New Spectrum Policies and Technologies

Creating a Real Time Spectrum Market

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Abstract

Spectrum is a resources controlled tightly by the FCC and other national and international regulatory bodies. The methodology for controlling spectrum is threefold: allocation of specific bandwidth, control of transmission characteristics such as power, and use to which the spectrum is put. All three of these restraints result in highly inefficient use of bandwidth and in technology changes which try to circumvent the regulator and not try to maximize the effective utilization of the bandwidth. This paper discusses a new set of technological alternatives which address the broader question of: "Given the capabilities of technologies at all levels of the communicating chain, what are the optimal means and methods for the real time allocation of bandwidth, in a truly open economic market, to maximize bandwidth availability and utilization". This may be called the "Utilitarian" approach to bandwidth rather than the current "Rawlsian" approach of allowing the smallest user the smallest amount of access possible.

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1. INTRODUCTION

Bandwidth is a limited commodity which is controlled by national regulatory bodies. Their approach to control is based upon 19th century ideas of power control and interference and have not veered greatly from what Marconi understood at the turn of the 19th century. The allocation process is also based on the ideas of property law, namely bandwidth is distributed as a piece of property to its users and the owner has the same as property rights over that bandwidth commensurate with the owner of a piece of land. There may be certain restrictions but they are de minimis.

Let us begin by making certain observations concerning spectrum:

- *Bandwidth currently owned or shared*
- *Owned bandwidth uses at most 10% of what is available*
- *All Bandwidth can be shared*
- *Bandwidth can be considered a property right so sharing can be done at a price/transaction*
- *PHY/MAC standards only take presence when put in silicon, in silicon when a standard*
- *Real time Sharing bandwidth is a market process with micro-transactions*
- *Solution should be readily deployed and shared, not in silicon but higher level*

The driving factor to reconsider policy on bandwidth control is that currently there are many highly economic ways to improve efficiency through processing. The adage, “Silicon is Free” can be used as a liberating elements on the allocation of bandwidth. Currently the regulatory mechanisms which control bandwidth take no note of what can be done in a regulated environment. For example, cellular systems get fixed blocks of bandwidth no matter what they use it for and no matter how efficiently they use it. It is their spectrum and they cannot share it with anyone else unless they agree.

1.1 Current Spectrum Management

Spectrum is currently allocated by the FCC in three distinct fashions:

1. Auctioned: This process takes a block of spectrum and sells it at auction to the highest bidder. The use of the spectrum may or may not be delimited and all one has to do is pay for it and then it becomes a property right to the owner. In fact, the Nextwave case is a classic example of where the FCC did not even require payment, all Nextwave did was bid then go bankrupt. The FCC in its wisdom transferred title to the bidder after they offered the highest price but before they paid for it! There are no financial institutions in the world who act that way.

2. Shared Low Power: This is the Part 15 approach, name after the FCC codes regulating low power transmissions. In this is everything from 802.11 to garage door openers and CB radio. This area is has become the development ground for many new technologies.

3. Legacies: The legacy bands are the TV bands in VHF, radio bands for broadcast radio, and amateur radio bands. These are not auctioned and have some power restrictions and usage restrictions.

There is a fourth band but not controlled by the FCC and that is the Military, Intelligence, Government bands.

1.2 Utilization and Usefulness

There have been many abuses of this policy. Nextwave is but one example. A more blatant abuse of spectrum policy is the continuing allocation of VHF bandwidth to the broadcast stations. The spectrum is blocked for television and in the US today more than 97% of the people, not viewers but people, have either cable or satellite access. That means that 3% have none, and most likely that 3% is not even watching. Thus almost 0% of the people watch television over the air. The usefulness to the people of the spectrum is zero. In addition, the over the air stations pay nothing for the use of the spectrum. Therefore this spectrum is not used, not paid for, and applications for use of this spectrum are prohibited by the networks. This is just one example of the current spectrum inefficiency policy.

At the other extreme is the growth of the 802.11 services. In this environment, power is limited as is bandwidth, but by agreement between users sharing is possible. The low end of sharing is between a server and the clients that are using it. Nothing, however, would prohibit servers from talking to each other and sharing interconnection space.

