# Wireless vs Fiber: Who Is The Winner

The competition between wireless and fiber has become more intense over the past few years. In addition it can be seen in the actual deployment of fiber that companies such as Verizon have limited the deployment to high end business applications and also to the inter-connection backbone for the wireless plant. This paper examines the changes in the technology that allow for potential deployment of an all wireless plant for both residential and commercial usage. The reasons for such a change are several fold; technological, operational, and financial. Our conclusion is that technology has progressed in wireless at a high competitive manner and that bandwidth is readily available. Using wireless may now be the means to provide voice and data as well as bandwidth intensive uses such as video as well. 

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# 1 INTRODUCTION

Fiber has been considered a technology which can support almost any amount of bandwidth desired. It has become the workhorse for backbone networks and for all business date intense applications. However the entry into the consumer market has been mixed. In the early 2000s we had pursued a broad based approach to fiber to the home focusing on extra-urban markets. We saw that fiber could provide a triple play offering and as such there may be adequate revenue to provide reasonable returns assuming a modest market penetration of 25% or more.

However, as we soon discovered, the costs we had understood were to be burdened by costs we had not envisioned, namely the franchise process. Thus the capital requirements were almost dominated by franchise procurement costs and not the physical laying of the fiber. We soon saw that the incumbents were facing the same problem. The barrier to entry was the cable company and surprisingly the towns themselves who saw this as revenue grab, with no understanding of the economics involved. Towns demanded almost 100% coverage, albeit with the cable incumbent at no more than 75%, and in addition they demanded universal service, namely free service for those below a certain income level, as well and free local fiber which they could resell with no payment to the company who provided it.

At the other extreme is the evolution of wireless, especially in the area of broadband. There are several key changes in this technology:

1. The key metric in wireless has been the bandwidth efficiency, namely the bits per second carried by an Hz on bandwidth. Classically we were limited by about 1 bps/Hz. Thus 20 MHz carried 20 Mbps. But that limit was due to silicon, which continued to evolve so that today we can readily do 10 bps/Hz.

2. Cellular Systems allow for multiple cell reuse. This of course has been around for a while and we generally get say 3:1 reuse or some other factor. Not a great deal has changed here.

3. Video Compression has allowed video, especially HD video, to be transmitted at 4 Mbps rather than 100 Mbps. Thus using H.264 and H265 we can attain great compression which maintaining quality.

These changes alone show three trends:

First, bandwidth can carry higher data rates than ever before. Thus capacity is expanding. The expansion is quite considerable. As the Chairman of the FCC has recently stated in the Wall Street Journal[1]:

*Smartphones, tablets and other wireless devices all rely on spectrum-the airwaves that transmit bits of information to and from these mobile marvels. Think of it as the country's invisible infrastructure. Spectrum is finite, and the demand for airwaves being created by data hungry,*

[1] WSJ, 6 March 2013, Julius Genachowski Editorial.

*Internet connected devices is on pace to exceed supply. How significant is the spike in demand? Today's smartphones generate 50 times more mobile traffic than a traditional cell phone. For tablets, it's 120 times more traffic. As a result, American wireless networks are running at the highest utilization rate of any in the world*.

That growth in demand for usage does not mean that the bandwidth should grow the same amount. In fact is quite the opposite. First, with 4G LTE and OFDM we have 10 time the capacity in existing bandwidth. Furthermore with enhanced coding of video and images, as well as the more smoothed out traffic characteristics of data versus voice, we attain a more efficient system. The FCC Chairman, as one would expect, fails to understand the technical aspects.

Second, the data demands per service are decreasing due to advanced compression so that the demands on capacity per usage are decreasing. This means that we have technology which can compress data demands. We need not use massive amounts of bandwidth of the services provided, we can compress them.

Third, the number of services and number of users are expanding exponentially. This benefits the networks by spreading out the traffic demands in a much smoother manner. Typically with voice we would see less than 5% of the available bandwidth used. The reason is that voice is quite peaked, and cannot be smoothed out. Video surprisingly can be smoothed out and data clearly can. Thus we can expand services with no significant demands in bandwidth using such integrated usage algorithms.

Fourth, we are learning how to better use networks as integral parts of our overall data utilization methodologies. They are no longer just means to get from point A to point B but they become added sources of data enhancement and bandwidth demand reduction using such technologies as Network Coding.

Thus the revenue potential is driven by users and services, while to costs are driven by capacity per unity bandwidth. The above shows that the trend in wireless is higher revenue at lower costs. This was not anticipated two decades ago when the wireless revolution first took hold.

This paper examines the following:

1. The evolution of the bandwidth usage paradigm between wireless and fiber. We argue that many if not most applications can be handled more than adequately with an all wireless network. Fiber we argue is too costly, too over-burdened with political overhead and too over-influenced by the incumbents, especially CATV providers. One can envision all wireless infrastructures, devoid of expensive labor costs and devoid of local franchise burdens.

2. We examine several key questions whose answers lead us to examine new technologies. The intent is to find large scale technical opportunities for investment and development.

3. We examine several technologies, some more developed than others, but all allowing for dramatic expansion of wireless networks and all potentially offering significant upside revenue potential.

## 2 PRIOR WORK

Some twenty-one years ago or more I had written extensively on the deployment of wireless for data and voice.

Specifically in my 1992 application for a Pioneer Preference at the FCC I had proposed continuing work specifically on the following, taken directly from my FCC filing[2]:

*The following technological approaches will be deployed, integrated, tested, and optimized to determine their effectiveness in providing the specified service quality goals.*

*1. Adaptive Network Management: Adaptive Network Management, ANM, is a system that uses in-situ sensors to monitor the power and signal quality throughout the network. The number of sensors will greatly exceed the number of cell locations. This set of dynamic measurements will then be used in a feedback schemes to adaptive change the characteristics of the cell transmit power and other characteristics to maximize the service quality. Specifically, the Petitioners have individually designed a proprietary network management system that uses the in-situ sensors that monitor all key signal elements. These elements are power, frequency, interference, noise, and other significant signal parameters. The system then transmits these signals back to a central processor which then generates an optimal signal to control the cell site transmission characteristics, such as power, frequency and other factors. The overall objective is to optimize the system performance from the user's perspective.*

*2. Gateway RF Digital Front Ends: A broadband, digital front end will be used to act as a gateway to interface the air interfaces of CDMA, TDMA and other access methods through the same cell and in the same frequency band. This system will permit multiple air interfaces to be gateway into the same network access point thus reducing the need for a single standard, and increasing the ability to provide a national network. This front end has been developed by Steinbrecher Assoc, of Woburn, MA. The system element allows, through its use of large gain bandwidth product front end and fully digital RF processing, the ability to handles many different and simultaneous multiple access methods, such as TDMA and CDMA. This ability goes to the heart of interoperability and standards. CDMA Backbone Network: The Petitioner will use a CDMA air interface and access methodology. The Petitioner fully supports the efforts of QUALCOMM in their development and implementation of CDMA in the 800 MHz band and their recent movement of this to the 1.85-1.90 GHz bands. Although there is no uniqueness in the use of CDMA, the Petitioners argue that this technology has specific characteristics that allow for the delivery a maximum benefit to the public.*

*3. Co-Located Distributed Switch Access: Unlike other proposed schemes which use redundant MTSO accesses, this trial will focus on Central Office Co-Location methods that reduce capital and operating cost redundancies. The co-location approach will minimize access line costs and eliminate the need for a MTSO. The adjunct processors at the Central Offices will*

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[2] FCC Pioneer Preference Filing, May 3, 1992, by Telmarc Telecommunications.

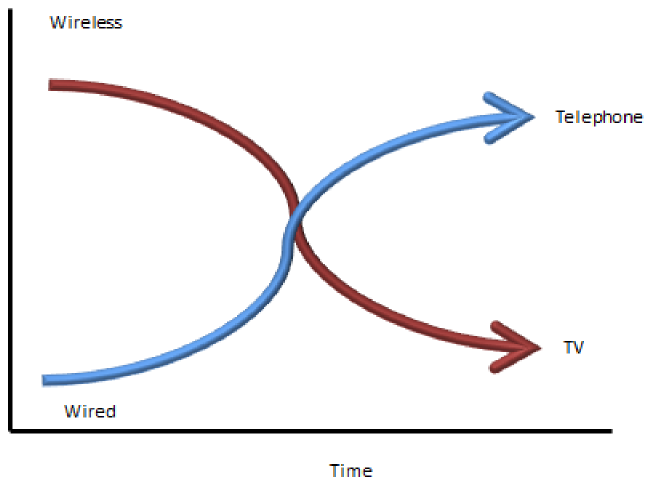
*be interconnected by a high speed bus to allow for adequate control and call hand-off. Co-Location is achieved via the intelligence that is contained in the CDMA cell sites and the adjunct processor distributes communications and processing capabilities. The fundamental existence of this capability was demonstrated by QUALCOMM in their CDMA trial, albeit not in the Co-Location context. The QUALCOMM QTSO was in effect a no Co-Located adjunct. The Petitioners propose to request access from the PUC in the Commonwealth of Massachusetts to access New England Telephone on a Co-Locations basis. The public good achieved is through the reduction in costs and the ability to use existing capital assets provided by the LECs. The uniqueness of the Petitioners proposals are the fact that extensive use of adjuncts will be made in the system operation.*

*4. Adaptive Beam Forming Phased Array Technology: One of the current problems with a cellular systems will be the use of broad beam antennas and the inability to provide additional antenna gain on both transmit and receive to the individual portables. With the use of adaptive beam forming antennas, the service to lower power portables may be improved. The Petitioners approach will include such capabilities. Time dynamic control of these multiple bean antennas will permit higher localized gain on portables, which will in turn allow for lower transmit power and thus longer portable battery life. The Petitioners have been discussing the use of the technology developed at the Massachusetts Institute of Technology's Lincoln Laboratory in this area.*

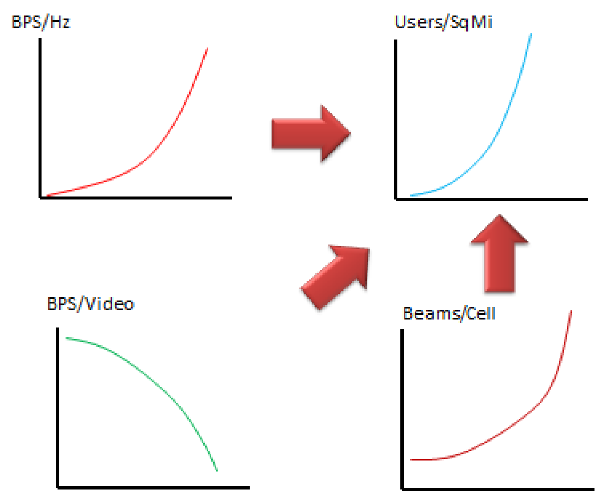
Some of these have been deployed but some still are nascent but can be technological breakthroughs requiring implementation. We will demonstrate that the advances we had proposed at that time have to some degree been advanced but that they still present significant opportunities for further advance in such markets.

