Broadband Alternatives

Synergies of Fiber and Wireless

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Abstract

This paper presents an analysis of a fiber and a wireless based system design for the deployment of broadband services. It also looks at the ability to integrate these two technologies. The driving force is that fiber is truly broadband but is very labor intensive in its deployment. Whereas, wireless achieves the best in a Moore's law price decrease and is very low in labor content, the issue is bandwidth and it limitations. Fiber can readily provide in well excess of 1 Gbps with superb QoS whereas wireless can provide 10 to 100 Mbps with dramatic costs reductions but with less QoS. The question is how does one combine these technologies and moreover how does one do so in a time of rapidly changing technical and economic change. Is there a stable solution or even a stable path to follow?

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 This has been prepared by Telmarc for the purpose of assessing and evaluating options for towns in New Hampshire and Massachusetts for broadband. The author is also a Research Affiliate at MIT and the assistance of his doctoral students is recognized and appreciated especially Yong Wen.

1 INTRODUCTION

Broadband, what is it and why would anyone want it? Any discussion must commence with some understanding of this question and some attempt to seek its answer. Politically we all want it. Practically, the consumer, for the most part, has no idea in general what they are buying or why.[2] They want faster downloading of pictures but beyond that there is little to drive the business. Verizon, for example, now sells DSL for $19.95 per month, and as of the data of this paper has fallen to $14.95, and will most likely even go below that, it is already well below cost!

Let us consider a simple example; there is a market with DSL and cable modems. DSL provides a modicum of high speed, albeit in a rather cumbersome manner and limited by a distance limitation. Cable can provide video, voice and data, and the data is limited by the sharing mechanism on the last segment of the cable, namely if too many are on at once then blocking occurs. The solution is just more points of distribution. Along comes a new supplier of broadband, why should the consumer change, what is the difference, what makes the consumer change their mind and select the new player. Is there an application that requires data rates well in excess of what is being offered by the incumbent? Is there perceived value on the part of the consumer?

Let us again take a simple example. In a town with cable modems and DSL, the new entrant may have an advantage if they provide some form of mobility. Say an 802.16 or meshed 802.11 system, allowing portability to downtown, one's office, and other locations. The perceived "value" may then be the portability. But what if the cellular carrier offers such service, which it may very well do, then the only perceived value would be price, unless there is a demand for greater speed. Price in a commodity market with competition, as we had seen in the telecom meltdown, leads inevitably to price wars and another meltdown. The consumer has no idea as to value and focuses only on price.

Now move to the fiber only space, no mobility here, only bandwidth and data rate. Does any consumer really want 1 Gbps or higher, and if so for what and at what price? There is no study showing that this is doable in a market sense. The only approaches are "me too" triple plays of video voice and data, and in that market one cannot give more features to voice, possibly a different channel line up, and yes a higher data rate but again for what purpose?[3]

Perhaps these questions are posed based upon a world view looking backward. Perhaps they are the equivalent of saying in 1990 that the only use for the ARPA net was email, and some FTP, but only for the techy user. Perhaps the world wide web equivalent is on the horizon or even more. That may be true but the extent of investment is substantial to deploy a true broadband system. What is the possible change agent to make broadband truly desirable.

1.1 Services

Services are those elements of a business which are offered to the consumer, whoever that may be. Services in a broadband market are divided generically into two areas; on net and off net. The off net services are the typical set of service we see in the triple play market; video, voice and data. The on net services, however, are dramatically different. They are a set of services enabled and facilitated by the fact that the user now has access to a fully connected local broadband network fabric, which if properly priced, creates a new paradigm for service provisioning.

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[2] We base this assertion on having performed over 20,000 questionnaires in Massachusetts, New Hampshire, and Vermont over the period of 2003-2005. We have done several time space questionnaires and have correlated the results. We have also performed may focus groups as well.

[3] In our previous paper, Broadband a Local Paradigm, 2004, see www.telmarc.com for access, we demonstrate a true market for broadband which is driven by local needs.

On net services are not at all well defined at this period of time. The status is like the Internet fifteen years ago, when the Internet was primarily email. Who would have required significant bandwidth for only small amounts of text messaging. There was some FTP downloading but even that was limited by the failure to have access to a wide set of servers and moreover the potential security issues related to an FTP environment. The web approach and the ability to use a DNS for address conversion dramatically changed all of that.

1.1.1 Service Elements

The following Table depicts the details of the typical services to be offered over a broadband network. There are however six services being offered to three market segments, for a total of eighteen offerings. There are thus sixteen offerings not factored into the current revenue stream. Also not that the other offering do not require any significant capital to deploy. If such is required it becomes customer supplied.

		Off Net			*On Net*	
Services	*Video*	*Internet*	*Telephony*	*Portal, Best Effort*	*VPN*	*SLA Circuits*
Characteristics	Analog, Digital video, HDTV, Video on Demand, Pay per View	Broadband Internet access, 10/100 Base T connection with max 100 Mbps rate. Average customer access is 2 Mbps shared	Currently reseller only	IP access portal allowing access to all On Net users via local routers and DNS. Designed as "best effort" transport with no security on the network.	A Virtual private network for On Net connection allowing secure, authenticated and fire walled interconnections	A point to point or point to multipoint service with a service level guarantee including guaranteed minimal data rate.
Residential	Standard home video offerings.	An offering typically twice that of cable modem maximum access speed but guaranteed independent of overall network load.	NA	Generally for local resident access to community servers, library etc.	Can be used as part of a commercial offering.	NA
Commercial	As for the home.	An offering typically twice that of cable modem maximum access speed but guaranteed independent of overall network load.	NA	Can be used for non-secure best effort LAN access	Primarily a commercial offering to hospitals, schools, business, local government and public safety.	Example would be the delivery of a 2 Mbps Internet backbone connection. Another would be DS3 to OC 48 level local or regional service.
Reseller	Network open for video providers.	Network open for IP providers	Access for IP telephony or will sell UNE access to reseller.	Available but not priced at this time.	NA	Same as commercial.
Pricing	See Tariff Sheet	Targeted to compete with incumbent.	UNE access at 50% of the ILEC UNE, currently $7.00 per month per residential UNE	Not in current Business Model, anticipated residential at $40 per month per portal.	Not in current Business Plan. To be priced on level of service required.	Not in current Business Plan. 2 Mbps service would be typically the combination of a portal fee and the SLA rate from Level 3 backbone provider at network PoP.

1.1.2 Demand

The demand for data handling capacity is measured by the demand per user and then creating a loaded demand across all users in a queuing based approach.

The services have data rate demands, say R for each, and the total demand rate per HH at any time instant t is:

$$R_{HH}(t) = \sum_{i=1}^{N} N_i(t) R_i(t) P_i(t)$$

Where we for example have N TV sets each using R bps and with a utilization of P %. The total rate per cell is:

$$R_{Cell}(t) = N_{HH} R_{HH}(t)$$

We now generally approach this is a simpler fashion, namely using peak and off peak loads. We design the network for peak periods, that is we assume all customers are on at any one time. If we consider MPEG 2 video for NTSC quality than using 2 Mbps per channel per HH is reasonable. Clearly HDTV can increase this to in excess of 12 Mbps per HH per channel. It must be made very clear however that video has a very sinister characteristic, it is always on and always pumping data, whether one is viewing it or not. That pumping of data, the broadcast quality which is fine for a broadcast medium like the airwave, has a more difficult problem in a wireless world of limited spectrum.

The following table depicts the typical characteristics of loads for each service:

Service	*Peak Data Rate (bps)*	*Loading (% time at peak)*	*Utilization (Hrs/day)*	*Number Peak Hours per Day*	*Number per HH*
Video	2,000,000	100%	7	5	2
Voice	4,000	25%	0.8	18	3
Data	10,000,000	5%	8	18	3
On Net	100,000,000	1%	12	18	3

1.2 Elements of Change

Change is the dominant driver in the deployment of the broadband infrastructure. Change of a regulatory environment, at least perceived in 1996 with the new Telecom Act, allowed many players to enter the market.

In the past, the time constants of change (ie the average length of time for a change to occur in the market) were ranked as follows:

$T_{Technology} > T_{Regulatory} > T_{Demand}$

This meant that demand was the most fickle and that there was some regulatory risk, but you could design a system and then do sensitivity to the faster changing elements. The reason for this was that the technology base was stable over the demand period and the prices of the technology were also relatively stable. The change agent was typically consumer demand.

Today we have it reversed:

$T_{Technology} < T_{Regulatory} < T_{Demand}$

This means that the demand is more stable and predictable than the technology. In particular we have both technical functions and more importantly technical costs changing with time constants less than a year! The typical example of this is with wireless technology. Take an 802.11 router as an example, four years ago it was retail $300-400. Now it is $19.95, four months ago it was $29.95. The price factors in wireless deployment, exclusive of bandwidth, have been significant factors in driving the market. The deployment of 802.11, 802.15, 802.16, and 802.20 will all increase this volatility. The regulatory world is at best playing catch up in this environment.

The key questions one see addressed in a wireless fabric can be phrased simply as follows:

- Spectrum: how much and how easy can it be made available
- Coverage: how far depends on how much power and who else is there
- Capacity: how much power and how much bandwidth
- QoS: data does not care, “every packet is an adventure” is the word of the day, unfortunately if fails for voice and video!
- Backbones: Wireless is great but it needs a backplane, that is fiber
- Connectivity: How do we interconnect all of these elements
- Ownership: Who owns the infrastructure and where does the infrastructure begin and end, what is the customer’s required element?
- Microcells or possibly optical processing: It is possible to have just antennas and amplifiers and do all processing remotely and use optical processing as a part of this, it is much, much cheaper!

1.3 Expectations

One of the problems we face in assessing the broadband developments are the establishment of reasonable expectations. There are two ways to look at expectations; first, related to the reality of what actually occurs and second, related to the expectations of others. This discussion of expectations is critical since in the dot com boom there was no reality and there were only expectations, and no one had the same but they were all exaggerated. If one is not careful broadband can meet the same fate. Let us discuss each of the rules on expectations.

