I+N_0)$ at perimeter (dB)	34.9	33.2	31.9	28.0	28.0	28.0
Req. C/I for 10^{-6} BER (dB)	18.0	18.0	18.0	24.0	24.0	24.0
C/I margin (dB)	**16.9**	**15.2**	**13.9**	**4.0**	**4.0**	**4.0**
Upstream:						
Transceiver power (dBm)	15.0	15.0	15.0	15.0	15.0	15.0
Antenna gain (dBi)	23.0	23.0	23.0	23.0	23.0	23.0
Transceiver EIRP (dBm)	38.0	38.0	38.0	38.0	38.0	38.0
Max path length (miles)	17.5	20.0	22.0	5.7	5.7	5.7
Wall penetration loss (dB)	0.0	0.0	0.0	0.0	0.0	0.0
Path loss (dB)	152.3	154.0	155.3	145.0	145.0	145.0
Receiver antenna gain (dBi)	18.0	18.0	18.0	23.0	23.0	23.0
LNA gain (dB)	28.0	28.0	28.0	28.0	28.0	28.0
Transmission line loss (dB)	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0
Net received signal (dBm)	-70.3	-72.0	-73.3	-58.0	-58.0	-58.0
Receiver sensitivity (dBm)	-87.0	-87.0	-87.0	-83.0	-83.0	-83.0
Fade margin (dB)	16.7	15.0	13.7	10.0	10.0	10.0
Req. received signal (dBm)	-70.3	-72.0	-73.3	-73.0	-73.0	-73.0
Thermal noise (dBm)	-106.2	-106.2	-106.2	-106.2	-106.2	-106.2
Receiver noise figure (dB)	7.0	7.0	7.0	7.0	7.0	7.0
Co-channel interferer (dBm)	0.0	0.0	0.0	6.2	6.2	6.2
$C/(I+N_0)$ at perimeter (dB)	28.9	27.2	25.9	20.0	20.0	20.0
Req. C/I for 10^{-6} BER (dB)	14.0	14.0	14.0	18.0	18.0	18.0
C/I margin (dB)	**14.9**	**13.2**	**11.9**	**2.0**	**2.0**	**2.0**

Link budgets for the OFDM-based BFWA System operating at 700 MHz frequencies using CPE with outdoor antenna

Description	Supercell (16QAM-Downstream/QPSK-Upstream)			Minicell (64QAM-Downstream/16QAM-Upstream)		
	Hot Humid Avg Terrain	**Inland Avg Terrain**	**Dry Area Avg Terrain**	**Hot Humid Avg Terrain**	**Inland Avg Terrain**	**Dry Area Avg Terrain**
Downstream:						
Transmitter power (dBm)	47.0	47.0	47.0	34.0	34.0	34.0
Transmission loss (dB)	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0
Antenna gain (dBi)	18.0	18.0	18.0	23.0	23.0	23.0
Transmitter EIRP (dBm)	63.0	63.0	63.0	55.0	55.0	55.0
Receiver sensitivity (dBm)	-92.0	-92.0	-92.0	-86.0	-86.0	-86.0
Fade margin (dB)	21.0	20.0	18.0	10.0	10.0	10.0
Req. received signal dBm)	-71.0	-72.0	-74.0	-76.0	-76.0	-76.0
CPE antenna gain (dBi)	23.0	23.0	23.0	23.0	23.0	23.0
Wall penetration loss (dB)	0.0	0.0	0.0	0.0	0.0	0.0
Propagation loss (dB)	157.0	158.0	160.0	154.0	154.0	154.0
Max path length (miles)	**25.0**	**27.0**	**30.0**	**10.5**	**10.5**	**10.5**
Thermal noise (dBm)	-106.2	-106.2	-106.2	-106.2	-106.2	-106.2
Receiver noise figure (dB)	5.0	5.0	5.0	5.0	5.0	5.0
Co-channel interferer (dBm)	0.0	0.0	0.0	6.2	6.2	6.2
$C/(I+N_0)$ at perimeter (dB)	30.2	29.2	27.2	19.0	19.0	19.0
Req. C/I for 10^{-6} BER (dB)	9.0	9.0	9.0	15.0	15.0	15.0
C/I margin (dB)	**21.2**	**20.2**	**18.2**	**4.0**	**4.0**	**4.0**
Upstream:						
Transceiver power (dBm)	15.0	15.0	15.0	15.0	15.0	15.0
Antenna gain (dBi)	23.0	23.0	23.0	23.0	23.0	23.0
Transceiver EIRP (dBm)	38.0	38.0	38.0	38.0	38.0	38.0
Max path length (miles)	25.0	27.0	30.0	10.5	10.5	10.5
Wall penetration loss (dB)	0.0	0.0	0.0	8.0	8.0	8.0
Path loss (dB)	157.0	158.0	160.0	154.0	154.0	154.0
Receiver antenna gain (dBi)	18.0	18.0	18.0	23.0	23.0	23.0
LNA gain (dB)	28.0	28.0	28.0	28.0	28.0	28.0
Transmission line loss (dB)	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0
Net received signal (dBm)	-75.0	-76.0	-78.0	-67.0	-67.0	-67.0
Receiver sensitivity (dBm)	-96.0	-96.0	-96.0	-92.0	-92.0	-92.0
Fade margin (dB)	21.0	20.0	18.0	10.0	10.0	10.0
Req. received signal (dBm)	-75.0	-76.0	-78.0	-82.0	-82.0	-82.0
Thermal noise (dBm)	-106.2	-106.2	-106.2	-106.2	-106.2	-106.2
Receiver noise figure (dB)	7.0	7.0	7.0	7.0	7.0	7.0
Co-channel interferer (dBm)	0.0	0.0	0.0	6.2	6.2	6.2
$C/(I+N_0)$ at perimeter (dB)	24.2	23.2	21.2	11.0	11.0	11.0
Req. C/I for 10^{-6} BER (dB)	5.0	5.0	5.0	9.0	9.0	9.0
C/I margin (dB)	**19.2**	**18.2**	**16.2**	**2.0**	**2.0**	**2.0**