## 3 BANDWIDTH AND THE NEGROPONTE SWITCH

About 20 years ago Prof Negroponte published his switch concept: simply TV would go from wireless broadcast to fiber and telephony would go from copper wires to wireless. We show the idea below. The idea was that TV which was being broadcast would move to fiber, or “wired”, in the Negroponte context, and that voice which was “wired” on copper lines would move to wireless.




But what has really happened? The graphic below details the changes.



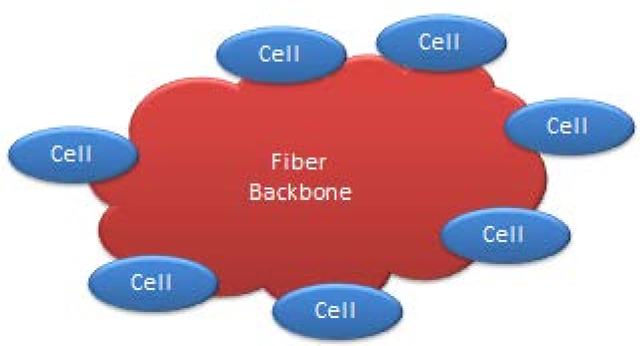

Namely:

1. Bandwidth efficiency has changed dramatically. QPSK/CDMA led to OFDM, which is why Qualcomm bought Farinon, and we saw BPS/Hz gone from 1 to 10. Can this continue? We suspect so, there is a Shannon limit but that is driven by signal strength and noise and bandwidth. OFDM starts to approach such a limit but only for existing antenna configurations. Thus if we change the antenna configuration as we shall demonstrate we can again push this limit.

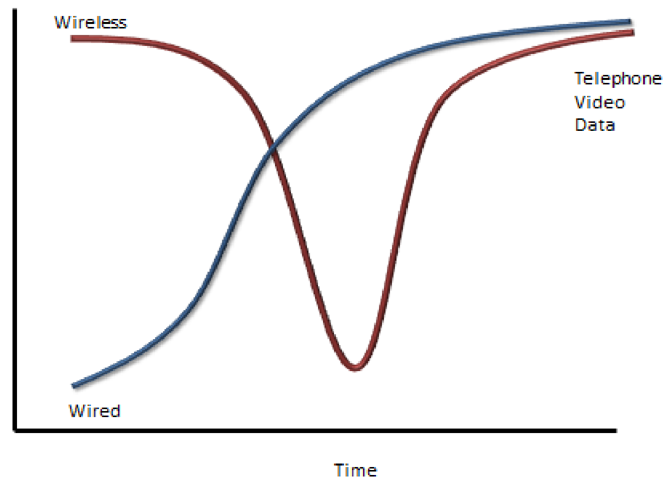
2. Video codecs have brought down HDTV from 200 Mbps to 2 Mbps. Compression algorithms like those in H.264 and H.265 provide significant quality at low bit rates. Using integrated IP video, enabled by these protocols, will allow us to push the envelope. Add to this the use of network coding and we obtain low data loads on higher capacity links

3. Multi beam antennas have allowed beam pointing per subscriber. Although implemented in a limited fashion, this allows not only cell re-use but increased power per user. The key issue here is where is the user; mobile or fixed. In addition it depends on the degree of mobility, fast or slow.

The result, the number of instantaneous, yes I mean instantaneous, video channels per user can explode to exceeding high numbers. How:




Stick fiber in the backbone and wireless at the edge, all IP. The we have the re-switch as below:




This shows the Negroponte switch goes back on video, namely video for the "last mile" can be all wireless, and yes with the same or even less spectrum.

# 4 PROBLEMS AND TECHNOLOGICAL OPPORTUNITIES

There are still many problems that exist in the telecommunications world. Problems lead to opportunities when solved technically. We first address some of these problems and then present the technologies.

## 4.1 HOW CAN MANY USERS EFFICIENTLY ACCESS WIRELESS SPECTRUM IN A REAL TIME MANNER WITHOUT HAVING A CENTRALIZED SPECTRUM REGULATORY BODY?

The use of spectrum is controlled by the FCC or other regulatory bodies. The policies for the allocation of spectrum follow concepts of 12th century property rights. That is if you are given rights to use spectrum then you have those rights for say period of time and the spectrum is your property, and no one else can have access to it. If there is an intruder the enforcer is the FCC. Owning spectrum was a barrier to entry to any new competitor.

However, most spectrum lays fallow. Even cellular spectrum, in many parts of the United States is unused most of the time. For years this was not as problem since there was neither the demand nor the technology to utilize this unused spectrum. Now, however, technology can allow us to use it, in a non-interfering manner, and the demand for spectrum is growing in a near unbounded manner.

In 1993 there was an article by a popular writer, George Gilder, who before the dot.com bubble burst, was viewed as the seer of all technology. Gilder looked at spectrum and said that it should be shared.[3] He used the paradigm of the Qualcomm CDMA technology to argue for the existence of technology to do it. In response to Gilder, I and Prof Medard wrote a policy/technology paper in 1994 which addressed the Gilder conjectures.

Let me return to what we said in 1994 about Gilder. Gilder's conjectures were as follows ad our comments at that time followed as well:

***"(1) Many Users can occupy the same spectrum at one time.*[4] *There exists a well-defined set of protocols that allow this and prevent collisions.*[5] *There further exists a set of workable multiple access/interface technologies that can be interchangeably used.*[6]**

*Gilder assumes that there is a well-developed technology base that can be operationally available and that permits multiple systems to operate simultaneously and that the industry as a whole has agreed to how best to handle the interference problem."*

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[3] Gilder, G., "Auctioning the Airwaves", Forbes ASAP, April, 1994, pp. 99-112.

[4] Gilder, p. 100.

[5] Gilder, p. 112.

[6] Gilder p. 112.

Gilder was at that time looking to CDMA as the enabler. He failed to understand that CDMA had limitations and that he was stretching a bit too much. However, looking back he had a point, one which said that if we could develop a set of protocols then many users in a relatively free and open environment can share spectrum. Thus Gilder may eventually be correct if we were to interpret his prognostications on future inventions.

***"(2) Frequency and modulation/multiple access schemes are utterly unnecessary.***[7]

*Gilder assumes that worrying about the technical details such as modulation and multiple access is a secondary factor, at best."*

This is an interesting conjecture. Again we have over the past fifty years been looking at the physical and what we now call the MAC layers as the place to do battle with access to spectrum. Perhaps we are looking at the wrong place. Perhaps the battle should be at a higher layer or at some new place.

***"(3) Networks can be made open and all of the processing done in software.***[8]

*Gilder assumes that hardware is de minimis in terms of its interaction with the operations and that all changes and operational issues are handled in software."*

***(4) Broadband Front Ends replace cell sites in functionality at lower costs.***[9]

This conjecture is based upon the Steinbrecher hypothesis, namely that some simple device can replace all of the features and functions of a cell site, such as network management, billing, provisioning, and many other such functions.

***(5) It is possible to manufacture spectrum at will.***[10] ***Spectrum is abundant.***[11]

This conjecture assumes or posits that spectrum can be "created" de novo from a combination of what is available and the technological "productivity" gains.

***(6) Spectrum can be used any way one wants as long as one does not interfere.***[12] ***New technology makes hash of the need to auction off exclusive spectrum; spectrum assignment is a technological absurdity.***[13]

[7]Gilder, p. 104.

[8]Gilder, p. 104.

[9]Gilder, p. 110.

[10]Forbes, p. 27.

[11]Gilder, p. 100.

[12]Gilder, p. 111.

[13]Forbes, p. 27.

The last conjecture is the one that says that given the above five conjectures, spectrum can be used in an almost arbitrary and capricious fashion, allowing the assumed technology to handle the conflicts, and not having to have the FCC handle the conflicts via a spectrum allocation process. The last Gilder conjecture states that technology obviates the needs for spectrum allocation of any form.

Specifically there are several available bandwidth spectra available but using different modulation and multiple access schemes. The details on all of these systems are known or can be readily known to the user. The user now wants to create an amalgam of these disparate elements and provide to itself what would appear as a single broadband channel.

How then do we make this work? This is the technical challenge. Several technical questions arise:

How do we look into the multiple spectra and determine what the PHY/MAC or similar protocols are? How do we determine how to talk with the cloud? This is a physical and logical question. We need some form of broadband radio which can then interpret with a minimal data set what it needs to talk and then to do so.

How do we know who has capacity and whether it is useful for our application?

How do we negotiate with the other users and owners of spectrum in a real time fashion creating what might best be called a micro transaction? What compensation do we provide and who and how is all of this kept track of?

What is the performance gain achieved by this process. What are the roadblocks in the delivery of the ultimate performance levels? What are the optimal processes for the execution of this approach?