The issue we address in this paper is simply:

How does one, using all elements of technology, establish a means and method to maximize the overall economic use of spectrum in a rapidly evolving technology space with equally fast evolving demands by the users of the spectrum and its applications?

Thus there are several dimensions for obtaining more efficient use of bandwidth. The classic bandwidth optimization approach was that of Shannon. Shannon assumed a single user with a fixed bandwidth and power level communicating in a noisy environment. He then concluded that there is a maximum rate of communicating in such an environment. That is the essence of the famous coding theorem. Namely, there exists a code, he could not tell you what it was, that allowed you to transmit at a rate called the channel rate, which was a fast as you could communicate. Now we rephrase the problem, and say; given some bandwidth, how can N users maximize the use of the bandwidth between and betwixt each other by a means that considers the economic benefit of the bandwidth as a key determinant. That is we include now in the process the ability to have different bidders for bandwidth on a real time basis.

We now argue that the issue of bandwidth allocation and management should be considered as both a technical and economic mix, that is by having technology create a real time market for access to capacity in a spectrum domain we can create a new view of "spectrum Management". That is we can let the market take direct control of who uses what for what purposes and at what costs. The role of the FCC would then be relegated to assuring that the free spectrum market functions in a manner consistent with market rules; policeman and law enforcer. The FCC would possible regulate total bandwidth, but other than an be a policeman to insure that fraud does not occur, it would do nothing more.

In today's world there are several factors which are control factors for bandwidth utilization. They are:

1. ***Power:*** The power issue relates to two extreme positions. Classically it was an interference issue. At certain levels in an economically shared environment it will be less of one. The second extreme issue is cost. High power requires higher cost equipment. A third issue was also present, the Shannon issue, that is higher power provided potentially higher overall data throughput rates. This we will argue will be less of an issue.

2. ***Bandwidth:*** The bandwidth dictates the data rate, to some degree. The spectral efficiency of some modulation scheme dictates the number if bits per second per Hertz, e.g. unit bandwidth. The more complicated the scheme the greater the efficiency. However that efficiency goes up against the power required to maintain a level of service, such as a bit error rate. The more bits put in a given spectrum the more power required to discriminate between then so that reliable communications is obtained.

3. ***Frequency:*** This is the center frequency. Certain bands do better than line of sight since they reflect and have good multipath capabilities. Other frequencies, such as those above 6 GHz start to get absorbed by moisture and no matter what do not work well.

4. ***Protocols:*** All that has been said about the above three issues relate to the physical means of communications. Protocols, using intelligent signalling above the basic physical layer starts to change the. Such protocols as CDMA allow multiple users to use the same spectrum by spreading signals so that any one user looks like noise unless properly processed. MAC layers such as those

used in Ethernets allow for sharing using request response mechanism for available bandwidth. Slots of time or bandwidth can be assigned to users. IP systems also work this way, sending packets via available routes and attempting to efficiently load balance links in a network. TCP on top of IP ensures end to end control over the packets. Current developments in the IP space also allow for some forms of priority packet thruput to enable some form of quality of service, such as MPLS. Thus in the protocol domain of spectrum management there is a great deal of work in the sharing process already, at least in concept. The initial construct of a packet system was Norm Abramson's Aloha packet network, which was a radio based network. That was almost 40 years ago!

5. ***Economics:*** Bandwidth has a financial value to the user. That financial value may be time dependent. For example, cellular spectrum is not used a great deal at 4 AM. In contrast, if spectrum were money and were fungible, then the "float" associated with spectrum could be used as the float in a personal checking account is used by the bank when the owner of the account is sleeping, and even when awake. Is there a way to create a market, and indeed a real time market, for bandwidth. So that it is more efficiently used and valued. In a bandwidth "market", using protocols similar to those mentioned above, expanded and modified for a micro level transaction, one can envision the buying and selling of bandwidth on demand.