Reality Based: I have called this Fiorelli’s Law after the person who first articulated this clearly. Simply stated there is some reality, namely what actually occurs or is actually achievable, we call this reality. Then there is the expectation of some person or class of persons. Then there is a response we call dissatisfaction, this is the degree at which the judging group responds negatively or positively to the outcome reflected in the reality. In fact dissatisfaction may be time varying as are expectations and reality. We state this law as:

Dissatisfaction=K [Expectations-Reality]

Not that a negative dissatisfaction is a satisfaction. That is if reality exceeds expectations we may be very satisfied. This law works when one is building something and reality is what we all see when the work progresses, or fails to. The expectation is what one or more individuals have assumed to be the progress and it may be based on what they were told or some inner feeling. The dissatisfaction is what results from this mismatch. This form of dissatisfaction is a simple form based upon what one would expect in an engineering world.

Relative Expectations: This rule in an operative format is stated as “Avoid Ambiguity of Expectations”. It states that all parties to the project may have their own expectations, stated or otherwise, and the level of group dissatisfaction is give by mixing the group, namely:

$$Dissatisfaction = K\sum_{i=1}^{N}\sum_{j=1}^{N}\left(Expect_i - Expect_j\right)^2$$

Note in this case we measure only dissatisfaction and not satisfaction. If we can manage the expectations of the group then reality may be irrelevant! This is market dissatisfaction. Reality in this world may be very illusive, all there may really be is expectations.

2 USER ENVIRONMENT

The environment is a dominant factor in the design of any network. The environment is a combination of factors: distribution of potential customers, topography, types of structures, market penetration achieved, and other such factors.

Let us consider a simple example of a town. Let us first make a set of assumptions:

A= area of the town in sq mi or acres

R= number of miles of roads

HH= number of households

Then we create two ratios;

$$HH / mi = \frac{HH}{R}$$

And

$$HH / sqmi = \frac{HH}{A}$$

Now let us further introduce two more factors;

F= frontage of a HH, e.g. the number of linear feet of a house in the town. This may vary but we can crate an average. Remember that houses may be on both sides of the street. Thus HH/mi includes HH on both side of the street and F is the length of the front of a single HH.

S= average square feet per HH coverage measured in land occupied. Recall that there are 44,300 sq ft per acre. There are 27,878,400 sq ft per sq mile. Or 629.31 A/sq mi.

We can show that:

$$A = K_1(S(HH))$$

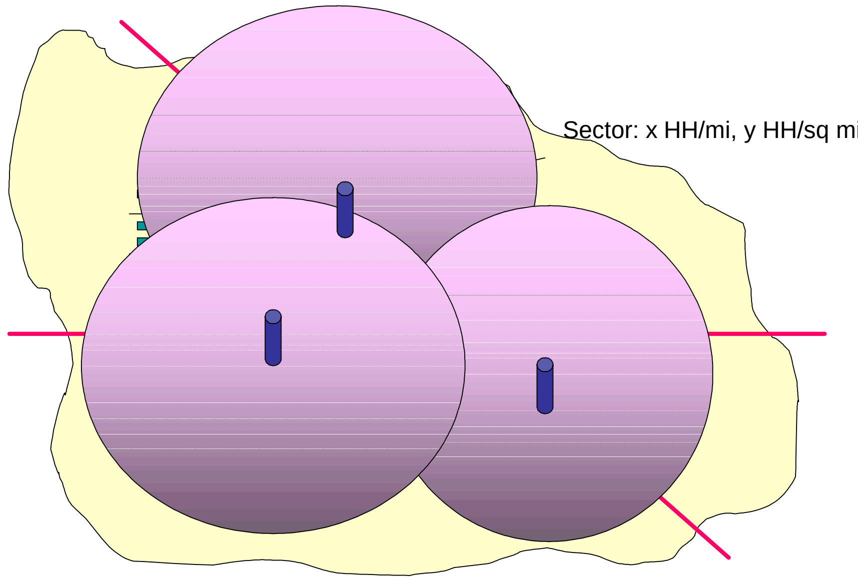
And

$$L = K_2(F(HH))$$

Where the constants K are to be defined based upon actual data.

2.1 Linear Environment: Streets

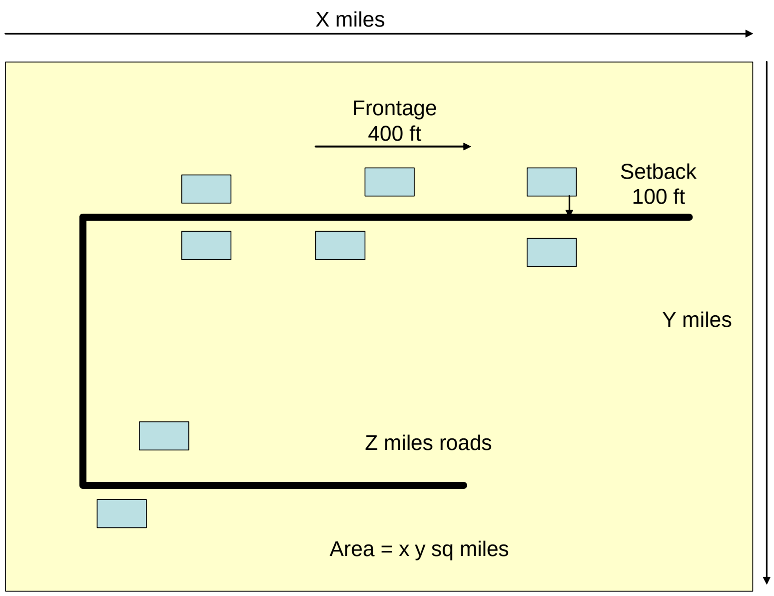
Let us now consider a typical town. This is shown below. There are streets and there are large areas of uninhabited acreage. The streets may have heavy density of population or may be sparse. The wireless antenna are generally assumed to have an effective radius of coverage. The coverage however may be quite more complex due to hills, trees, buildings, and other factors. For design purpose we shall assume circular.



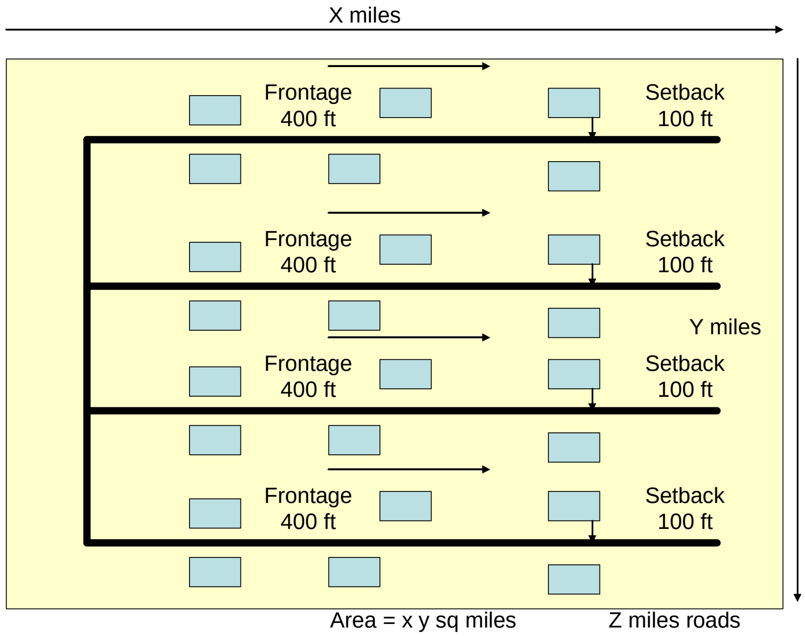
We further have a certain number of HH and these then can be ratioed on a per linear mi basis, which is what we focus on for fiber and then on a per sq mi basis which is the wireless focus.

2.2 Area Environment: Coverage

Consider now a bit more detail. The figure below shows a simplified town of x miles by y miles with z miles of roads. The town has an average frontage of say 400 ft, the distance in front of a home, and an average setback of 100 ft, the distance from the pole to the center of the side of the house. This may be a dense town or a sparse town.



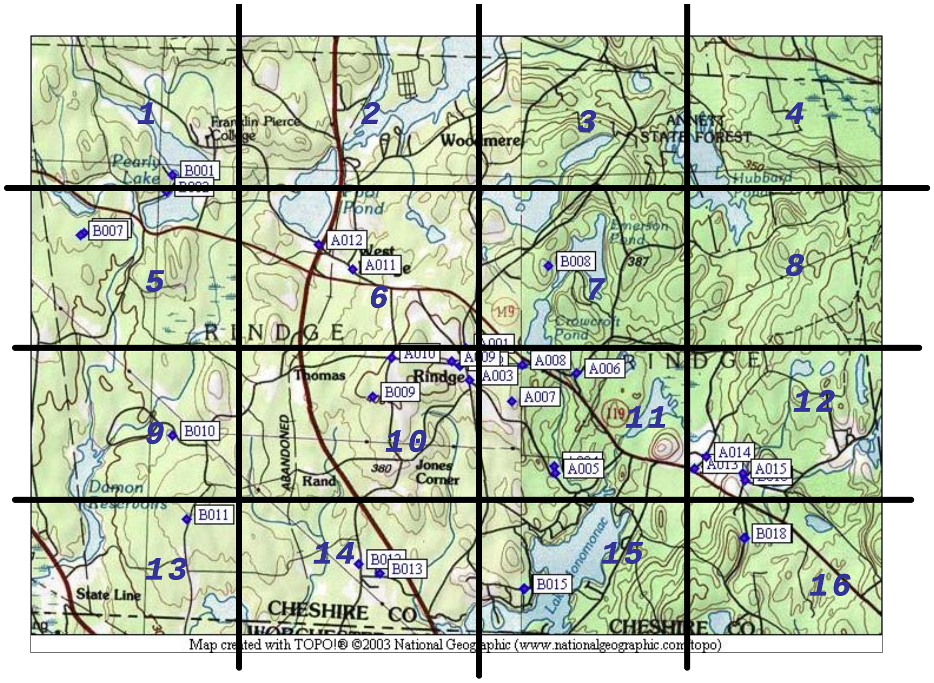
Now consider a dense town. Let us assume the same frontage and set back but now assume that we have just streets with the same characteristics back to back. This means that the town is all homes and nothing else. This defines a boundary condition of a dense packed home. We then define the max miles as the total number of street miles if we densely pack the homes, 400 ft apart and 200 ft from the street with another house just behind it. On and on in this configuration, densely packed with narrow streets.



The following table demonstrates the calculation related to these various design factors.