What functions are performed by the elements of an architecture and how well do we have to perform them. A suggestion is the following:

1. Assess: Determine who is out there and what capacity they have
2. Demand: Determine what capacity is needed now
3. Authenticate: Check entities in domain and determine who is trusted
4. Bid: Enter into auction with entities in domain for capacity
5. Assign: Assign capacity to source entity to meet demand and resulting from auction
6. Manage: Coordinate multiple simultaneous demands between entities and self-entity
7. Pay: Conclude payment for capacity
8. Clear: Clear resources when no longer needed

The next question is where do we perform these functions? Clearly they are not PHY/MAC functions since this would require massive changes to a plethora of PHY/MAC implementations and frankly they would not function well there. They are not IP nor are they TCP related functions. We suggest layer 5, the session layer. This can be shown below. Specifically they become shareable applets which can be placed at this layer and sent back and forth amongst users employing the TCP/IP fabric.

There are now several key questions which can be posed:

1. What is the capacity in terms of say data carrying which a single network can effect with n users distributed in various locations?[14]

2. What is the capacity of an interconnection of disparate networks?

3. What schemes can be developed to maximize throughput?

4. What changes can be made to the architecture to optimize internetwork flow?

5. What optimizations can be made on each of the functional elements, what are their limitations?

## 4.2 HOW CAN ONE CREATE A BANDWIDTH ON DEMAND MARKET SO THAT EXCESS BANDWIDTH, WIRED AND/OR WIRELESS, CAN BE INTERCONNECTED BY ANY USER(S)?

Bandwidth is typically provided on a determined amount basis. The "pipe" providing the backbone or local access is engineered to allow a certain amount of capacity. Total capacity is backbone limited and end user capacity is last mile, foot, or inch limited. If we can provide a Gbps or Tbps backbone, then how do we extend that flexibility to the end user? If some users have multiple connections, can we integrate them, can they be used in a manner which allows a perception of integrated bandwidth, or must we allocate on path by path.

## 4.3 HOW CAN ONE HAVE ACCESS TO A REASONABLE AMOUNT BANDWIDTH ANYWHERE IN THE WORLD AT A REASONABLE PRICE?

Rural and third world access to broadband is something that is quite limited. Fiber to users is not reasonable and wireless using terrestrial coverage is also potentially quite expensive. This has always been the opportunity for satellites. The low earth orbit satellites ("LEO"s) were often thought of being the solution. However they never truly materialized for a variety of reasons. Again the question is one of using shared wireless as we have discussed above. This may be possible in conjunction with some form of a satellite solution. Are there others?

## 4.4 HOW DOES A FULLY MULTIMEDIA COMMUNICATIONS SYSTEM OPERATE SO THAT ANY COLLECTION OF USERS CAN COMMUNICATE IN A FULLY INTEGRATED AND INTERACTIVE MANNER (E.G. USING AS MANY SENSES AS POSSIBLE AND IN A CONVERSATIONAL MANNER)?

Multimedia communications is a bit messy. It is not sending bits back and forth, there are no zeros and ones, and it involves humans communicating with each other in groups. It is not just

[14] See the paper by Gupta and Kumar, The Capacity of Wireless Networks, Univ Illinois.

the Internet with a video link and audio. It is a great deal more, it is conversationality and community and using whatever senses are available. Multimedia communications is creating an experience in displaced communications.

Clearly true broadband should be the facilitator for this effort of multimedia communications. But a true broadband is just a part of the solution. We need to develop that concept of displaced conversationality.

## 4.5 HOW DOES ONE CREATE THE MOST EFFECTIVE BROADBAND LOCAL INFRASTRUCTURE AND WHAT ARE THE MEASURES OF THE EFFECTIVENESS?

Are local networks nothing more than mini Internet backbones or are they mini-Internets or are they nothing more than last mile connectors to the real Internet. What is the local network and is it one thing or many, is it one technology or many, is it open or is it proprietary?

There is a great deal of fundamental questions regarding local broadband networks. The first is generally the question of how fast. The development of the Internet was a gradual process with the initial driving factor being connecting university and government computer systems. The first set of computers was well defined and the evolution was controlled by a small group of collegial designers.

The local broadband infrastructure we now envision is being developed in a highly contentious environment; ILECs fighting with cable companies and again destroying any new entrant. Cable companies have no interest in asking what the best architecture is, it is a CATV system slowly changed to maintain monopoly control. The ILECs no longer have any R&D groups and thus rely on whatever the vendors pitch at them. Thus there is no independent thinking about what the "best" network architecture should be. There is no Bob Kahn and Vint Cerf; there is no group at MIT, USC, Illinois, talking through the issues based upon intelligent give and take. Add to this is the fact that the FCC, the main regulatory body is generally clueless about what this means, it is managed by lawyers and there is no venue for open technical or even business discussions.

## 4.6 HOW DOES ONE INTERCONNECT DISPARATE NETWORKS (WIRE AND WIRELESS) IN A REAL TIME MANNER AND WITH DE MINIMIS COSTS OF INTERCONNECTION?

Enron is a known economic and business fiasco from the dot.com period. Hidden in the Enron story was an attempt to create a real time market for bandwidth. Energy, electric power, is fungible but is a commodity that can be traded back and forth. It is like corn, but unlike corn cannot be stored, it has to be used when generated. Like corn it is the same everywhere, power companies can connect to the "grid" and down load their desired amounts. In any time sensitive commodity market there is a secondary; call it derivative, market which deals with futures and future contracts. I can enter into an agreement for a price to be assured that I will have so much power at such and such a time at such and such a price. It costs me but I know it is there. Thus the futures help to stabilize the market by smoothing out fluctuations by compensating people for standby power, albeit it may never be used.

Bandwidth is the same. If I have 150 Mbps bandwidth I have used it or it goes away.

### 4.7 How does one provide a communications environment which establishes a level of privacy and even anonymity while allowing protection from abuse and threat?

Privacy, unfortunately, is not a Constitutional right delineated in the US Constitution or even the Bill of Rights. The penumbra, shadow, of privacy was constructed by the Supreme Court for reproductive rights but there the coverage seems to end. Furthermore the right to be left alone, as stated by Justice Brandeis in the famous Weaver and Brandeis paper, is just a wish, and anonymity does not exist. In today's world, created out of the slaughter of innocents, decimates any sense of privacy and destroys any attempt at anonymity.

### 4.8 Summary

| *Question* | *Technology*<br>*Some Questions of Interest* | *Regulatory*<br>*Barriers to Implementation* | *Market*<br>*Incentives to Implementation* |
|---|---|---|---|
| ***How can many users efficiently access wireless spectrum in a real time manner without having a centralized spectrum regulatory body?*** | What is capacity of a multi-element wireless network?<br>What are the optimization criteria for a multi-element network?<br>How can the session layer approach be implemented/optimized?<br>If nano-transactions are effective, what are the optimal nano-transaction mechanisms?<br>How do you implement a multi-element gateway for optimal performance?<br>How does one use a software defined radio to affect this approach? | FCC issues exclusive licenses, how can the regulatory body provide incentive for sharing? | **Incumbents want to protect their assets; can this be monetized to be in their best interest?** |
| ***How can one create a bandwidth on demand market so that excess bandwidth, wired and/or wireless, can be interconnected by any user(s)?*** | How does one create a universal networking gateway between all networks and users?<br>Is the layered architecture a basis for inerrability or is some other paradigm more appropriate?<br>If such a network is implemented, how does one manage such a network?<br>How does one implement the last mile? | International regulatory bodies have control of carriers. Trans-border issues are also a concern. | **Incumbents want to control end to end but this is not totally affected in current markets.**<br>**Customers want this very much and at a premium.** |

| *Question* | *Technology Some Questions of Interest* | *Regulatory Barriers to Implementation* | *Market Incentives to Implementation* |
|---|---|---|---|
| ***How can one have access to a reasonable amount bandwidth anywhere in the world at a reasonable price?*** | What is the maximum coverage and capacity for a wireless network?<br>How can wireless grids be combines using satellites to provide large area coverage.<br>How does one optimize the TCP/IP capabilities in a fully integrated grid using satellite elements? | Regulatory bodies specify who can be a carrier and demand licenses. There is a limit to creating a market.<br>Last mile extensions are typically the most costly and of greatest delay because of local ordinances. | **Low earth orbit satellites were shown to be uneconomical compared to their expectations; the time constants of satellites exceed that of the network technologies. How can satellites be part of an integrated global network?** |
| ***How does a fully multimedia communications system operate so that any collection of users can communicate in a fully integrated and interactive manner (e.g. using as many senses as possible and in a conversational manner)?*** | How does one model a multimedia communications network (e.g. Petri nets?)<br>Can a multimedia network be built on top of the web or does it require a full new fabric?<br>Is the session layer the correct approach to establishing multimedia sessioning, if so what are its performance factors and how can it be optimized? If not, what is? | This may be a standards issue rather than a regulatory issue. | **This may have a sweeping change on distribution channels in many product and services areas and as such may be viewed as a threat to entrenched players.** |
| ***How does one create the most effective broadband local infrastructure and what are the measures of the effectiveness?*** | Is there a fundamental difference between a local broadband IP network and an international broadband backbone IP network, if so why and what are the optimality criteria? | Franchise control delimits anything done locally. There is 30K or more franchising entities and if the product is in any way video enabled then it requires local contractual approval. | **This could be threat to incumbents and local towns themselves may want to play in this area.<br>It also competes with Internet backbone players by creating a new Internet outside of the existing Internet.** |
| ***How does one interconnect disparate networks (wire and wireless) in a real time manner and with de minimis costs of interconnection?*** | What are the optimal uses of optical, broadband and conventional signalling processors in a multi element wireless fabric?<br>What are the optimal uses in a multi element wireless network for optical signal processing elements?<br>What are the tradeoffs between broadband and optical processing, how can they be optimally integrated?<br>How does one create a real time software configurable gateway between disparate fiber networks? Can this be done on an on demand basis, on an auction basis, and what are the optimality criteria? | Interconnection and access is controlled by the FCC and all regulatory bodies. The incumbent defines the entry costs. The FCC is generally clueless about opening this interface. | **Incumbents have strong vested interests.** |

| *Question* | *Technology*<br>*Some Questions of Interest* | *Regulatory*<br>*Barriers to Implementation* | *Market*<br>*Incentives to Implementation* |
|---|---|---|---|
| ***How does one provide a communications environment which establishes a level of privacy and even anonymity while allowing protection from abuse and threat?*** | **How does one design an anonymous communications network?**<br>**How does one design an anonymous transaction network (e.g. cash purchases without video cameras to blind salespersons)?**<br>**As with encryption, how can authentication and anonymity are balanced, are there analogs?** | **Federal law is a major block to entry since September 11th.** | **There are demands to protect identity from theft but not clear that this is the way.** |

# 5 KEY TECHNOLOGIES

Technology has always been the driver for enhancing wireless. Having discussed some of the problems we now present some suggested technologies which are implementable and enhanceable in the next decade. Currently all of these can be shown to work. However commercialization and integration of them will lead to significant advances.