1.3 Technology Alternatives

We consider two simple examples of this concept of Economic Bandwidth Access, EBA. They are at two extremes but provide an reasonable representation of what the potential could be:

1. Wireless Meshes: A wireless mesh or grid is an architecture wherein the spectrum rules are those of Part 15, namely low power. Thus the entities operating in the network need to share between each other capacity so that they can have a greater coverage area. In any small area, the entity has full control over its capacity which may be all there is available. However, due to power restraints it cannot go beyond that area. Thus entities may want to enter into micro transactions with other entities, even ones far distant from any one entity, to establish a virtual network based upon some form of micro transaction mechanism.

2. Overlay Networks: These networks are at the other extreme. They may have lots of power and even bandwidth. But, they may work in a NEW frequency regulation domain, one where spectrum, power, and even others assets are sharable via a transaction mechanism. Unlike the low power mesh approach, the overlay approach allows for large scale transactions, permitting multiple users to have access via again micro transactions to significantly more spectrum resources. One could envision cellular systems entering into such agreements and allowing third parties to have access to cellular spectrum on demand but at a price. The key to this domain of operation, however, is that the FCC does not currently sanction such.

1.4 Overall Objectives

We argue in this paper that there are two attractive opportunities for the expansion of bandwidth utilization, one which can be accomplished within the current regulatory environment and one which requires a regulatory change. We strongly urge the rewriters of the new Telecommunications Act to consider not only empowering the FCC but mandating the FCC to incorporate shared micro transaction capabilities into the allocation of bandwidth, and when so doing, refrain from any auction process creating a long term property right. The FCC must be mandated to establish alternatives to bandwidth auctions which reflects the markets ability to utilize bandwidth using the most available technologies in a manner consistent with the ever changing capabilities of those technologies.

The question is why now for concern about spectrum. Our answer is:

- *Great demand for bandwidth and capacity in wireless networks.*
- *We can foresee problem, but few/none are creating/have yet created solutions at the appropriate scale*

- *Significant Development in physical and MAC layers allowing multiple users to interface with one another: 802.11 etc*
- *Vast interference problems in unlicensed bands are emerging*
- *Public Safety institutions seek revenue from enabling access to their bands by commercial users*
- *Wireless is starting to take off as a broadband interconnection mechanism*
- *All of the focus is on low level technology requiring great investment in ASIC development and standards*
- *Higher layer approaches allow a floating on top of the growth in PHY/MAC*

We then address the issue as to what is fundamentally different about our proposed approach, The answer is simply the session layer rather than silicon. This is a software versus silicon issue. Specifically:

- *This is a Session layer approach, lies above all other layers and is software based.*
- *This is an architecture as well as element approach, taking control over an overall implementation*
- *Architecture is modular based on functions, is intended as a platform enabling isolated solutions to knit together, like being an operating system that enables others to write applications*

The we in developing a system approach address the economic underpinnings of this approach. Specifically we look at:

- *"Cellular" one owner of dedicated spectrum, use it or let it lay fallow, managed spectrum*
- *"WiFi" no owner and no control, use if you can, non-cooperative*
- *"WiMax" expansion platforms*
- *"Shared" spectrum – FCC looking at expanding ways in which spectrum allocated, such as frequency commons concept, interference temperature concept etc, many users who are intelligently utilizing in cooperative*
- *Transmitters are fixed and/or mobile*

2. REGULATORY ENVIRONMENT

We briefly review the regulatory environment to set the stage for optimal use of spectrum.

2.1 Spectrum Utilization

We shall assume that spectrum is available in blocks of arbitrarily large bandwidth. Let us assume, for example, that there is 100 MHz of bandwidth available. This bandwidth then is to be divided amongst several players who will in turn provide services to end users and thereby create value, provide a set of goods, and obtain an overall economic benefit to all players. The Government, in turn, may seek to obtain a share in the value of the spectrum thus provided in one of many fashions; specifically through a one time or a usage fee base.

The question that we pose is as follows:

"What are the optimal ways to allocate the spectrum so that the consumer is benefited in an optimal fashion and that there is an effective competitive market created that sells the widest variety of services at the lowest possible price?"

This is in a sense a Pareto optimal solution of the spectral allocation problem.

Let us begin by posing a simple problem. We shall use this problem throughout the paper. Specifically:

Given K MHz of spectrum, how should we allocate it amongst N users and M service providers to maximize the overall public good for a foreseeable long time horizon. We assume that M and N are unknown.