Frontage	*Setback*	*Length*	*Width*	*Area*	*Max Miles*	*HH max*	*HH/mi*	*HH/sq mi*	*Sq mi/mi*	*Max Cell Capacity (Users)*	*Max Cell Radius (mi)*	*Number Cells*
100	150	3	5	15	132	13,939.20	105.60	929.28	0.11	20	0.08	697
150	150	3	5	15	132	9,292.80	70.40	619.52	0.11	20	0.10	465
200	150	3	5	15	132	6,969.60	52.80	464.64	0.11	20	0.12	348
250	150	3	5	15	132	5,575.68	42.24	371.71	0.11	20	0.13	279
300	150	3	5	15	132	4,646.40	35.20	309.76	0.11	20	0.14	232
350	150	3	5	15	132	3,982.63	30.17	265.51	0.11	20	0.15	199
400	150	3	5	15	132	3,484.80	26.40	232.32	0.11	20	0.17	174
450	150	3	5	15	132	3,097.60	23.47	206.51	0.11	20	0.18	155
500	150	3	5	15	132	2,787.84	21.12	185.86	0.11	20	0.19	139
550	150	3	5	15	132	2,534.40	19.20	168.96	0.11	20	0.19	127
600	150	3	5	15	132	2,323.20	17.60	154.88	0.11	20	0.20	116

Now let us consider a specific town, namely Rindge, NH. The town is shown below. We have divided the town into sixteen equal sectors. The town has about 120 miles of roads and comprises a total 68.5 sq mi of area. It has just slightly more than 2,800 HH.



The summary details for a sector by sector analysis is shown below. We have calculated the maximum miles and actual miles. In a fully dense packed town with the frontages by sector we would have expected 825 miles. We find 120. This tells us that this is a loosely packed town with a great deal of rural empty space. It also tells us that the streets are where the houses are and that wireless coverage is delimited to streets.

Sector	Frontage	Setback	Miles	Length	Width	Area	Max Miles	HH max	HH Actual
1	67	70	4.23	2.1	2.1	4.57	86	13,588	91
2	65	60	23.12	2.1	2.1	4.57	101	16,341	662
3	126	100	4.40	2.1	2.1	4.57	60	5,058	61
5	170	70	5.20	2.1	2.1	4.57	86	5,355	128
6	222	162	9.45	2.1	2.1	4.57	37	1,772	168
7	80	70	9.15	2.1	2.1	4.57	86	11,380	227
8	120	350	1.50	2.1	2.1	4.57	17	1,517	29
9	300	200	2.13	2.1	2.1	4.57	30	1,062	42
10	517	170	11.08	2.1	2.1	4.57	36	726	223
11	597	269	11.35	2.1	2.1	4.57	22	397	268
12	456	177	5.21	2.1	2.1	4.57	34	789	81
13	130	60	1.75	2.1	2.1	4.57	101	8,170	32
14	124	77	4.80	2.1	2.1	4.57	78	6,669	174
15	879	619	21.00	2.1	2.1	4.57	10	117	598
16	175	150	6.30	2.1	2.1	4.57	40	2,428	76
Total			120.66			68.58	825	75,369	2,860

Now ewe have calculated the details for this town and these are shown in the following table. Also above we see that the max HH would be 75,369 and the actual is 2,860. This the ratio of actual to max is about 4%. This is again a rural town.

Fill Ratio %	HH/mi	HH/sq mi	Sq mi/mi	Max Cell Capacity (Users)	Max Cell Radius (mi)	Number Cells Capacity	Number Cells Coverage	Max Number Cells	Min Fiber Backbone (mi)
0.7%	1.06	19.90	0.05	20	0.57	5	1	5	2.6
4.1%	6.58	144.80	0.05	20	0.21	33	1	33	6.9
1.2%	1.01	13.34	0.08	20	0.69	3	1	3	2.1
2.4%	1.48	28.00	0.05	20	0.48	6	1	6	3.1
9.5%	4.52	36.75	0.12	20	0.42	8	1	8	3.5
2.0%	2.63	49.65	0.05	20	0.36	11	1	11	4.1
1.9%	1.68	6.34	0.27	20	1.00	1	1	1	1.5
4.0%	1.39	9.19	0.15	20	0.83	2	1	2	1.7
30.7%	6.27	48.78	0.13	20	0.36	11	1	11	4.0
67.5%	11.94	58.62	0.20	20	0.33	13	1	13	4.4
10.3%	2.38	17.72	0.13	20	0.60	4	1	4	2.4
0.4%	0.32	7.00	0.05	20	0.95	2	1	2	1.5
2.6%	2.22	38.06	0.06	20	0.41	9	1	9	3.6
510.7%	61.35	130.80	0.47	20	0.22	30	1	30	6.6
3.1%	1.89	16.62	0.11	20	0.62	4	1	4	2.4
						143		143	50.4

The above analysis shows several interesting facts. First we have a capacity dominated system. This is driven by the video requirement. Video will drive all system requirements. It is the most demanding of the data streams, being on at all times and streaming at a constant rate, never off! The analysis shows that we require 143 base stations for 100% coverage, again capacity driven. We also require a backbone fiber, whether we have the customers or not of about 50 miles.

We can make a simple calculation:

1. 50 miles of fiber is properly chosen will cost $25,000 per mile and for the 50 miles we have $1.25 million. That is $500 per HH passed. At 25% penetration this is a cost of $2,000 per subscriber! Again the video is the driver in this design. We will perform a detailed analysis latter.

2. Each set of 20 subscribers requires a base station and each subscriber requires a terminal. If the base station is $5,000 then this is $250 per subscriber for the BS and say $250 for the terminal, plus $250 for an IP video box. This is $750 per subscriber for the electronics.

3. Headend electronics are shared and are the same for any IP based system.

4. Thus we have at 25% penetration a capex per sub of almost $3,000. We will compare this latter with the fiber only system.

2.3 Coverage versus Capacity

We have already discussed the issue of coverage and capacity. We shall get a bit more detailed in the latter section on wireless economics but here we can frame the issue in general terms.

2.3.1 Coverage

Coverage means how far can we cover one or more users from a single cell site, We define a term call effective radius of coverage and from that determine the number of square miles we can cover.

Coverage describes a regime of wireless operations wherein one tries to attain the maxim area which the signal can achieve. Coverage does not look at the number of users just how large an area can be achieved.

One may view this as a link budget issue or one wherein effective multipath signals can be processed in a non line of sight design.

Simply stated, the design can be first viewed in a line of sight model using a link budget approach. It can be readily shown that the energy per bit to noise spectral density ratio, $\frac{E_b}{N_0}$, which determines overall communications link performance, can be given by[4]:

$$\frac{E_b}{N_0} = \frac{P_T G_T G_R}{PLR_0 kT}$$

Where we know the power transmitted and gains of the antenna the data rate in bps and the path loss. Path loss, PL, can be a more generalized term and the other elements of modulation, coding, multiple access can also effect the choice of operating value for $\frac{E_b}{N_0}$.

Instead of getting into the details of a specific system we can create an effective radius of coverage for a specific system implementation, call it r_{eff}. We will use this hence forth. This yields an affective coverage area:

$$A_{eff} = \pi (r_{eff}^2)$$

From the $\frac{E_b}{N_0}$ constraint we know that there is a maximum effective data rate which this cell can sustain, we call this $R_{\max}$.

Now if we define the user density per sq mile as $D_{users/sqmi}$ and the average data rate per user as R_{user}, we can relate this as follows: if coverage is to dominate then we must have:

$$R_{\max} > R_{user} D_{users/sqmi} A_{eff}$$

Otherwise we have a capacity domain. What this says is as follows:

For low power by definition the area will be small and the data rate generated in the area will be small and if small enough will place it in the coverage domain.

Thus coverage is determined by maximum power transmitted, gains of antenna, and path loss. Generally the FCC controls power and gain and the only determinant is path loss, namely effective radius and in turn coverage area.

Coverage is generally determined by the maximum data rate, but only in a secondary manner.

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[4] See McGarty, Satellite Optimization, IEEE Aerospace 1977.

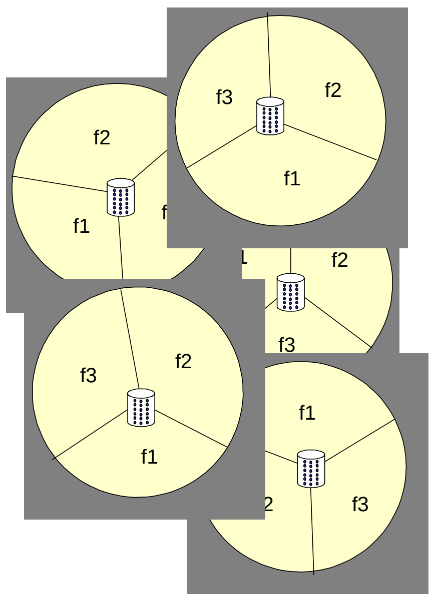
2.3.2 Capacity

Capacity is determined by how much we can handle in a single cell, within the coverage area. Capacity is the limit effected by the number of users not by the p[physics of propagation. Capacity is what we generally see as the limiting factor.

Let us go thru a simple capacity analysis:

1. We assume that we have a certain amount of bandwidth, say 30 MHz.

2. We assume we break that up into three segments of 10 MHz apiece, so that they do not interfere with one another. We will simplify all the analysis since we are focusing on economic issues not engineering details. We will ignore bands for protection or isolation and the like. The antenna are shown below for the layout of the system. Each sector of a 3 sector beam is with one of the three 10 MHz bands.



3. We assume we have some form of air interface with a modulation and multiple access system which means that in the 10 MHz we can support 30 Mbps of signal carrying capacity. One must always be careful to distinguish between bandwidth in MHz and signal carrying capacity in Mbps. This can be achieved by some form of modulation or even with OFDM. Each system has its metric.