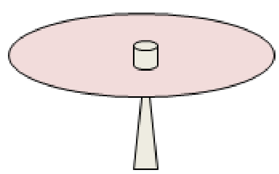
## 5.1 OFDM

OFDM is a classic modulation and multiple access methodology which was theoretically optimum but practically impossible when it was conceived some forty years ago. However with the advent of low costs and exceptionally high capability silicon chips this has no longer been the case and the LTE or $4^{th}$ generation wireless systems use this technology.

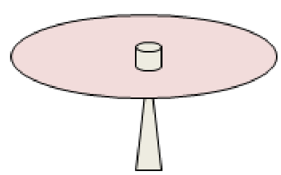
## 5.2 MULTIPLE BEAM ADAPTIVE ANTENNAS

Let us consider three antenna schemes.

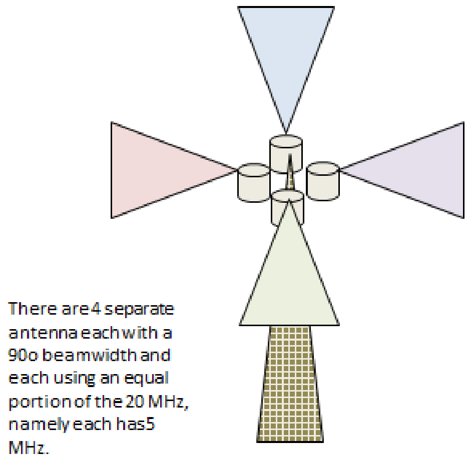
First let us consider a classic case of an omnidirectional antenna. It covers $360^{o}$ and transmits the full 20 MHz signal everywhere. This is like a classic radio station or TV station antenna.



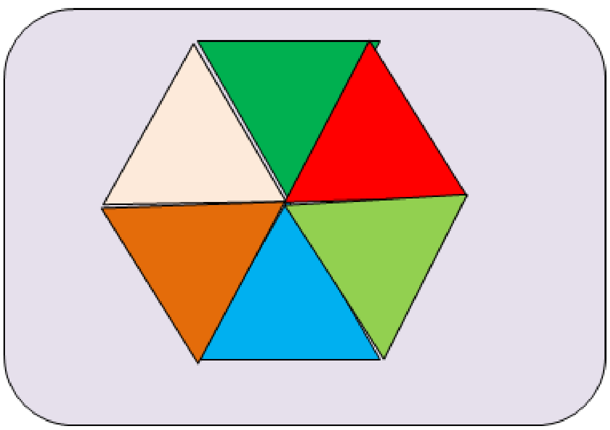
360° Antenna coverage with full bandwidth, say 20 MHz



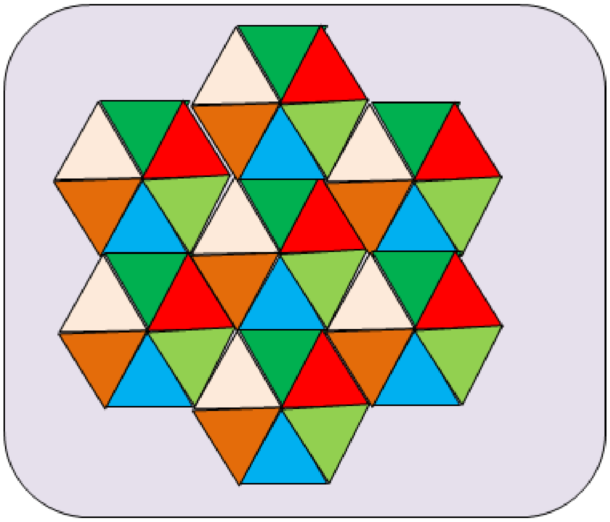
Now consider adding several different antennas, each with a different beam, from a separate antenna. We evenly assign a fraction of the 20 MHz bandwidth to each beam.




Now we can graphically look at a coverage area and have the six sectors and see what a single antenna could do if for example we add 6 beams and then combine them again and again...

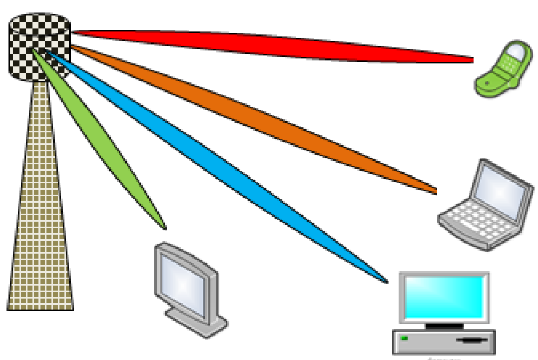


Here we have above the large regions covered by 6 beams. But we can reuse them as we show below:



In the first block we use 20 MHz once, in the second we use it again and again, and here we use it 7 times. Thus with cell structures we can reuse spectrum by inserting smaller cells.

However the users may or may not be in a specific beam. For example, one beam often has 70% or more of the customers and it gets saturated. Thus we would like to put beams where the customers are and not just a priori.



Note in the above, we use a sophisticated array antenna which can generate multiple beams, narrow and of high power, to be pointed at where a user is, thus making sure that antenna power is maximally utilized at all times and further that reuse between the equivalent of cells is also maximized. Two things happen when one uses an adaptive antenna:

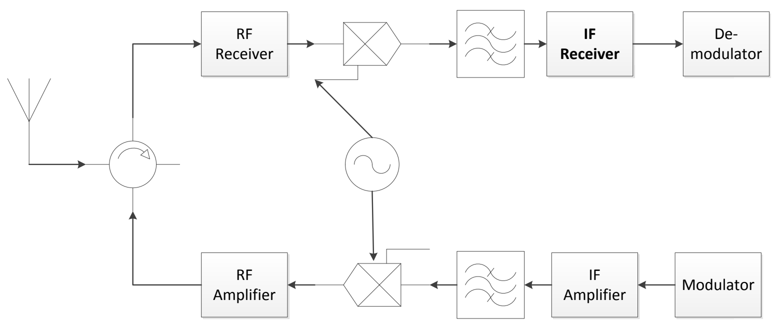
First, power per user is increased so that effect capacity per user is increased. An increase of an order of magnitude is also possible.

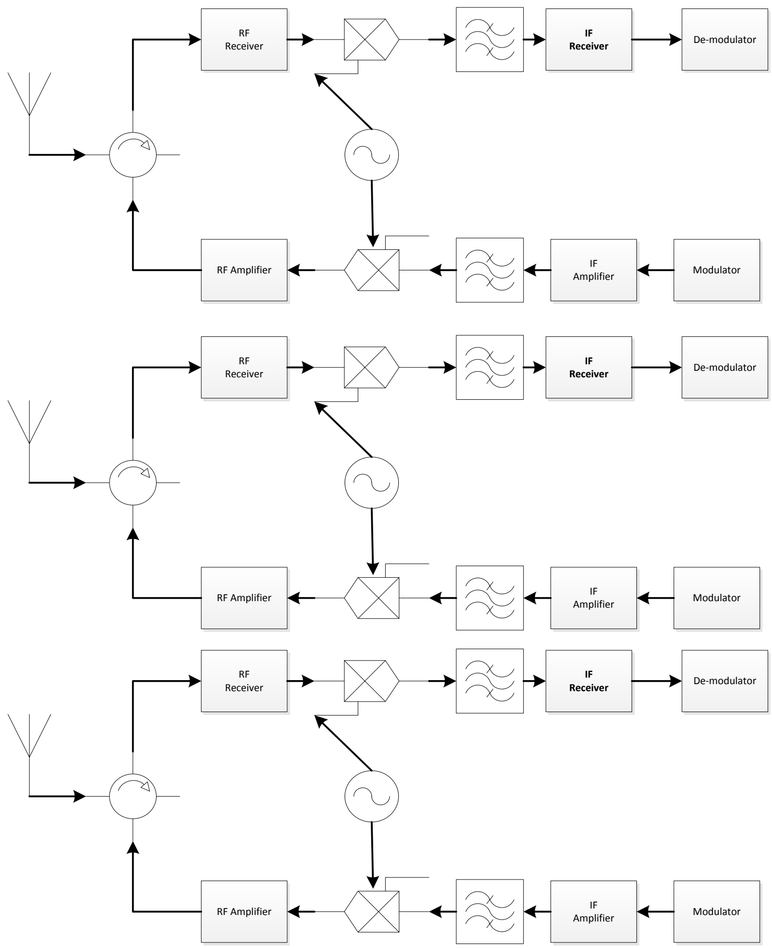
Second, the reuse factor, say seven in the prior case, is now increased also an order of magnitude.

The combination of the two factors increases tot total spectral efficiency by two orders of magnitude!