This problem begs the question of what is the specific optimization criteria. It also begs the question of who is doing the allocation. Let us first discuss the issue of optimization and then defer the issue of who does the allocation. In many ways we seek the "market" to do the allocation directly, and this may not always be a readily achievable goal.

As to optimization, what is in the maximum public benefit? From the end users perspective the benefit should be optimized if the widest possible variety of service be available, at the highest quality, and at the lowest possible price.

2.2 Constraints

Let us discuss some of the constraining issues that delimit the possibilities. The are:

- Scale Economies: W could take the K MHz and divide it equally amongst the M providers. If M is 1,000, then each gets K/1,000 KHz. Let us assume that that is enough spectrum. However, the infrastructure costs, such as billing, sales, customer service, network management and others may have significant scale economies. Each provider will have N/M customers, by assumption, and scale may be reached at some value K which is much greater r than that number. The result is inefficient use of spectrum because of inefficient use of infrastructure, capital as well as operating infrastructure. The market could resolve this by having the small companies get merged into the larger ones, as was the case with cellular. This has been shown to be economically costly to the customer. There are costs of consolidation that drive up the total costs and thus increase the effective inefficiencies.

- Critical Market Size or Customer Base: There is a critical customer base or market size. Marginalizing the market amongst several players may result in a marginalization of the customer base. Whether it is the same service or different services, there may be just too small a total customer base for any one service. Digital Termination Services is an example of where this applies. This was the 10 GHz services that were developed in the early 1980s. There was a market but it was very small.

- Extent of Competition: By definition, a single competitor is a monopolist and as is well known the monopolist has the advantage of a demand curve that is manageable and thus charges a monopoly rent. The duopolist also sees similar manageable demand curves. Cellular and the Local Exchange business are examples of where monopolies and duopolies have stymied innovation and price competitiveness. All one has to do is to look at the Inter Exchange Carrier (IEC) business and see that since 1984 prices have halved and services have exploded. Thus competition has been a dramatic market stimulant.

- Market Confusion: The existence of too may providers of the same or similar service may cause market confusion. The PC market is an example. The confusion in PC software was also a similar example. There is a cost to this confusion and the consumer must bear that costs. However, the gains of competitive pricing often drives down that cost and the et effect is minimal.

- Technology Availability: With many competitors there may be a problem of technology availability or of the manufacturers not being willing to invest in the development of new technology, or that they may not have enough volume to produce for a specific service provider, or that there may not be enough usage of a set of specific service features.

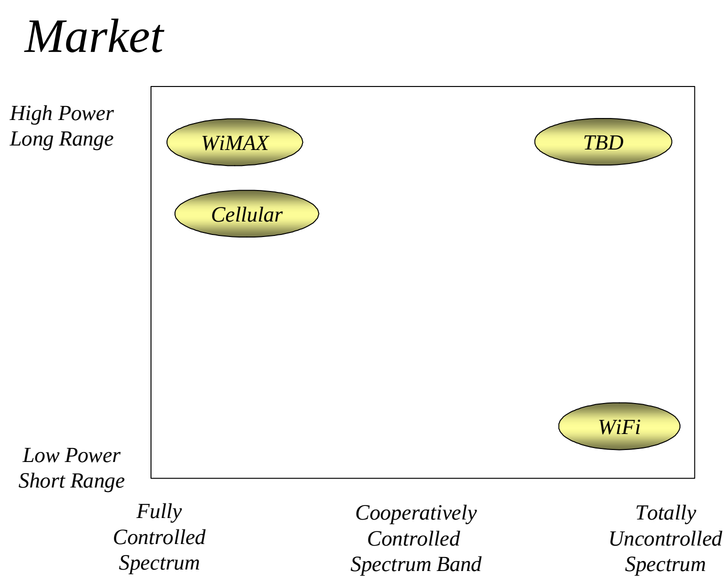
- Interconnectivity: This may be the most significant factor in the development of any new telecommunications technology, the ability to interconnect into the existing set f monopoly local exchange carriers. All new and innovative alternative carriers have had this problem. The LECs have raised various barriers to entry. Such carriers as MFS and Teleport have battled hard and long to achieve mere co-location of their switching equipment. Others, such as Telmarc Telecommunications, have battled to obtain Common Carrier status and eliminate access fees. This factor may be the one barrier that cannot be dealt with other than through regulatory relief. In fact, it is illegal in certain states, such as Virginia and New Jersey to be a Local Exchange Carrier, if you are not the entrenched monopoly player. Clearly there will be major legal and regulatory battles on this front.