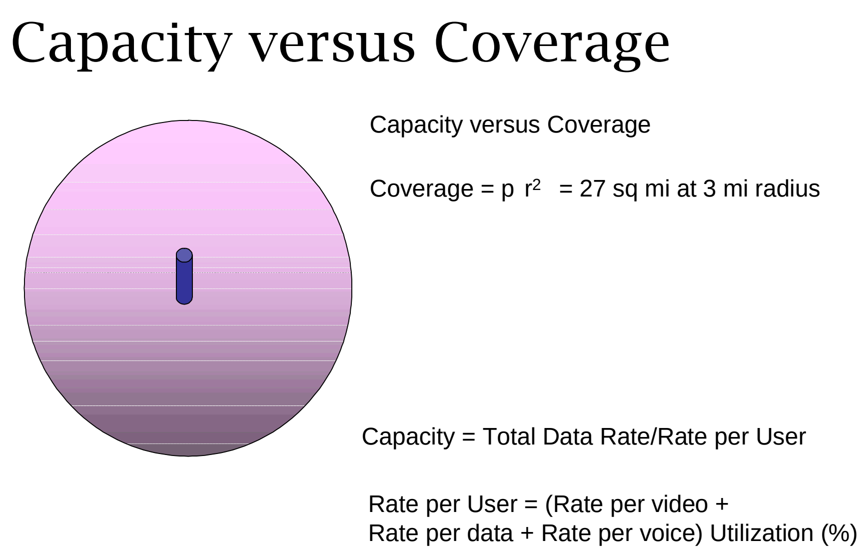
4. This with a 3 sector antenna we have the ability to handle 90 Mbps per cell, and this can be reused from cell to cell.

5. Now assume we have a combination of video, voice and data. Assume that we use NTSC video and MPEG 2, thus requiring 2 Mbps per video and we use IP video. Thus we have with voice and data a data requirement of on average at peak of say 3 Mbps.

6. This means that we can in a single 90 Mbps cell handle up to 30 HH of 1 TV set each or say 20 HH of 1.5 TV sets each. We choose the latter.

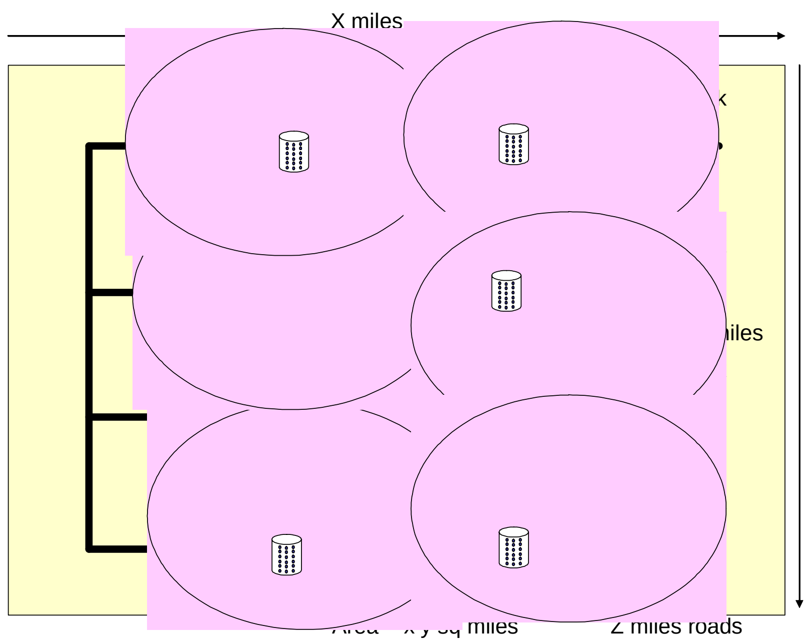
7. The metric then for this design is 30 MHz band.

We summarize these issues graphically below.



2.3.3 *Coverage and Capacity Applied*

We can now apply the coverage and capacity analysis to our simplified town. This is shown below. As a rule of thumb, no matter what, if there is any video we are capacity limited, we never will have a coverage limitation unless there are so few customers. So how do we build the system. As shown below we have pole mounted antennas with feeds from a fiber backbone. The fiber has a strand per local mini base station and a mini base station handles up to 20 HH.



This then leads to several final design questions.

1. How many base stations do we need? Since we argue for capacity domain we are dominated by video and the answer is 20 HH per cell.

2. How many miles of fiber backbone do we need? This will depend on the denseness of the region. If we have a metric of $\frac{HH_{actual}}{HH_{\max}}$ which is much less than one, such as in Rindge, then the base stations are determined as follows:

Let the density of HH be the ratio of the capacity of HH in a single cell divided by the area of that cell, determined by the overall density related to the capacity level:

$$A_{capacity} = A_{Total}\left[\frac{HH_{capacity}}{H_{Total}}\right]$$

And the effective diameter of this cell is:

$$D_{capacity} = \sqrt{A_{capacity}\frac{4}{\pi}}$$

This yields a total fiber distance of:

$$D_{fiber} = N_{cellscapacity} D_{capacity}$$

And finally:

$$N_{cellscapacity=}\frac{HH_{Total}}{HH_{capacity}}$$

3. Is there a simple design metric which can be applied? Yes, we look at the effective coverage as we have just stated,

4. Is there a point where fiber is better rather than wireless? That all depends. We shall study that issue latter in this report.

5. Do we need a fiber backbone or can we have a fully meshed network using wireless all the way? The problem is cumulative bandwidth or more importantly video carrying capacity. There is just not enough.

6. What are the performance issues with wireless? That will also depend. 802.16 will have some QoS issues and we shall discuss these latter.

3 FIBER

3.1 Network Elements

The following are details on network elements, interconnections, and interfaces. The system uses a Passive Optical Networking over a fiber to the user network.

The following then builds from the overall network and then provides detail on each element. We also present details on the routes via strand mapping and the interconnection of the elements.

The network has standard three layers; layer 1 is the physical PON layer, layer 2 is the Ethernet layer using standard MAC protocol, and layer 3 is the standard IP layer. The network is connected town by town by a backbone network. We show that connectivity in detail herein. It should be noted that our intent is to build out a regional network of 41 towns ultimately and that this will be fully interconnected. The current design is for only an additional ten towns.

3.1.1 Overall Network

The overall network elements are shown below. They include:

Customer Premise Systems:

1. Fiber Drops: These are the drops from the pole to the customer premise.

2. CPE/ONU: This is the optical/electronic interface which connects the fiber to the home or end user electronic systems.

3. Set Top Converter: This is the device which converts channels, un-digitizes video, and supports pay per view systems.

Fiber Network:

1. Fiber on Poles: This is the fiber on the poles which is a combination of backbone and distribution fiber. The size of the fiber is determined by the local design. The details are provided in the financial model.

2. PON Interfaces: These are the optical splitters. Note from the Applications we stated that the system is E PON. The backbone network is 1 to 10 Gbps backbone and uses up to a 32:1 splitting. The splitting will be described shortly.

Headend:

1. Video Headend: This is a standard video headend with a set of antennas. The current design has two, one north and one south. Ultimately with a fully connected network this may be reduced to one.

2. Internet Headend: This is merely a router, firewall, server, and DNS (domain name server) allowing network connectivity.

3. Optical/Electronic Headend: This is the collection of equipment interfacing with the fiber network and the electronics on the headend side.

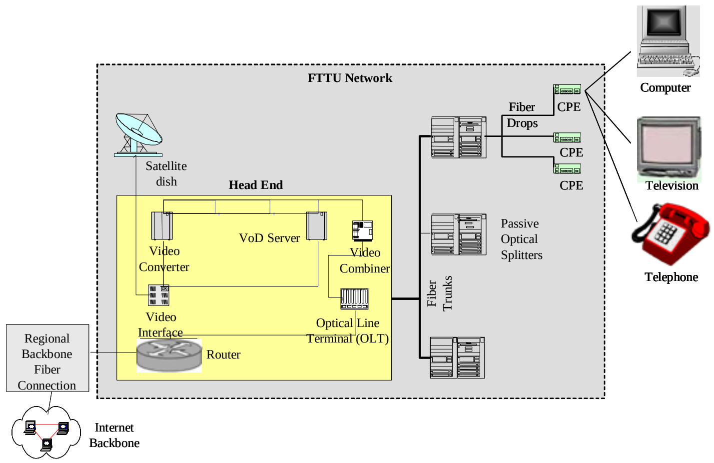
Operations Support Systems:

1. Billing: This is an integrated billing system.

2. Customer Care: This is an integrated customer care system.

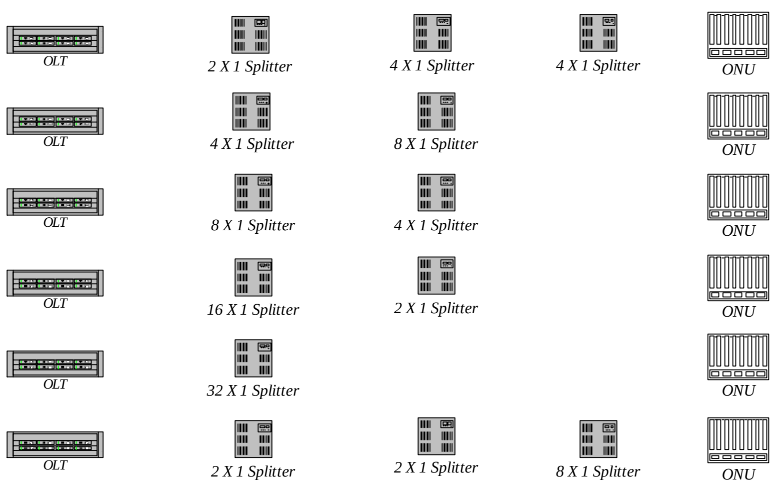
3. Network Management: Manages the overall network.

These are the key system elements. We now provide more detail.