## 5.3 BROADBAND FRONT ENDS

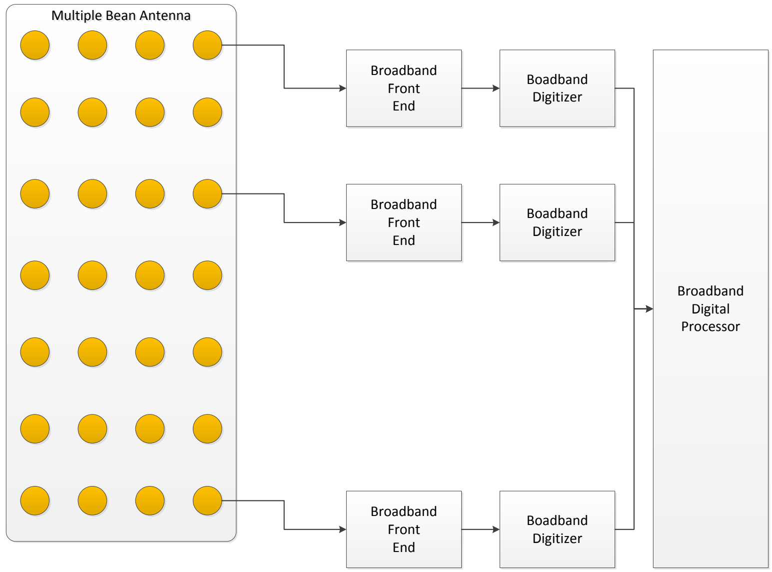
A broadband front end is a complex front end processor which simply samples all the RF received from each sensor and then digitizes this massive data stream and does the processing in software rather than hardware. One of the major problems of microwave systems is that they have narrow bandwidths. For example if we have a center frequency of say 2 GHz, then the maximum we can generally run the system at is a bandwidth of about 1% or less, namely 20 MHz. That means for every 20 MHz we need another antenna, receiver, transmitter, and other such elements.






The Broadband Front End Interface, BFEI, is a technological implementation which consist a wide-band air interface for receiving or transmitting electromagnetic signals. It consists of a collection of analog-to-digital converter subsystems for digitizing collected signals. It then digitizes the received signals for common processing. The front end of this device is the air interface.

The following Figure depicts the BFEI. Simply, there is an array of monopole transmit/receive antennas, followed by a Broadband Front End Amplifier, BFEA, which recovers a received signal or transmits a signal. The front end is a broadband processor where it may cover 50% or more of the typical center frequency. Namely if the center frequency is 2 GHz then it goes at least from 1 GHz to 3GHz. That is a typical spread and some may even go more. Then it is followed by a sampler, it samples and digitizes the signal on receive at Nyquist rates for the center frequency, in this case at 2 Gsamples per second and at say 16 bits per sample. That is 32 Gbps data stream, one from each antenna dipole. Say we have a 16X16 dipole that is 256 dipoles and a total data stream of 256X32Gbps or 8Tbps in the Broadband Digital Processor.




Now let us consider a bit more detail.

One design entails an air interface (RF interface with digital formatting) comprises a three-layer meta-surface with layers oriented normal to the electromagnetic-wave-capture boresight.

(i) The air-interface layer partitions the area of the meta-surface into a collection of small capture-area epixels (electronic pixels) and separates the incident-wave polarization vector into two orthogonal components in each of the epixels.

(ii) An energy-capture layer is adjacent to the air interface layer. Within the boundaries of each epixel, the wave energy of the two orthogonal polarization vectors is captured and converted into TEM energy in 50-Ohm coaxial lines.

(iii) A signal-isolation layer comprises a system of waveguide-beyond-cutoff segments that attenuates back-hemisphere energy.

The characteristics of a typical device may be as follows:

Capture Area. The capture area would be essentially equal to the physical area of the nxn-epixel metasurface. Aperture efficiencies greater than 90% are required over a spread of a 6:1 frequency bandwidth. Recall that if we go from 500 MHz to 3 GHz we have such a bandwidth, namely 6:1. In most mobile systems such a coverage provides considerable coverage of available bandwidth.

Beamwidth: The beamwidth must be acceptable down to the lowest frequency. Adaptive beam forming based on user demand is an essential element of the design. We have determined that at low frequencies that beamwidth of less than $30^{o}$ are achieveable. Clearly at higher frequencies we can achieve much narrower spot beams on a per user basis. The antenna in this configuration allows for band sharing and load balancing on a real time basis. Dynamic Adaptive Load Assignments (DALA) is a critical factor in such a Broadband Front End Design.

Beamforming: A beamforming experiment demonstrated that the 32 Epixel array could form beams within a cone defined by 22.5 degrees off boresight.

Polarization separation: The isolation between the two polarization vectors must exceed 20 dB over angle of arrival within the primary beam and over frequency over the entire frequency band.

Reciprocity: Most evaluation measurements is comparable in the RECEIVE mode.

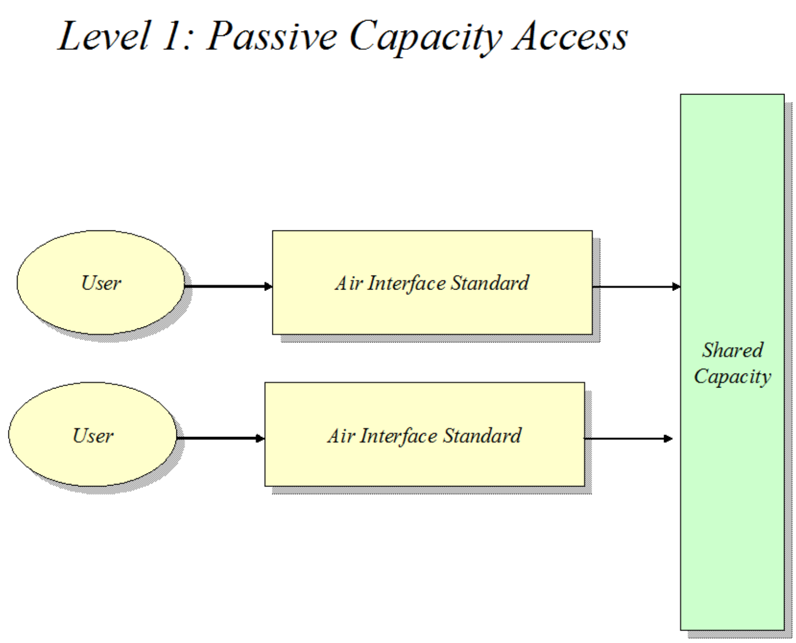
This design can now be implemented with currently available logic, dipole elements and RF diode receivers. The design will have a significant effect on capacity and coverage.

## 5.4 Adaptive Bandwidth Sharing

We can view the options to optimizing channel capacity by dynamically allocating spectrum between users. We have discussed this at length elsewhere.

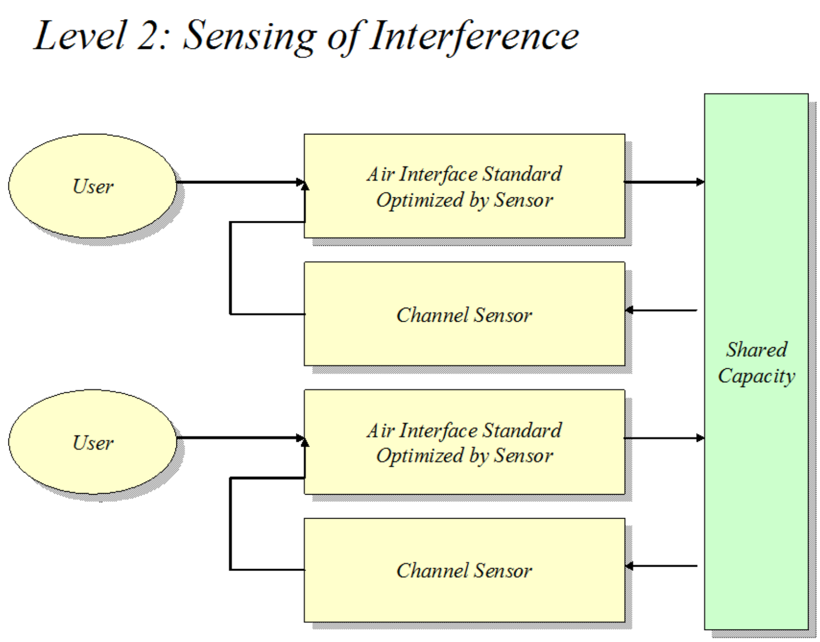
### *5.4.1 Level 1: Air Access Only*

The simplest approach is what is done with 802.11 and other air interface standards. For example CDMA is one of these in cellular. The standard is defined and it is a layer 1 or layer 2 level standard. It is fixed, it is standard, and it is generally in some ASIC implementation. It is a physical agreed to standard which requires RF and signalling cooperation. The implementation is shown below.



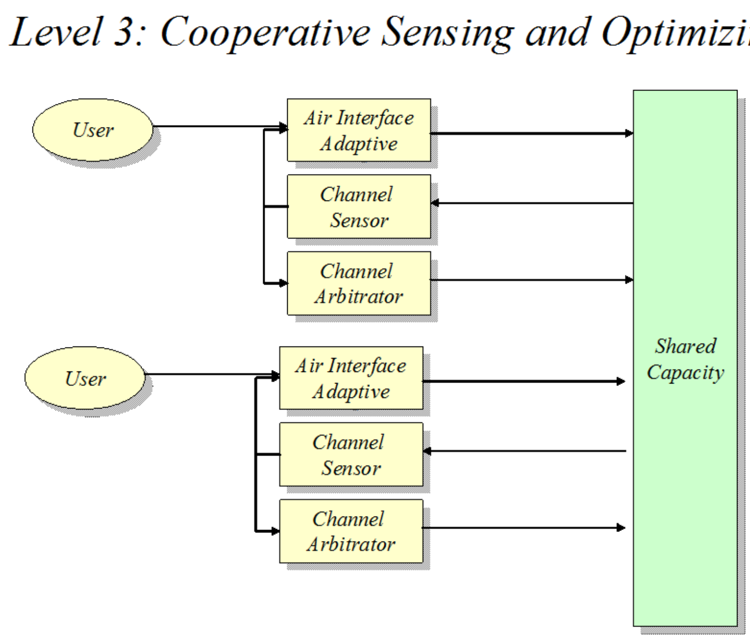
### *5.4.2 Level 2: Sensing and Adaptive Air Access*

The next approach is to sense the environment and modify the air interface in some manner. The modification may be signaling level modulation multiple access or even antenna parameters. In all cases the sensor sniffs the environment and there exists some optimization scheme assuming all players in the environment are non-cooperative or even hostile. This is shown below.