- Dominant Market Players: Any market with dominant players and having many others will generally be controlled by the dominant players. The Dominant players may effect the other players through the standards process, raising the cost to compete, through the regulatory process, raising the cost to provide service, and through the legal process raising the cost to litigate and operate. Admittedly, it has been shown, that through long term market forces, with all players being equal at the outset, any market will converge to a small set of stable and competitive players, if the market starts with a asset of dominant players with the ability to delimit the new competitors, then the new entrants will be at significant risk of failure through the power of the dominate players.

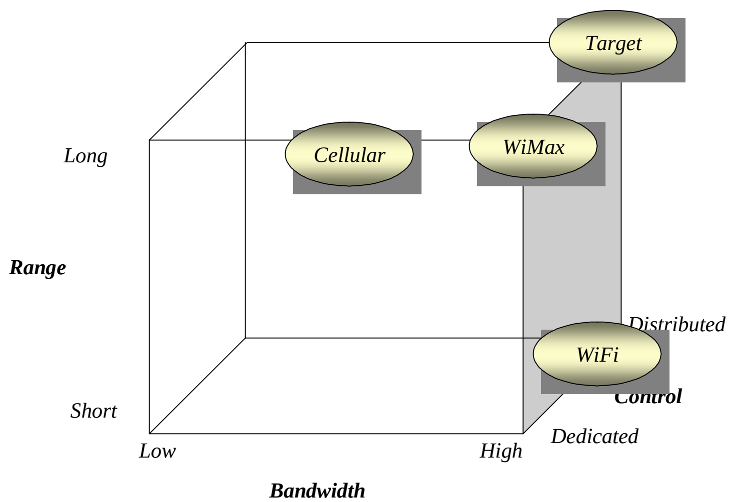
These and other factors will determine how the spectrum can be allocated. In the next section we present a discussion of the four canonical architectures.

2.3 Options and Evolution

There are options which can be explored and evolutionary paths available. This sections details some of those. The issue is how does one get from where we are today to the proposed environment of micro bandwidth markets on demand?



The view taken in this paper is for a technology as shown in the following. It enables long range, high bandwidth and distributed control. The distributed control is via an efficient micro transaction process or mechanism as developed herein.



2.4 Policy Approaches

We consider three policy directed approaches and details some of the advantages and disadvantages of each.

2.4.1 The Gilder Conjectures

Gilder has postulated several conjectures, which we summarize, and will return to after the analysis. These conjectures are as follows[2]:

***(1) Many Users can occupy the same spectrum at one time.*[3] *There exists a well defined set of protocols that allow this and prevent collisions.*[4] *There further exists a set of workable multiple access/interface technologies that can be interchangeably used.*[5]**

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. What has transpired since the Gilder conjectures were first presented is

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[2] See McGarty & Medard. In this paper written in 1994 there is a detailed analysis of the wireless conjectures posed at that time by Gilder. In the paper we looked at the conjectures in the context of 1994 technology and stated that they were unachievable. However, now looking at them in the context of a wireless grid or mesh world they conjectures if properly interpreted and be achievable and actually act as a set of guidelines for deployment and extension.

[3]Gilder, p. 100.

[4]Gilder, p. 112.

[5]Gilder p. 112.

that technology can allow multiple users in one of two extremes; universally agreed to standards with PHY/MAC such as 802.11 and all users sharing on a best efforts basis, and second, ownership of spectrum and no cross compatibility.

(2) Frequency and modulation/multiple access schemes are utterly unnecessary.[6]

Gilder assumes that worrying about the technical details such as modulation and multiple access is a secondary factor, at best. The truth of the matter is that they are critical. However they are also highly polyglot and must be dealt with individually but simultaneously.