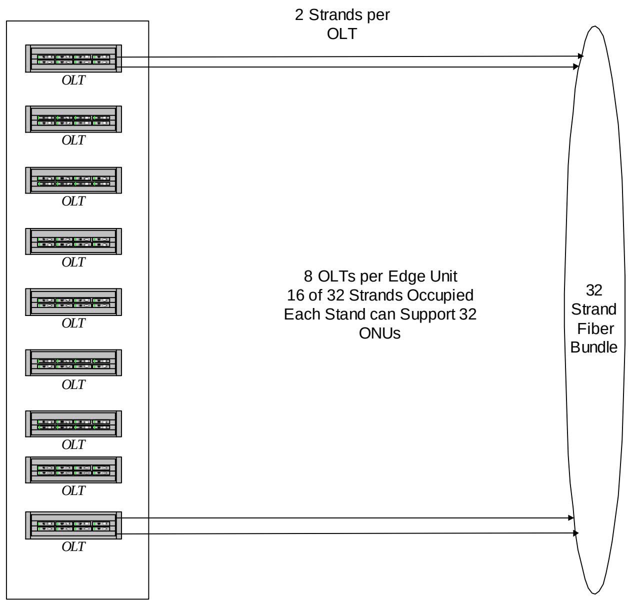


3.1.1.1 Fiber Plant

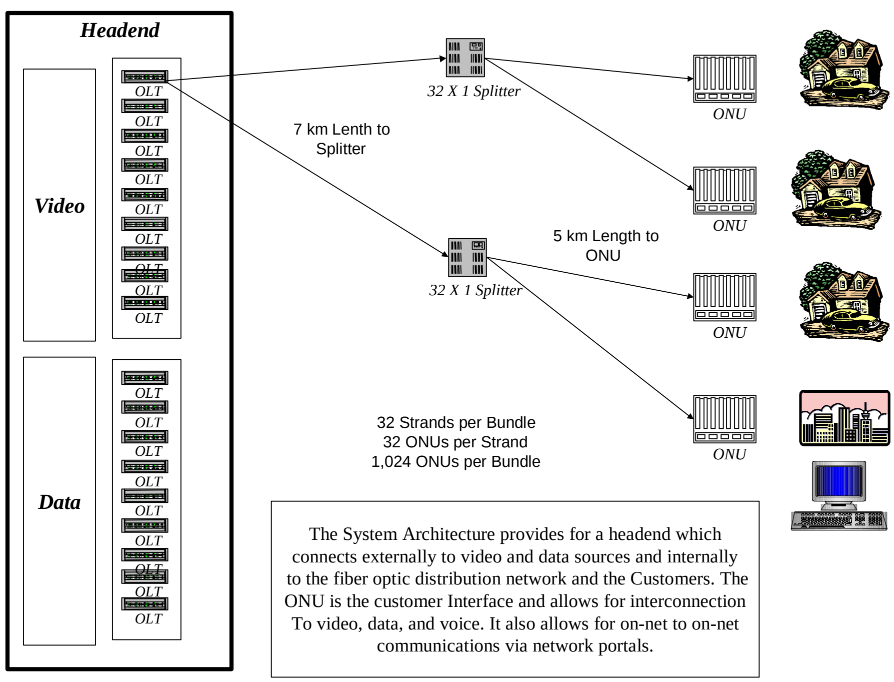
The fiber plant is all passive. The elements in the plant are the splitters as shown below and they are any combination which yields a 32:1 split maximum. The end devices the ONU and OLT are active but reside outside the outside plant.



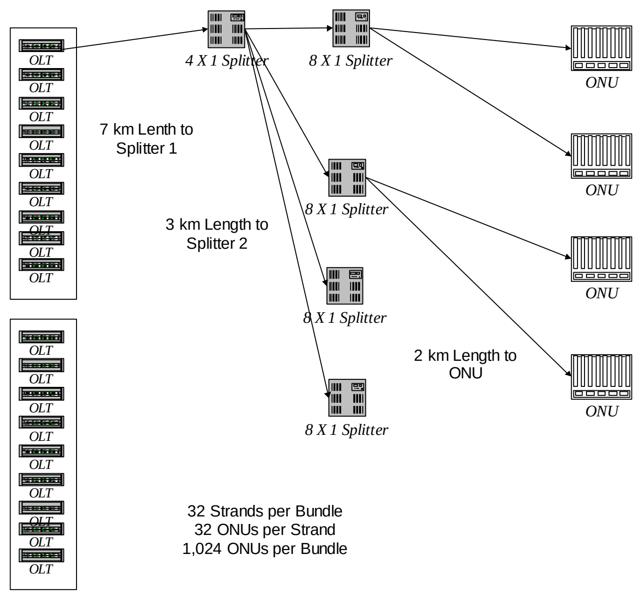
A typical design is shown below. It demonstrates 2 strands per OLT. It feeds a 32 strand fiber. Note that 96 strand fibers are readily deployed and the details will be left to the system engineer based on final strand mapping.



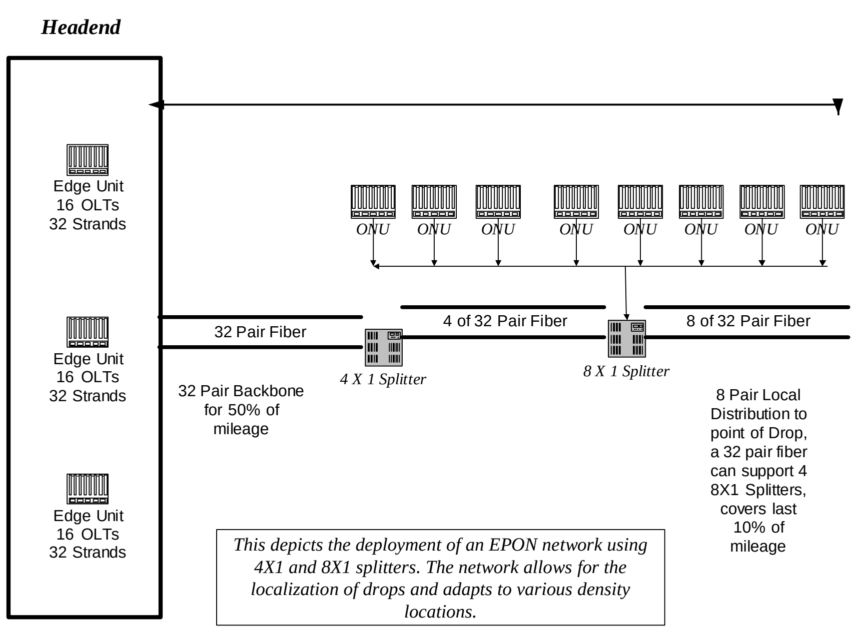
A typical build out is shown below. This time distance are also applied. This will appear as a hybrid active/passive design. The passive side is per town and this minimizes operations and maintenance costs. The active side is in one enclosed unite per town. The active equipment per town takes not more than 150-250 sq ft areas and can be readily housed in local space.



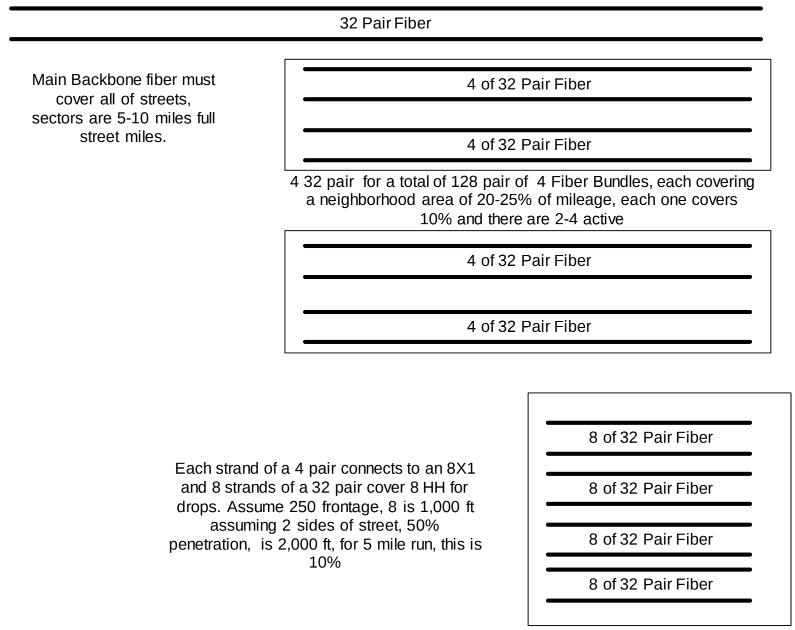
A more detailed design is shown below. In this design we show a 4:1 followed by a 8:1 splitter giving a full 32:1 split. Note that if more capacity is needed less splitting can be done or higher speed provided on the backbone or any combination of these.



The following is full detail on the distribution on the fiber network.



The following is the typical build plan for a section of the network describing the capacity and coverage elements of the typical design, The above are a complete description of the system design.



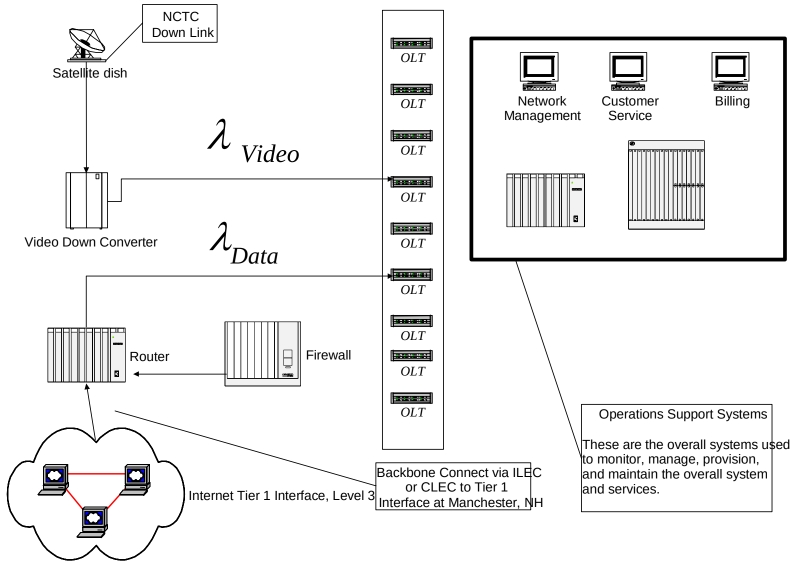
For a PON system one must always be concerned about having adequate signal. This is done by calculating the link budgets. The following is the link budget for this system.

Link Budget

	1510 nm Down	*1310 Up*
Fiber Loss	*0.25 dB per km*	*0.35 dB per km*
1 X 32 Loss	*18.2 dB*	*18.2 dB*
Connector Loss	*0.2 dB per*	*0.2 dB per*
1 X 8 Loss	*10.7 dB*	*10.7 dB*
1 X 4 Loss	*7.5 dB*	*7.5 dB*
1 X 2 Loss	*3.5 dB*	*3.5 dB*
Link Loss		
Maximum Loss	*23 dB*	*23 dB*
Link Margin		

3.1.1.2 End User Plant

The end user plant is what we would anticipate putting in or at the customer premise. The details are shown below. As described above, the drop is followed by an ONU and a set top box for any video services. This may make it possible for the end user to "self deploy" their systems, namely buy the box and deploy automatically, saving significant amounts in capex.