Link budgets for the OFDM-based BFWA System operating at 700 MHz frequencies using CPE with indoor antenna

Description	Supercell (16QAM-Downstream/QPSK-Upstream)			Minicell (16QAM-Downstream/QPSK-Upstream)		
	Hot Humid Avg Terrain	Inland Avg Terrain	Dry Area Avg Terrain	Hot Humid Avg Terrain	Inland Avg Terrain	Dry Area Avg Terrain
Downstream:						
Transmitter power (dBm)	47.0	47.0	47.0	34.0	34.0	34.0
Transmission loss (dB)	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0
Antenna gain (dBi)	18.0	18.0	18.0	23.0	23.0	23.0
Transmitter EIRP (dBm)	63.0	63.0	63.0	55.0	55.0	55.0
Receiver sensitivity (dBm)	-92.0	-92.0	-92.0	-92.0	-92.0	-92.0
Fade margin (dB)	11.8	10.5	10.0	10.0	10.0	10.0
Req. received signal dBm)	-80.2	-81.5	-82.0	-82.0	-82.0	-82.0
CPE antenna gain (dBi)	12.0	12.0	12.0	12.0	12.0	12.0
Wall penetration loss (dB)	8.0	8.0	8.0	8.0	8.0	8.0
Propagation loss (dB)	147.2	148.5	149.0	141.0	141.0	141.0
Max path length (miles)	**12.0**	**13.2**	**13.7**	**4.4**	**4.4**	**4.4**
Thermal noise (dBm)	-106.2	-106.2	-106.2	-106.2	-106.2	-106.2
Receiver noise figure (dB)	5.0	5.0	5.0	5.0	5.0	5.0
Co-channel interferer (dBm)	0.0	0.0	0.0	6.2	6.2	6.2
$C/(I+N_0)$ at perimeter (dB)	21.0	19.7	19.2	13.0	13.0	13.0
Req. C/I for 10^{-6} BER (dB)	9.0	9.0	9.0	9.0	9.0	9.0
C/I margin (dB)	**12.0**	**10.7**	**10.2**	**4.0**	**4.0**	**4.0**
Upstream:						
Transceiver power (dBm)	10.0	10.0	10.0	10.0	10.0	10.0
Antenna gain (dBi)	12.0	12.0	12.0	12.0	12.0	12.0
Transceiver EIRP (dBm)	22.0	22.0	22.0	22.0	22.0	22.0
Max path length (miles)	12.0	13.2	13.7	4.4	4.4	4.4
Wall penetration loss (dB)	8.0	8.0	8.0	8.0	8.0	8.0
Path loss (dB)	147.2	148.5	149.0	141.0	141.0	141.0
Receiver antenna gain (dBi)	18.0	18.0	18.0	23.0	23.0	23.0
LNA gain (dB)	28.0	28.0	28.0	28.0	28.0	28.0
Transmission line loss (dB)	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0
Net received signal (dBm)	-81.2	-82.5	-83.0	-70.0	-70.0	-70.0
Receiver sensitivity (dBm)	-96.0	-96.0	-96.0	-96.0	-96.0	-96.0
Fade margin (dB)	11.8	10.5	10.0	10.0	10.0	10.0
Req. received signal (dBm)	-84.2	-85.5	-86.0	-86.0	-86.0	-86.0
Thermal noise (dBm)	-106.2	-106.2	-106.2	-106.2	-106.2	-106.2
Receiver noise figure (dB)	7.0	7.0	7.0	7.0	7.0	7.0
Co-channel interferer (dBm)	0.0	0.0	0.0	6.2	6.2	6.2
$C/(I+N_0)$ at perimeter (dB)	18.0	16.7	16.2	7.0	7.0	7.0
Req. C/I for 10^{-6} BER (dB)	5.0	5.0	5.0	5.0	5.0	5.0
C/I margin (dB)	**13.0**	**11.7**	**11.2**	**2.0**	**2.0**	**2.0**

Appendix B. Equipment Cost Assumptions

The cost estimates shown here were obtained across a broad range of literary sources and interviews with equipment vendors and industry experts. These costs are determined from a forward-looking perspective, meaning the costs of building the network today with current technology and should be viewed as the costs of currently available BFWA equipment which do not necessarily reflect volume production costs for large scale deployment in the future.