(3) Networks can be made open and all of the processing done in software.[7]

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.[8]

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.[9] ***Spectrum is abundant.***[10]

This conjecture assumes or posits that spectrum can be "created" de novo from a combination of what is available and the technological "productivity" gains. However, if there is an economic market then real time micro-transactions involving the transactions of and access to bandwidth are readily achieved.

(6) Spectrum can be used any way one wants as long as one does not interfere.[11] ***New technology makes hash of the need to auction off exclusive spectrum, spectrum assignment is a technological absurdity.***[12]

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. To some degree that is what the users of 802.11 technology believe since the underlying applications are transparent to the user. However the service level or QoS issues are not taken seriously in current 802.11 technologies, not saying that they ultimately will not be.

2.4.2 Property Rights (Devaney Approach)

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[6]Gilder, p. 104.

[7]Gilder, p. 104.

[8]Gilder, p. 110.

[9]Forbes, p. 27.

[10]Gilder, p. 100.

[11]Gilder, p. 111.

[12]Forbes, p. 27.

There is another approach credited to deVaney looking at spectrum as a property right. Specifically he argues that we place all spectrum into the market, using deVany et al. property rights proposal (Stanford Law Review, 1969)

Two alternative spectrum ownership models then evolve: (i)Ownership with non-interference: own the spectrum and have absolute use priority; others can use it but only if they don't interfere with this absolute use priority UWB and agile radio OK; enforcement, (ii) Ownership with real-time leasing: own the spectrum and you can use it if you pay me; Identifiable emitter, Real-time price, long-term lease price, Perfectly competitive market, Software to negotiate and bill (BMI and ASCAP models), UWB and agile radio OK; billing

What are the results of these two models. Fulhaber et al argue as follows. Either model accommodates both private ownership and commons-type uses. However the questions remain: Who pays? And How robust with respect to scarcity? The authors further argue that in the medium term, both models are likely to have identical results (if all spectrum placed in market), namely moving all spectrum to markets and using dynamic allocation will free up so much spectrum the market price is likely to be close to zero: de facto Commons! In the medium term, there is no real scarcity since the results approaches zero price, except for "prime real estate," such as cellular-friendly spectrum and legacy spectrum.

2.4.3 Kwerel & Williams "Big Bang" auction

A third view is that proposed recently by Kwerel and Williams. It can be summarized as follows:

1. Announce auction 1 year in advance
2. All current licensees may put all or some of "their" spectrum in the auction. Not required; but then constrained from market for 5 years
3. FCC puts all "white space" bands to auction
4. Bidding is opened; anyone can bid for any band offered, or combination thereof.
5. Licensees may choose to accept a bid; if they do, they receive the bid money
6. Licensees may choose to reject the bid and keep the spectrum.
7. All spectrum placed in auction becomes private property, with all the technical (but not use) restrictions of the current licensee. Repackaging of some bands may be helpful
8. Secondary markets ensure that buyers and sellers can transact continuously. "Big Bang" creates liquidity
9. Spectrum can be aggregated, subdivided, bought, sold or leased.
10. FCC and NTIA retire from the allocation business.

This model for spectrum allocation is showing a total disregard for any technological solution and even worse any technological change. It further compounds the problems of a property right world with exclusion. Our approach is a property right world with inclusions via a micro transaction approach.