3.1.1.3 Head End

The following is the detail on the head end including the OSS with billing, customer services and network management. The current design show two wavelengths, λ_{Video} and λ_{Data} . We are also considering the use of IP video but at this time it is still a bit early. IP video would allow full integration and would eliminate the need for any headend.

4 WIRELESS DESIGN

The wireless design in many ways parallel the fiber design. There are several difference however and we demonstrate then here. The first area is to delineate the elements which are used in the wireless design so that we can utilize them in the costing model. The second is to demonstrate some design tools for the layout of minimal costs fiber backbone networks.

4.1 Elements

The elements of the wireless design are provided in this section. The overall schema has been discussed earlier but the details are show as in the figure below. The details are as follows:

1. An IP based system router is the basic input and output entry point to the local network.

2. In this example we demonstrate 5 sectors of 96 strand fibers. The fibers are driven by an OLT as with the fiber only system and there is no splitter element in the network. Each antenna and base

station are driven by a single strand. This is then a home run system. We generally design the system to use on half of the strands keeping the other half as spares and expansion.

3. The base stations or BSCs are micro cell in structure and are fed by an OE interface driver from the fiber. The BSC has full functionality for the input and output for the local coverage domain. Each BSC has a 1 to 10 Gbps fiber access.

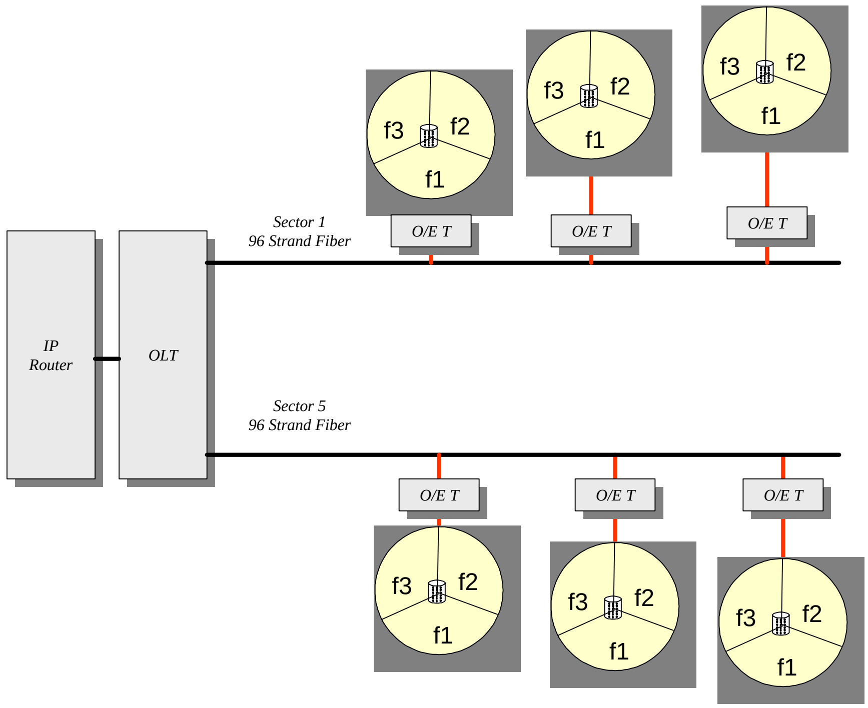
4. The BSC is connected to a three sector antenna. We may also deploy polarization diversity for added isolation. A single design allows for the support of N HHs.

5. The design of this system would also balance modulation with capacity. The following table shows how this varies for an 802.16 environment where we have bandwidth, modulation, coding, and the resulting total effective data rate.[5] Note that if we use a 10 MHz band per sector then each sector supports up to 37.4 Mbps for a total of 112 Mbps for the total micro cell BSC. If we assume 2.5 Mbps per HH then we could support up to 45 HH per microcell. We have chosen 20 herein for a design value.

Modulation	QPSK	QPSK	16QAM	16QAM	64QAM	64QAM
Code Rate	1/2	3/4	1/2	3/4	1/2	3/4
Bandwidth (MHz)	Effective Data Rate (Mbps)					
1.75	1.04	2.18	2.91	4.36	5.94	6.55
3.5	2.08	4.37	5.82	8.73	11.88	13.00
7.0	4.15	8.73	11.64	17.45	23.75	26.18
10.0	8.31	13.47	16.63	24.94	33.25	37.4
20.0	16.62	24.94	33.23	49.87	66.49	74.81

The following figure depicts the typical design using a fiber backbone and a set of three sector micro cells with BTS. The central facility controls all IP flow and we could extend and distribute that function as well. The fiber bundles go down streets and a single strand of fiber, or two if required, can then support each BTS which is located on some high point such as a telephone pole. The Optical and Electronic interfaces, O/E T are there to convert signals. The fiber can support 1-10 Gbps or higher as may be required.

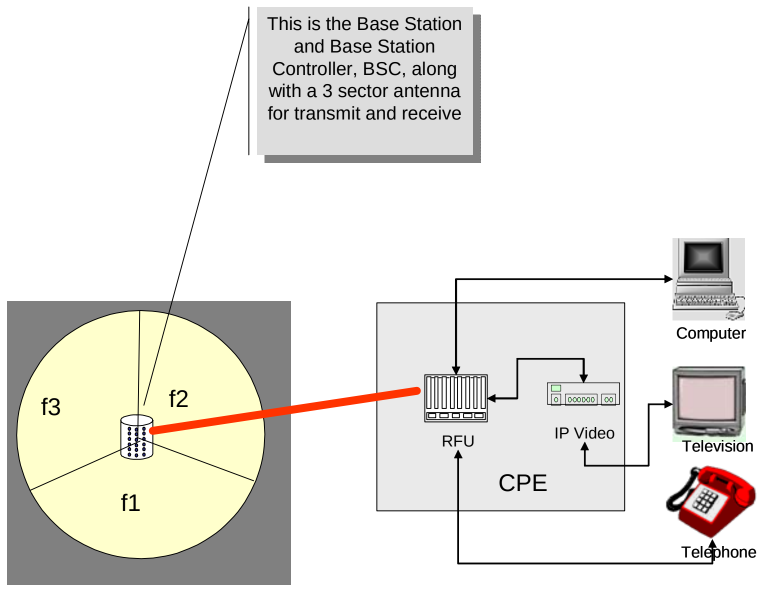
[5] See Bahai et al Theory and Application of OFDM p 360.



The above design shows that we need besides the fiber a set of small microcell BSCs as well as antenna. These are the additional elements.

The actual implementation can be shown. The BSC and antenna are pole mounted on local telephone poles and then can cover a small area of 10-20 HH. The issue will be how far can they cover at that height, say 30 ft. That will depend on local terrain and siting on the pole. The other issues to be concerned about is that to achieve maximum coverage the siting may have to be in the power space.

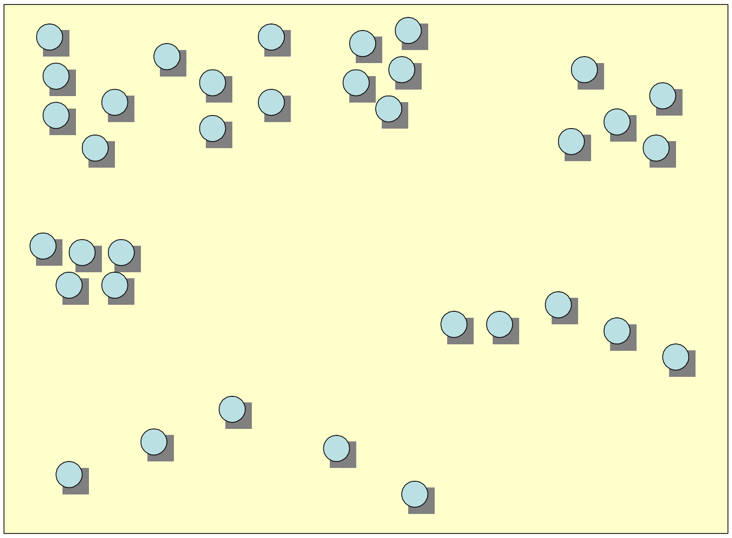
The final elements are those shown connecting to the home. We have an RF signal from and to the home, this may be line of sight or a non line of sight signal. It then interfaces with an RFU which converts and manages the link. Then the signal can be distributed to any one of the three elements in the home, however if it is a TV set then an IP video interface is required.



This then describes the elements of the wireless system. We focus on an 802.16 implementation of this design.

4.2 Deployment

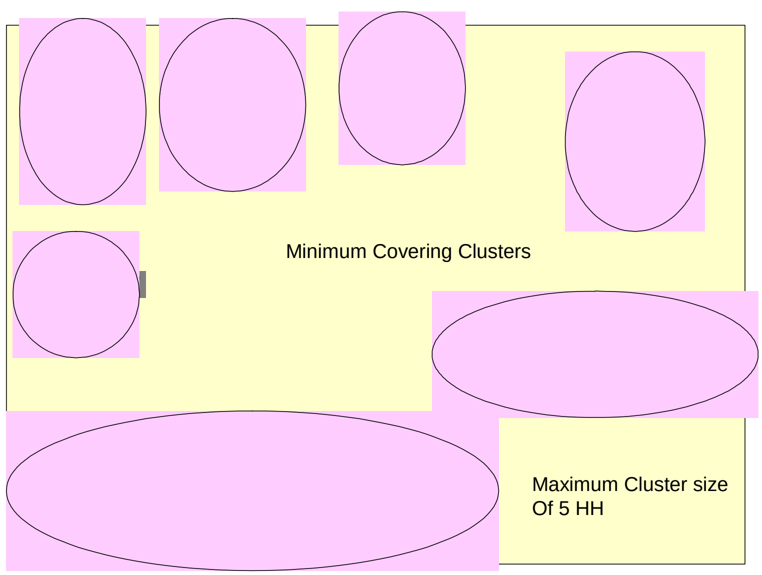
The deployment of the networks can be explained as in this section. Consider the area shown below. The dots indicate HH and the plot is an x,y plot grid. Now we desire to develop a fiber distribution network in a minimal cost way.



Let us further assume that we have a matrix showing the distance between all pairs of HH in this grid. This matrix is below.