### *5.4.3 Level 3: Sensing and Cooperation and Adaptive Air Access*

The third approach is the combination of the above plus a cooperative environment of users. This added element of channel arbitrator becomes a key element. There are two issues regarding this which make this unique; (i) the arbitration can take on an economic element, (ii) the arbitration is done at higher layers of protocols to allow it to be modified, distributed, and processed.




### *5.4.4 Implementation Strategy*

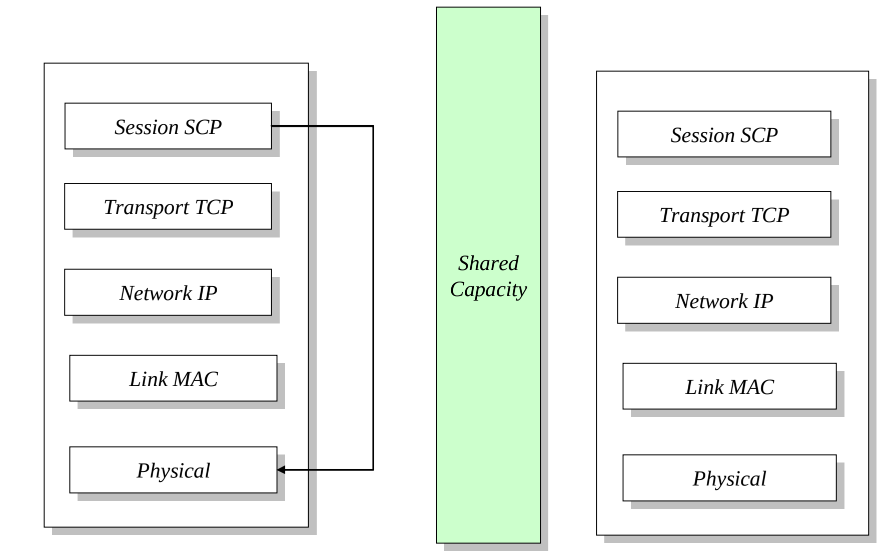
The implementation of the arbitrator model is akin to TCP/IP. It should be minimalists with enhancements and it should be at the software level not requiring an ASIC based standard. It also must interface with any and all standards at the lower layer. We argue that Layer 5, the Session layer is the best place for this to reside.

The uniqueness of our approach is that it is at the session layer. It is in software, it can be real time downloaded to other participants and updated real time (not requiring ASIC development), and it can optimize overall bandwidth utilization. Also the uniqueness allows the session layer to interface with any set of layer 1 and 2 standards, and uses TCP/IP for layer 3 and 4.

There are three steps involved. They are shown below:

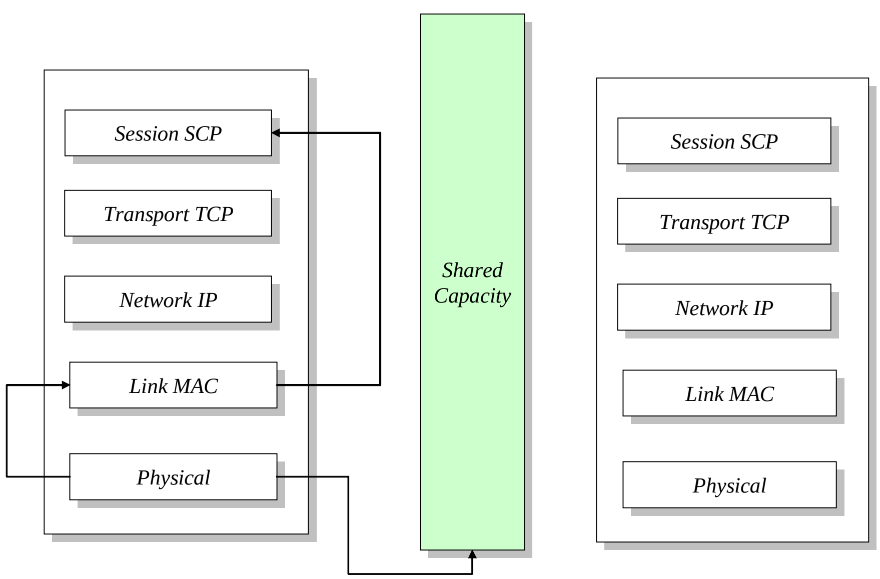
Step 1: This is the step of sensing the standard of the channel. This uses the standards in Layer 1 and 2 and their already defined characteristics. The Session implementation uniqueness is also that it contains a tool box for the implementation and integration of any standard.

*Step 1: Sense Air Interface Standard*

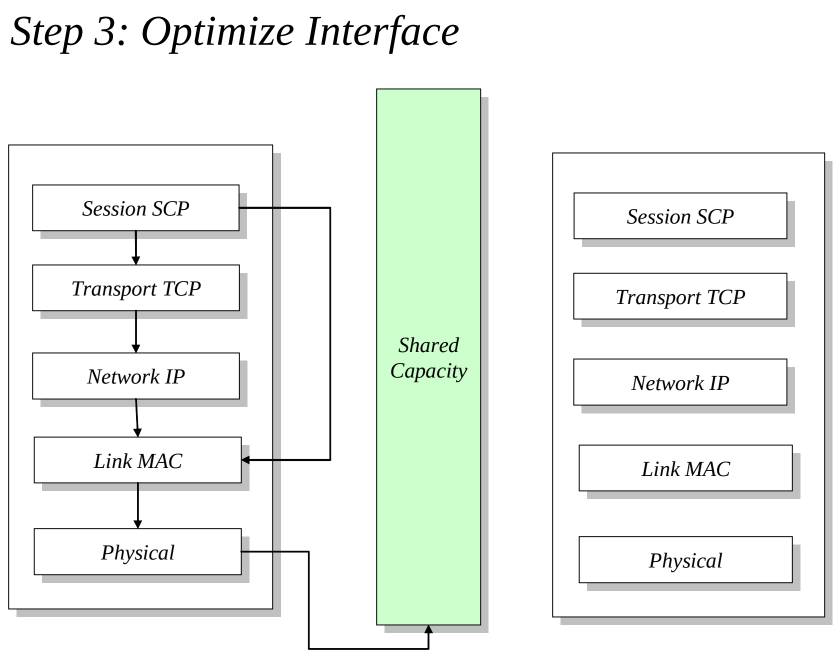



Step 2: This senses the interference on the channel. It uses a set of algorithms which can generally sense layer 1 and layer 2 signalling and uses the already existing signal and channel sensing elements of the standards sensed.

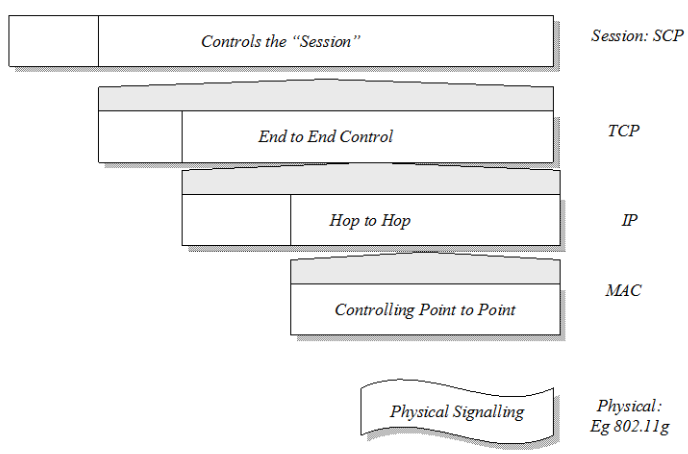
*Step 2: Sense Interference*




Step 3: This is the optimization via cooperation and coordination. A unique aspect is the establishment of micro-transactions which can be employed in this system.

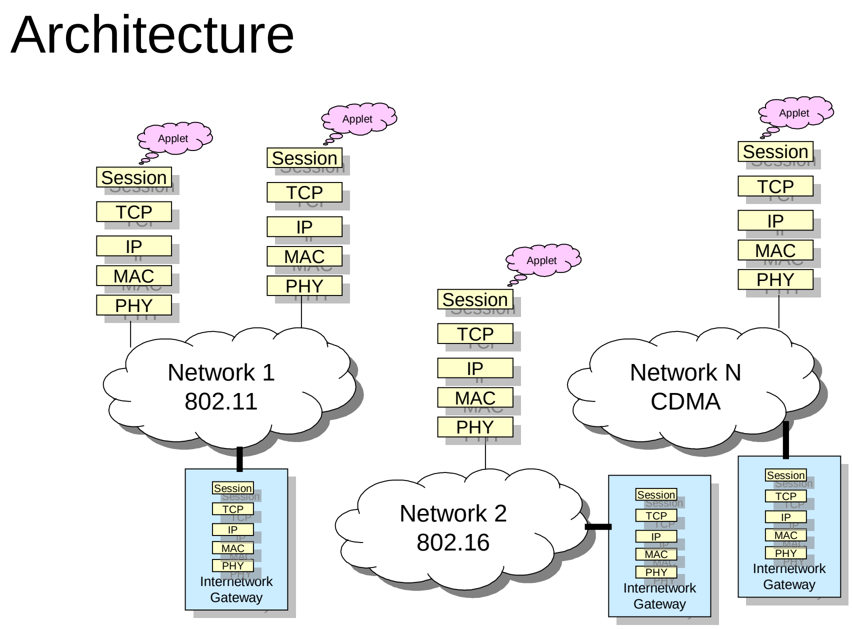



Thus the flow can be visualized at all layers as shown below:




### 5.4.5 *Architecture*

The architecture of a shareable spectrum system can be shown below. There must be applets which each user willing to share must have access to, these we place at the session layer and present in detail in the next section. There must also be some form of gateways between differing air interfaces. These may be physically separate gateways or they may be actual parts of the system elements, namely internal, as is currently anticipated in such systems as 802.16.[15]




## 5.5 Software Defined Receivers and Transmitters

Software Defined Receivers and Transmitters are a subset of the Adaptive Broadband approach. There has been a great deal of work in this area of the past few years and it continues. Simply it is a typical tuned bandwidth RF front end but now we use a software only set of processors for modulation, multiple access and signal handling. Thus a single front end may handle a variety of different signalling formats.