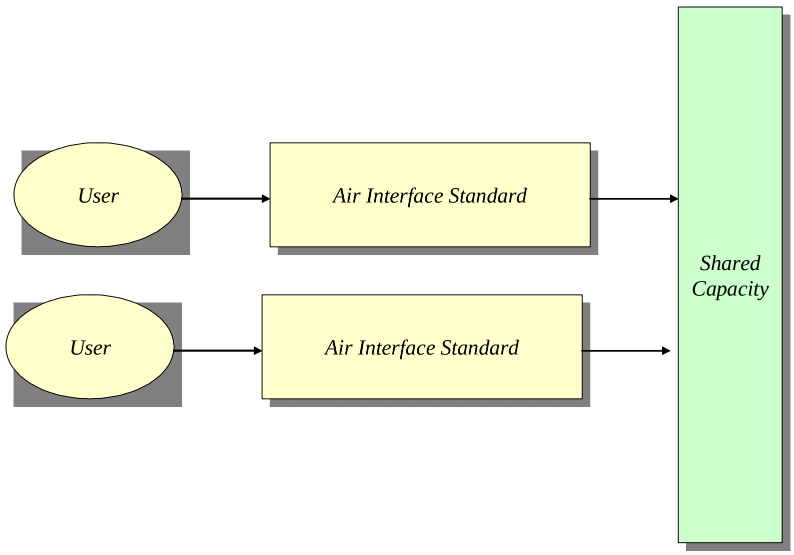
3. GENERAL ARCHITECTURE ELEMENTS

We can view the options to optimizing channel capacity in the following manner in three possible steps or levels. They are shown as follows:

3.1 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.

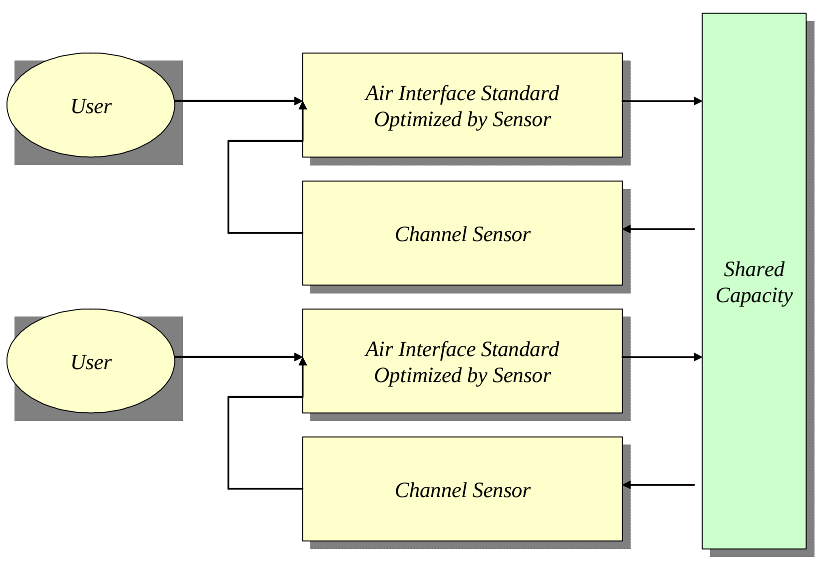
Level 1: Passive Capacity Access



3.2 Level 2: Sensing and Adaptive Air Access

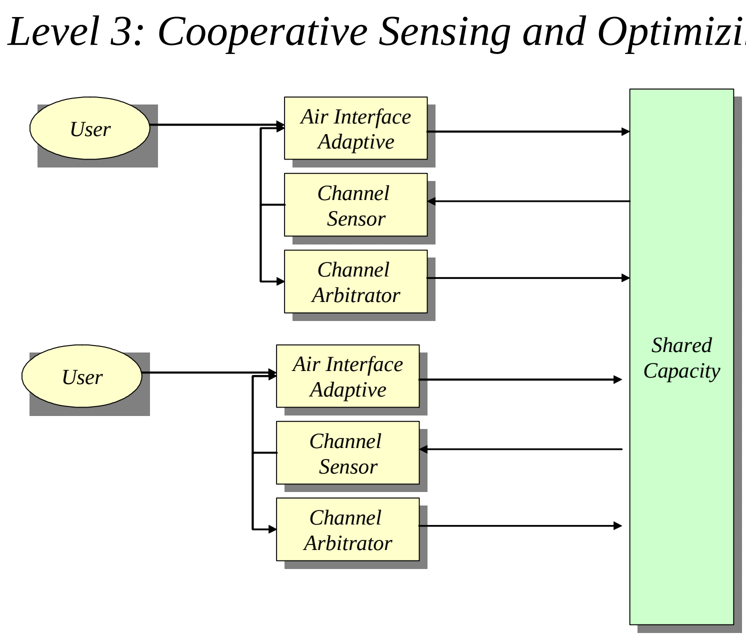
The next approach is to sense the environment and modify the air interface in some manner. The modification may be signal level modulation multiple access or even antenna parameters. In all cases the sensor sniffs the environment and there exists some optimization scheme assuming all players in the environment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

Level 2: Sensing of Interference



3.3 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.