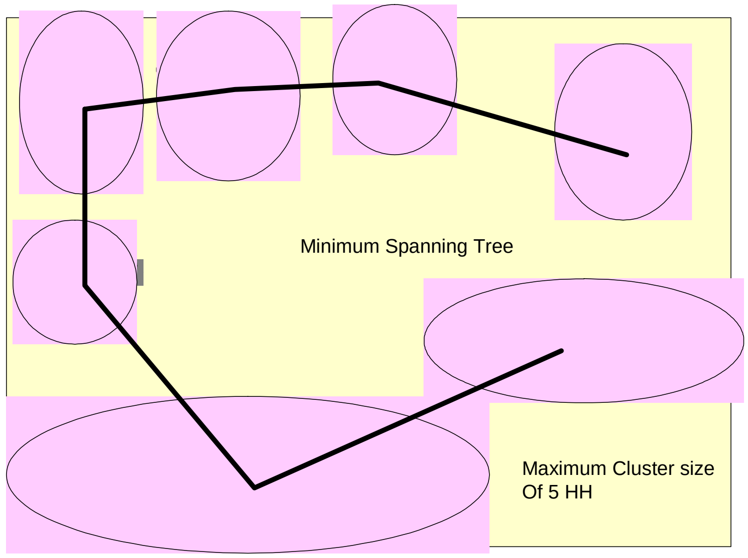
		From									
		1	2	3	4	5	6	7	8	9	10
	1		2	5	7	4	12	19	22	31	45
	2			5	7	9	12	33	23	12	9
	3				4	8	9	12	4	34	12
	4										
To	5										
	6										
	7										
	8										
	9										
	10										

Then we first cluster HH in a manner that satisfy: (i) no cluster can exceed the maximum capacity, in this case 5 HH, and (ii) each cluster has minimal distance between each HH in that cluster. This can be viewed as an artifact of the minimal spanning tree algorithm.[6] In fact we use the minimal spanning tree twice, first to establish the clusters and then to get the minimal span across clusters. We could easily do this for all nodes and reject the cluster approach.



The second step is then the minimal spanning tree for clusters. This is shown below. The distance in a minimal spanning tree, d^*, is the best we can do. It is substantially smaller than what we have calculated before.

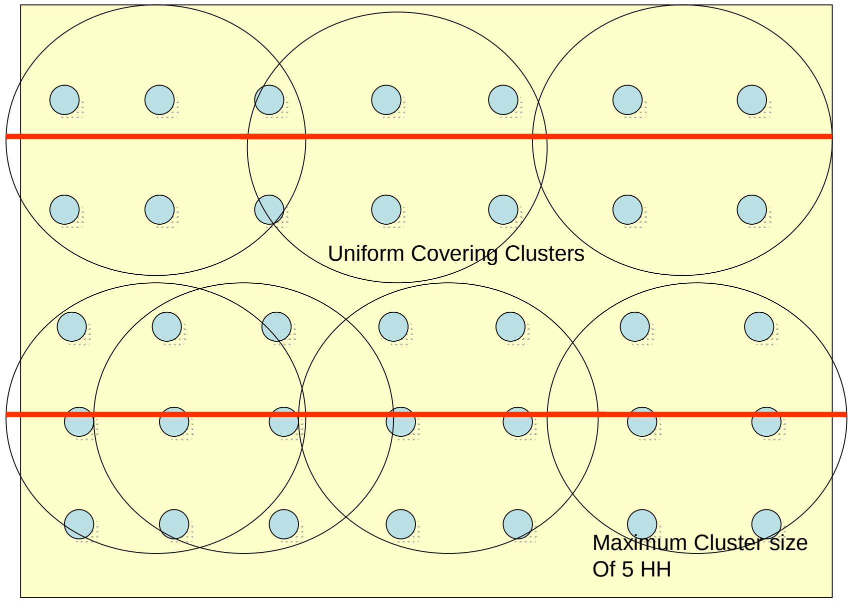
[6] See Tucker, Applied Combinatorics, Wiley 2004.



In our earlier analysis we took a town and divided it into sectors. Each sector has a certain population and area. Then we defined:

$$A_i = area\_\sec tor\_i$$
$$P_i = HH\_\sec tor\_i$$
$$D_i = \frac{P_i}{A_i}$$

We shall assume that the users are spread uniformly in a sector. This is an assumption that makes for the upper bound on distance for coverage. Then we know the maximum capacity per cluster in any sector and from that we obtain the number of clusters. We know the total are, area per cluster and then the diameter per cluster. We then merely add diameters up to determine a metric for the length of fiber backbone required. This is shown below. This calculation is a metric.



The analysis of the above is as follows:

The number of clusters is as follows:

$$N_{clusters,i} = \frac{P_i}{C_i}$$

The area per cluster is:

$$A_{cluster,i} = \frac{A_i}{N_{clusters,i}}$$

And the effective diameter of a cluster k in area i is:

$$d_{k,i} = \sqrt{\frac{A_{k,i}}{\pi / 4}}$$

Then for the sector i we have:

$$d_i = \sum_k d_{k,i} > d^{\min imum\_span\_tree}$$

The difference between the simplistic uniform and the actual minimal spanning tree, "MSP", approach depends on the density distribution of HH.

5 COST MODELS AND COMPARISONS

In this section we present a simple first order analysis of the capital per subscriber for both systems.

The following table presents this analysis for comparison along with the set of values for unit costs which we will use throughout. We have taken a static point of 25% penetration just to establish a base.

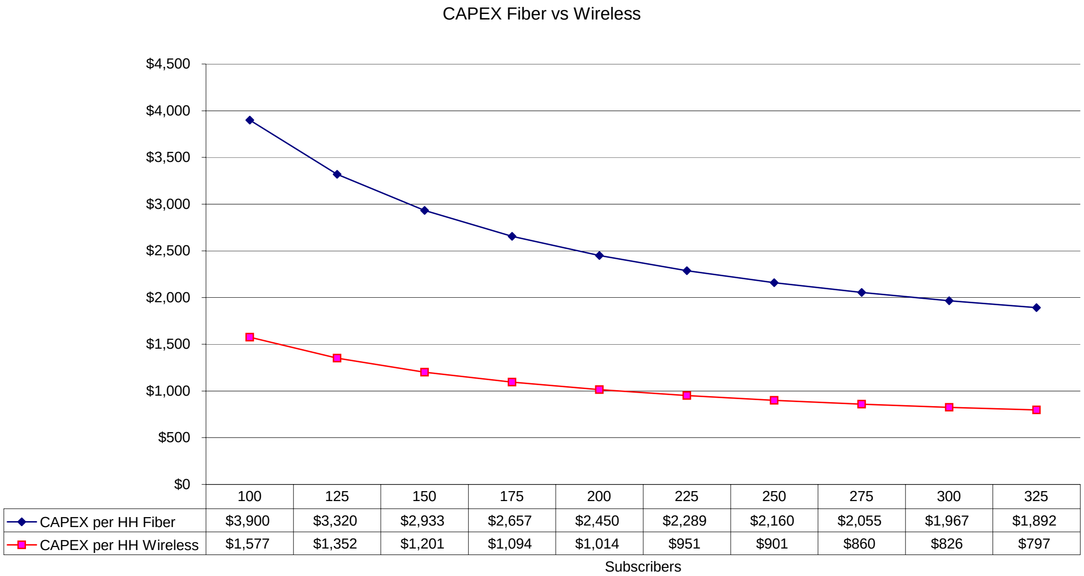
Element	*Comment*	*Fiber*	*Wireless*
Customers	Assume 4,000 subs with 25% target penetration. This is 40 HH per mile.		
Fiber Miles	Assume 100% coverage for fiber and 40% for wireless. Use baseline 100 miles.		
Fiber Cost	$25K per mile green field, plus $30K per mile make ready and $55K per mile buried. $37,500 per mile weighted fiber. $25,000 per mile by selection wireless.	$2,200	$1,000
Drops	$300 per HH fiber none for wireless	$300	
CPE	$500 per HH fiber $200 per HH wireless	$500	$200
Video	$200 per HH	$200	$200
Base Station	Assume $5 K per base station which is 802.16 target. Assume 20 HH per base station.		$200
License	We assume $40 per PoP, and we assume 2.5 PoPs per HH so we have an allocateble license fee of $400,000.		$400
Total		$3,200	$2,000

We now consider the sensitivity of the elements in the above table to customer penetration. This is shown below. In this analysis we have also use an MSP analysis rather than the upper bound from a uniform distribution assumption. Clearly the wireless design is always below that of the fiber design. There are several key assumptions we must be certain to clarify, specifically:

1. In all cases we have assumed that the license for dedicated spectrum is available. However in view of the small cell size and dramatically lower power requirement it is possible that this may be accomplished in a shared band. In that case interference must be added.

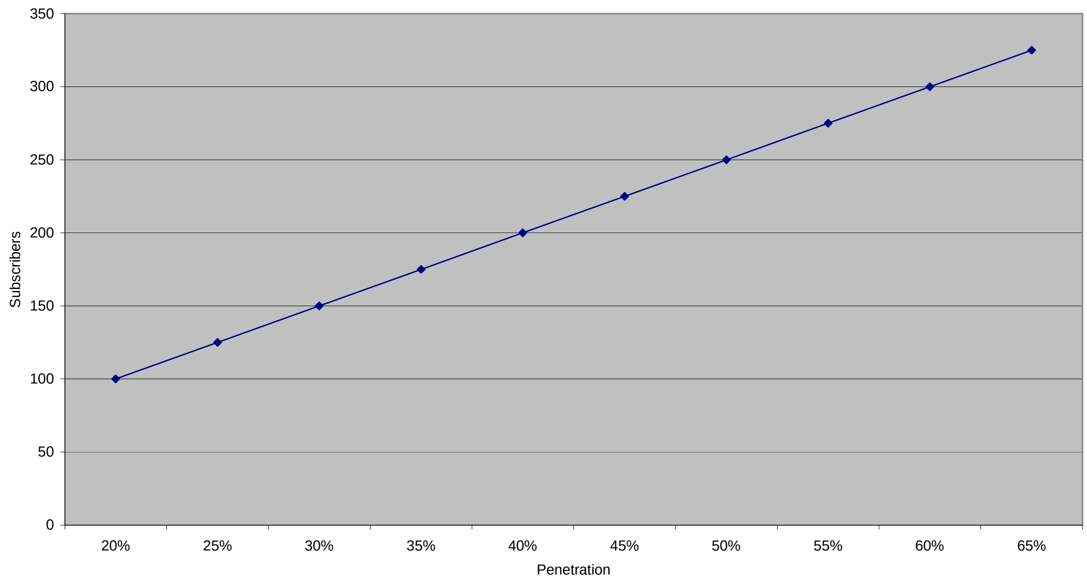
2. We have also assumed a $5,000 micro cell BTS for the site and that it is a full in cost. We have also assumed that such a BTS can be pole mounted and that it is operating always in a capacity limited domain. This may or may not be the case.