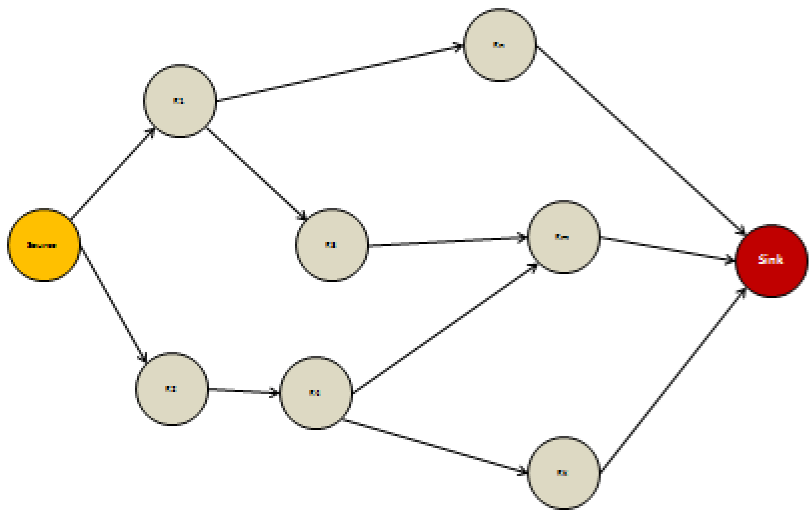
## 5.6 Advanced Coding

Advanced coding schemes have dramatically enhanced the capabilities of wireless to provide for video applications. One specific technology is network coding. Network coding is a scheme that uses the many multiple paths of transmission in a wireless IP based system as added forms of information rather than increased interference.

Network coding has been around as a specific focus for a decade. It has been implemented by several companies in some small scale but in so doing the companies has experienced dramatic improvements especially in IPTV applications.

[15] See: Eklund et al. IEEE Standard 802.16. IEEE Comm Magazine, June 2003.

Simply Network Coding is as below. This is what is called a multipath channel. Namely the signal is sent from the source and then hits many surfaces sending out new signals which in turn hit other surfaces and then at the receiver three signal are obtained. The classic problem is to choose the best, one single good solution.




The classic way of using this multipath channel was thus finding a good one and dismissing the rest. But the rest had information and there may be lots of them, Network coding is a way to look at the channel as a coder, and then to use all the received signals as decoded signals. McGarty and Schneider solve this problem in 1977 but then the processing electronics was not implementable. Thus when it was examined again in 2002 the technology was available. From this is where Network Coding came from.

The benefit of network coding is that less power and more throughput is available. As Sundararajan et al state:

*Despite the potential of network coding, we still seem far from seeing widespread implementation of network cod- ing across networks. We believe a major reason for this is the incremental deployment problem. It is not clear how to naturally add network coding to existing systems, and to understand ahead of time the actual effects of network coding in the wild. There have been several important advances in bridging the gap between theory and practice in this space. The distributed random linear coding idea, introduced by Ho et al., is a significant step towards a robust implementation.*

For multimedia systems we have from Lima et al:

*WHILE there has been abundant research aiming at ensuring a reasonable quality of video experience for wireless users, the task of providing video streaming of variable quality to a*

*heterogeneous set of receivers with different subscription levels is still an open issue. The key challenge is to serve wireless users with video streams that are both (i) of different quality, depending on subscription level, and (ii) with security guarantees to ensure that only authorized users will access the protected video streams.*
As Medard states in her comparison of source versus network coding:

1. *The source-based approaches consider the networks as in effect channels with ergodic erasures or errors, and code over them, attempting to reduce excessive redundancy*
2. *The data is expanded, not combined to adapt to topology and capacity*
3. *Underlying coding for networks, traditional routing problems remain, which yield the virtual channel over which coding takes place*
4. *Network coding subsumes all functions of routing - algebraic data manipulation and forwarding are fused*

## 5.7 Wireless Unlicensed Mesh Networks

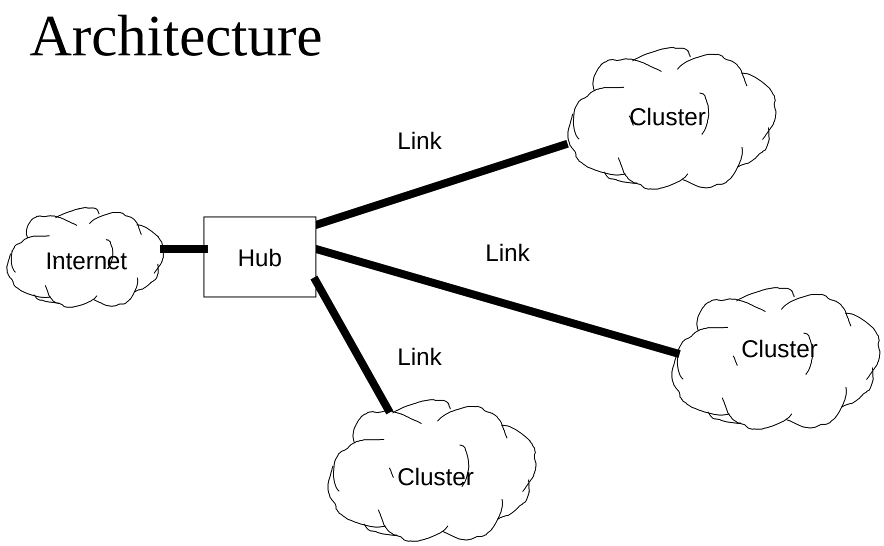
Wireless Unlicensed Mesh Networks focus on deploying in the unlicensed bands meshed broadband networks. We have developed several designs and systems and have experimentally tested several. This section details the architecture for the design and deployment of a broadband wireless mesh network using as a basis the existing unlicensed wireless broadband technology. The overall product specification is:

*"The provision of a broadband local mesh network which can provide access to multiple users in a wide geographical base and also enable Internet connectivity at a selected number of locations. The services provided must include the full set of broadband enabled services in a full wireless manner permitting roaming across the network by any user. The delivery of the services shall be of a manner consistent with a controllable quality of service. Security and access control shall be provided to each user or sets of users on an end user configurable basis. The networks shall enable in a simple manner the provisioning by network participants of a broad base of network enabled services which ride upon the overall network fabric."*

This document is a high level architecture for the proposed wireless mesh system. It builds on the design concept we deployed in the late 2000s and by focusing on enhanced services and enabling local networking and applications. The WUBN, Wireless Unlicensed Broadband Network, is a platform which focuses on the delivery of Internet access in a pure data format. This system design focuses on much broader and more demanding applications; video and voice, as well as penalizing local content providers to have access to the local network fabric in an open and modular fashion.

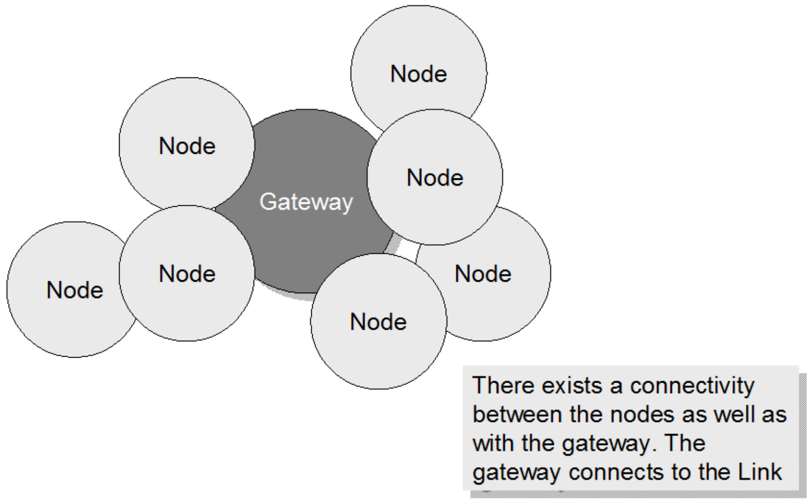
This architecture presents a design that builds on existing platforms such as WUBN, TCP/IP, click, and others and develops a unique multimedia enabled broadband platform for the delivery and provisioning of a wide variety of multimedia services over a large area using meshed wireless networking. The software enabled by this architectures readily distributed to users and the key value generated from the implementation of this architecture is the fully open broadband network using low cost of entry wireless backbone.

The overall system architecture is shown below, first we show the Internet, a central connecting point we cal a hub, and clusters. The clusters are groups of wireless entities with a connection to the hub. The hub cluster connection is for connectivity to the Internet backbone as well as interconnectivity to the local networking fabric.