CPE with Outdoor Antenna

Component	Cost/Unit
Outdoor transceiver and antenna unit	$450
Wireless modem and MTA unit	$150
Battery backup	$50
Installation cost	$250
Total CPE and installation cost	**$900**

CPE with Indoor Antenna

Component	Cost/Unit
Indoor integrated CPE unit	$500
Battery backup	$50
Installation cost	$0
Total CPE cost	**$550**

Base Station Equipment

Cell Type	Unsectored Supercell	4-Sectored Minicell	8-Sectored Minicell	16-Sectored Minicell
Wireless modem termination system	$146,450	$585,650	$1,171,250	$2,342,500
Transmitters and receivers	$45,500	$182,000	$364,000	$727,600
Racks and pre-wired systems	$5,700	$22,800	$45,600	$91,100
Trans. lines, antennae, and hanging kits	$32,700	$130,800	$261,600	$523,200
RF backup system	$35,700	$142,800	$285,600	$571,200
Routers	$78,000	$156,000	$232,000	$384,000
Network monitoring system	$21,700	$21,700	$21,700	$21,700
ADM for inter-base station SONET ring	$40,000	$50,000	$50,000	$50,000
Misc. site electronics	$5,000	$5,000	$5,000	$5,000
Backup power supply	$10,000	$20,000	$20,000	$20,000
Tower including painting and lighting	$150,000	$100,000	$100,000	$100,000
Total base station equipment cost	$570,750	$1,416,750	$2,556,750	$4,836,300
Installation cost (10% of equipment cost)	$57,075	$141,675	$255,675	$483,630
Total equipment and installation cost	**$627,825**	**$1,558,425**	**$2,812,425**	**$5,319,930**

Cell Site

Inputs	Serving Area Line Density (lines/square mile)				
	< 1,000	1,000 - 5,000	5,000 - 25,000	25,000 - 50,000	> 50,000
Land cost per square foot	$5	$7.50	$10	$15	$20
Land cost (30,000 sq. ft. lot size)	$150,000	$225,000	$300,000	$450,000	$600,000
Building cost (2,000 sq. ft. room size @ $125 per sq. ft.)	$250,000	$250,000	$250,000	$250,000	$250,000
Total land and building cost	**$400,000**	**$475,000**	**$550,000**	**$700,000**	**$850,000**

Headend Equipment

Headend Equipment	Cost/Unit
OC-48 ADM:	
- Up to 12 DS-3s installed	$40,000
- Up to 48 DS-3s installed	$50,000
- Optical distribution panel per 24 fibers	$4,000
Router:	
- Router shelf, up to 15 line cards	$50,000
- 12-port DS-3 card	$50,050
- 4-port OC-3 card	$25,410
- 1-port OC-48 card	$50,050
- 1-port 2.5Gbps Gigabit Ethernet card	$22,330
Soft Switch (Call Processor):	
- Capacity per call processor, busy hour CCS	60,000 CCS
- Call processor shelf, up to 8 call processors installed	$54,210
- Call processor unit cost	$81,320
Gigabit Ethernet switch	$34,650
Network management system	$40,000
Backup power supply	$20,000
Installation cost (% of equipment cost)	10%

Headend Land and Building

Inputs	Serving Area Line Density (lines/square mile)				
	< 1,000	**1,000 - 5,000**	**5,000 - 25,000**	**25,000 - 50,000**	**> 50,000**
Land cost per square foot	$5	$7.50	$10	$15	$20
Land cost (20,000 sq. ft. lot size)	$100,000	$150,000	$200,000	$300,000	$400,000
Building cost (10,000 sq. ft. room size @ $125 per sq. ft.)	$1,250,000	$1,250,000	$1,250,000	$1,250,000	$1,250,000
Total land and building cost	**$1,350,000**	**$1,400,000**	**$1,450,000**	**$1,550,000**	**$1,650,000**

Cost of Capital

Cost of Capital	Percent
Debt/equity ratio	45/55
Cost of debt	7.7%
Cost of equity	11.9%
Weighted average cost of capital	10.01%
Tax	39.25%

Economic life of Equipment

Default values for the economic lives of equipment and network infrastructure are based on their average projection lives adjusted for net salvage value as determined by the three-way meetings (FCC, State Commission, LEC) for 76 LEC study areas. The economic lives of CPE, base station, and headend equipment are based on the service life of digital circuit equipment, others are based categories used by theHM5.0a model.

Equipment and Network Infrastructure	Economic Life (years)
Customer premises, base station, and headend equipment	10.07
Building and land	47.82
Links to ISP/IXCs' POPs	19.29
SONET Ring structure except conduit	19.29
SONET Ring conduit system	50.92