3. We have not assumed any cost reductions on the wireless equipment. The fact is that the CPE and the BTS will also see significant cost reductions as volume increases. This may result in further downward pressure on the capes for the wireless design.



	100	125	150	175	200	225	250	275	300	325
CAPEX per HH Fiber	$3,900	$3,320	$2,933	$2,657	$2,450	$2,289	$2,160	$2,055	$1,967	$1,892
CAPEX per HH Wireless	$1,577	$1,352	$1,201	$1,094	$1,014	$951	$901	$860	$826	$797

For clarity we have shown the relationship between penetration numbers and percentage in the above model. The sensitivity to overall density is also a concern.



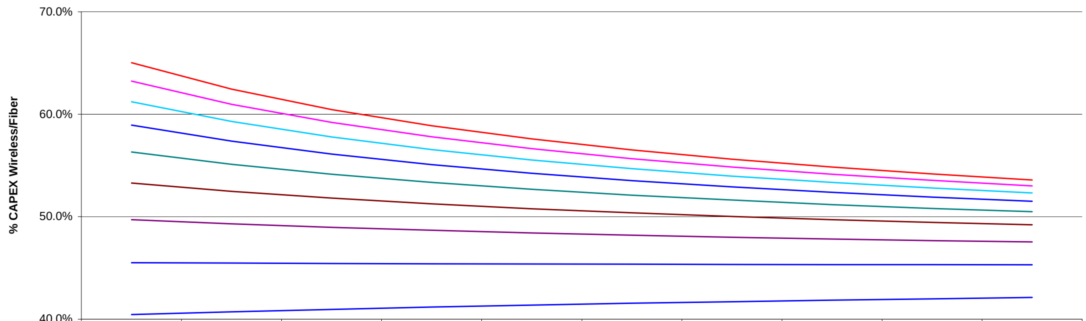
The following figure depicts the sensitivity of the ratio of capex for wireless to fiber. There are several interesting observations in this analysis:

1. At high populations the ratio is declining as the penetration grows. This means that wireless becomes more efficient at larger populations. However at low populations the ratio of wireless to fiber increases showing that wireless can become more costly, in a relative sense, as population decreases. Thus the relative analysis sows a generally lower costs but a significant level of sensitivity to user population.

2. There is some reasonable scale economies to this deployment for higher populations.

3. No matter what the design set in terms of user base the wireless design is always less expensive.

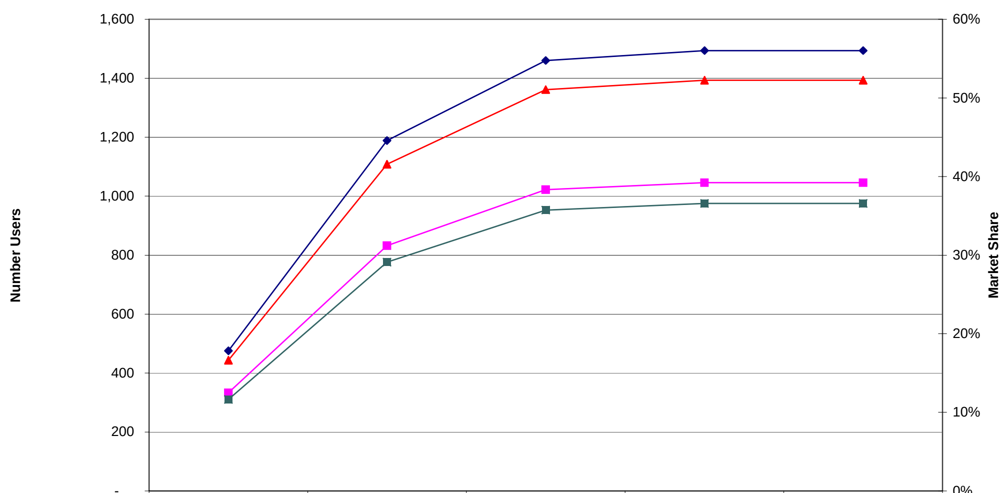
Seisntivity of Wireless to Fiber CAPEX/Sub



	20%	25%	30%	35%	40%	45%	50%	55%	60%	65%
100	26.4%	26.7%	26.9%	27.2%	27.5%	27.7%	28.0%	28.2%	28.5%	28.7%
300	34.2%	34.6%	35.1%	35.4%	35.8%	36.1%	36.4%	36.7%	37.0%	37.2%
500	40.4%	40.7%	41.0%	41.2%	41.4%	41.5%	41.7%	41.8%	42.0%	42.1%
700	45.5%	45.5%	45.4%	45.4%	45.4%	45.4%	45.3%	45.3%	45.3%	45.3%
900	49.7%	49.3%	49.0%	48.7%	48.4%	48.2%	48.0%	47.8%	47.7%	47.5%
1100	53.3%	52.5%	51.8%	51.3%	50.8%	50.4%	50.0%	49.7%	49.4%	49.2%
1300	56.3%	55.1%	54.1%	53.3%	52.7%	52.1%	51.6%	51.2%	50.8%	50.5%
1500	58.9%	57.4%	56.1%	55.1%	54.2%	53.5%	52.9%	52.4%	51.9%	51.5%
1700	61.2%	59.3%	57.8%	56.5%	55.5%	54.7%	54.0%	53.3%	52.8%	52.3%
1900	63.2%	61.0%	59.2%	57.8%	56.6%	55.7%	54.9%	54.2%	53.5%	53.0%
2100	65.0%	62.4%	60.5%	58.9%	57.6%	56.5%	55.6%	54.8%	54.2%	53.6%

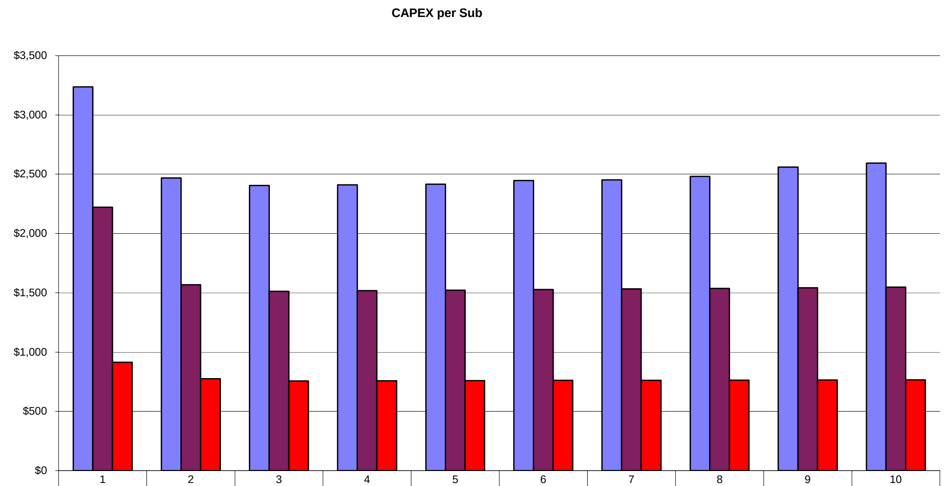
Penetration

We have also performed very detailed designs for multiple systems and this results contained herein demonstrates that. The following is s brief example of the results from a detailed design for a fiber system. First we show the penetration assumptions,



	1	2	3	4	5
Number Users Broadband Internet	475	1,189	1,460	1,494	1,494
Number Users Basic Video	333	832	1,022	1,046	1,046
Broadband Penetration %	17%	42%	51%	52%	52%
Basic Video Penetration %	12%	29%	36%	37%	37%

Now we demonstrate the detailed capex per subscriber for the fiber design. In this case we have also separated the fiber elements and the electronic element. The rule of thumb for wireless is that the fiber is generally 25% of the fiber in an all fiber design for the backbone and then the per user costs can be added on top. The rule of thumb analysis is generally a fairly robust approach to the design.



	1	2	3	4	5	6	7	8	9	10
Total CAPEX per Sub	$3,235	$2,467	$2,405	$2,410	$2,416	$2,446	$2,453	$2,481	$2,559	$2,595
Fiber CAPEX per Sub	$2,221	$1,567	$1,512	$1,517	$1,522	$1,527	$1,532	$1,537	$1,542	$1,547
Elec CAPEX per Sub	$915	$776	$756	$758	$759	$761	$762	$763	$765	$766

6 CONCLUSIONS

Our objective in this paper is to demonstrate that a wireless design for a broadband application, including video, was achievable and further that it was economically more viable than a fiber only design. To ascertain the major conclusions let us summarize several of the key assumptions:

1. Spectrum is available: This is key, no spectrum no wireless. Thus we must have dedicated or shared spectrum. This means that if it is dedicated that we can obtain it and at some reasonable price. If shared that it will not cause interference or drive us to a coverage domain which becomes uneconomical.

2. Video can be provided: We have assumed MPEG 2 IP video and that the links in a wireless system can support this. We have also assumed a certain usage pattern which may be too low thus driving up the costs.

3. BTS deployment is achievable and BTS costs are reasonable for microcell deployment: We have assumed that the BTS is at a rice point making it a fraction of the total capex and that further the BTS can be deployed readily on the available right of way.

4. Operating costs and their differences between fiber and wireless are no consequential: We have performed detailed analyses of the operating costs and this assumption seem correct.

The key results from this analysis are:

1. A simple model for design comparisons is achievable for the combined system.

2. An optimized fiber backbone can be obtained using a simple analysis of the user locations.

3. Mobility can be achieved in a wireless system thus enhancing services and making it distinctively different that a fiber, cable, or telephony based approach.

4. Fiber backbone is essential. Meshes or grids will not have the capacity handling required for video.

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