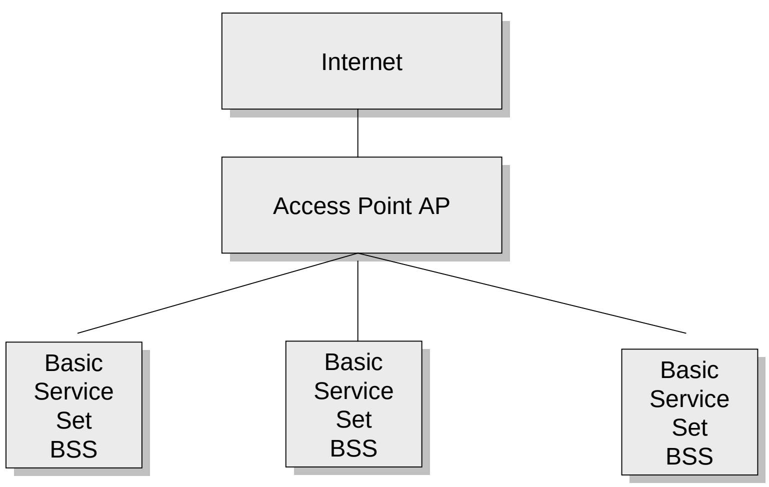

The cluster is shown below, consists of a gateway, the element connecting to a hub, and a collection of nodes. The gateway and nodes are all access points in a 802.11 context except that they can interconnect to one another; we shall detail that further when we compare this architecture to the standard 802.11 design. The terminology used here is also WUBN terminology.

# Cluster



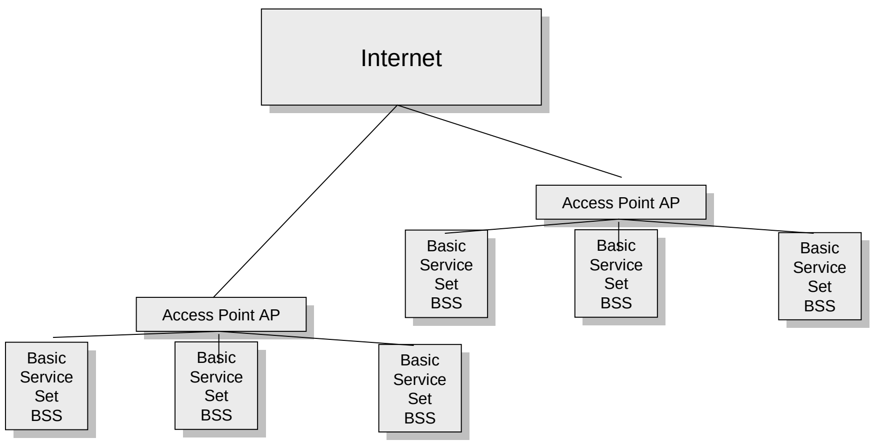

The 802.11 design is shown below. In the above, the Node or gateway is the AP but the AP in an 802.11 design is the single connection point. WUBN uses the click router design to implement their specific router capabilities. The BSS in the 802.11 design are the end user devices such as 802.11 cards in a laptop. They have no routing capability.

# HW Architecture 802.11



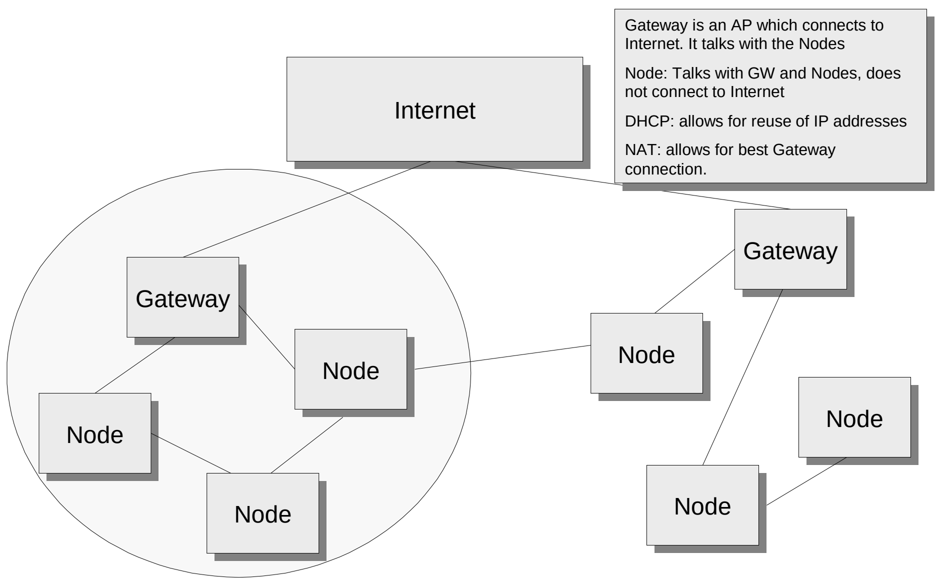
In addition the standard 802.11 can appear as a hub based design but again the AP are the single point of connection to the BSSs. This is a star-type architecture as compared to a mesh design.

# HW Architecture 802.11

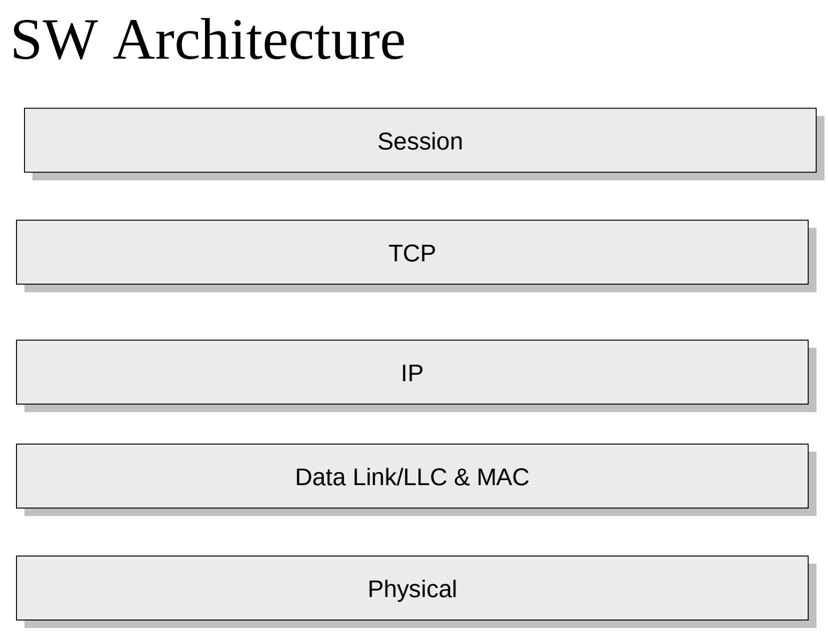



The WUBN design is true mesh like. We use the clusters but as shown below the clusters can even inter-communicate if the can reach each other with a wireless link.

# HW Architecture



The overall WUBN architecture is shown below. It uses all of the standard elements but does modify MAC layer to avoid timeout delays and avoid other features such as RTS and CTS delays. It also uses the click route to implements the routing table which is key to a WUBN design. It does not use the standard routing that one finds in a standard 802.11 AP.




The specifics of this design are shown below. This layers architecture is generally what WUBN does and what this overall architecture requires.

# SW Architecture

IP
Routing: Static; Dynamic (RIP and OSPF); Dynamic Host Configuration Protocol (DHCP); Network Address Translation (NAT); PPPoE, QoS; Roaming; Network Layer Security; Firewalls; VPN

LLC
802.3 Standard

MAC
Bridging (MAC Address Table), Max Simultaneous Connects, Spanning Tree Loop Rejection, Switching); MAC Sub-layer (Error Control, Congestion Management, Packet Aggregation, Data Protection); DLC Security (MAC Access Control, Protocol Filter, MAC Address Pair Filter, Authentication, Encryption)

# 6 CONCLUSIONS

The driving limitation of wireless has been available bandwidth. Namely a system with say 20 MHz of bandwidth had limited capacity measured in bit per second. Under simple architectures if one had a single transmitter with an antenna which covered a full circle then one may have gotten a total of 20 Mbps from the 20 MHz. Namely the existing modulation efficiency of classic system was 1 bps per Hz of bandwidth. This was a technology limitation and not a physical limitation. Now in this world if we tried to transmit video, say MPEG 4, at 4 Mbps, we would only have capacity for 5 video channels. Not a great number.

This paper examined several technological advancements which are in many ways still works in progress. Yet each of these would move an all wireless broadband network forward considerably. We summarize them in the following manner.

| *Technology* | *Status* | *Impact* |
|---|---|---|
| **OFDM** | Completed and operational. There are some further enhancements which can be made here. | It has already provided a 10:1 bandwidth advantage |
| **Multiple Beam Antenna** | These have been deployed in military radar and sensing systems. The author personally deployed these decades ago, but not for communications purposes. Technology has advanced to allow low cost deployment. Martin Cooper was a strong advocate for a few years. | This is readily achieveable with the low cost design. It also needs significant software implementation for load balancing. |
| **Broadband Front Ends** | These systems have been developed for the Intelligence Community to monitor broadband communications. We have considered deploying the technology for commercial applications. Steinbrecher has been promoting this for a while. | The high speed front end is state of the art but can be implemented at cost effective levels. |
| **Adaptive Bandwidth Allocations** | To date no company has designed or deployed an operational system. | This needs significant development. It was designed for competitive bandwidth allocation between carriers but can be used in a single multi band carrier. |
| **Software Defined Air Interfaces** | There have been several designs here such as that by Vanu (Vanu Bose). Worked has not progressed for many reasons, mostly related to company management issues. | It is not clear how accepted this is except for small carriers. The reason seems to be to limit competition. |

| *Technology* | *Status* | *Impact* |
|---|---|---|
| **Advanced Network Coding** | Many systems have been built academically and Codeon has managed to capture the Paten base. This could represent an attractive acquisition. | The technology has been demonstrated and limited commercial use has been show. UUsee.com is using the technology and reducing video downloads by a factor of 100! Also Microsoft has implemented a similar system. |
| **Wireless Mesh Networks** | There have been several simple designs such as the MIT Roofnet design, the Meraki design and many more recent one. The author had extended the design for broader range and coverage. | The deployment of added unlicensed spectrum will drive demand. Enhancements to our designs would position a providers in a well ahead strategic advantage. |

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