3.4 Implementation Strategy

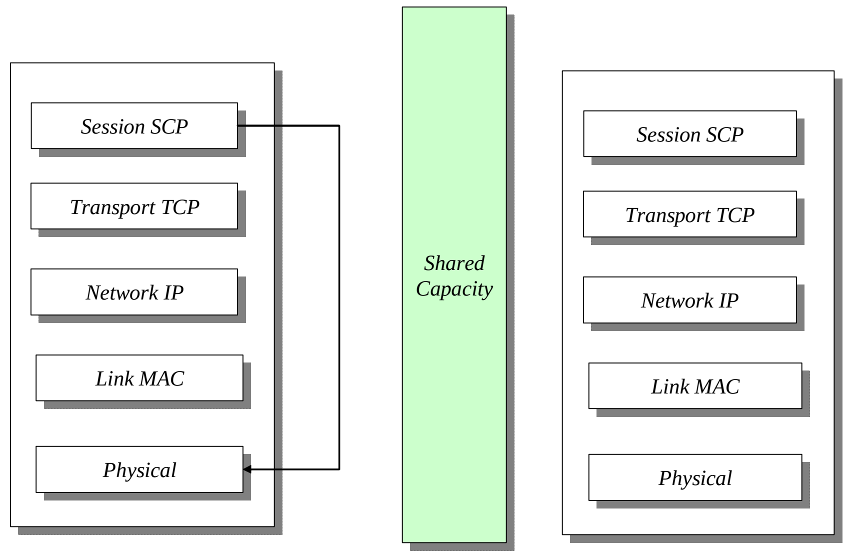
The implementation of the arbitrator model is akin to TCP/IP. It should be minimalists with enhancements and it should be at the software level not requiring an ASIC based standard. It also must interface with any and all standards at the lower layer. We argue that Layer 5, the Session layer is the best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

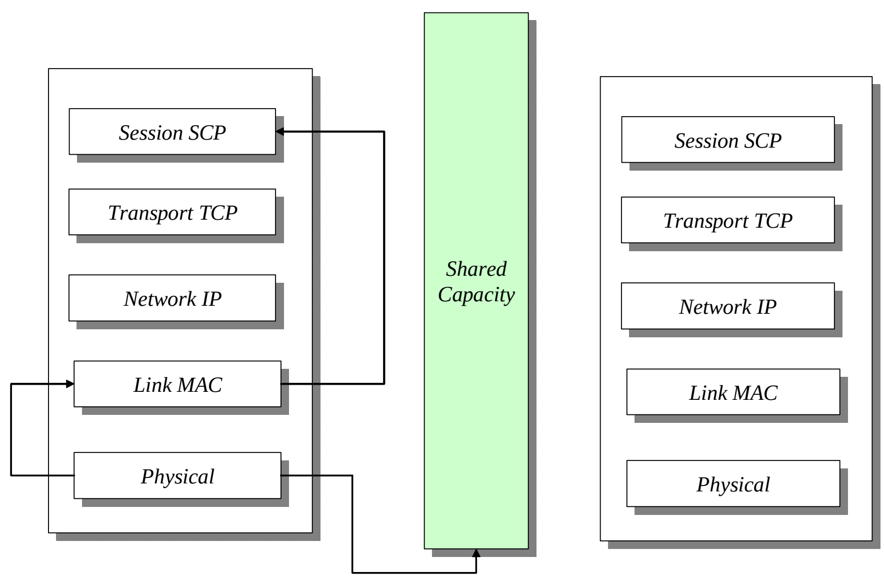
Step 1: This is the step of sensing the standard of the channel. This uses the standards in Layer 1 and 2 and their already defined characteristics. The Session implementation uniqueness is also that it contains a tool box for the implementation and integration of any standard.

Step 1: Sense Air Interface Standard

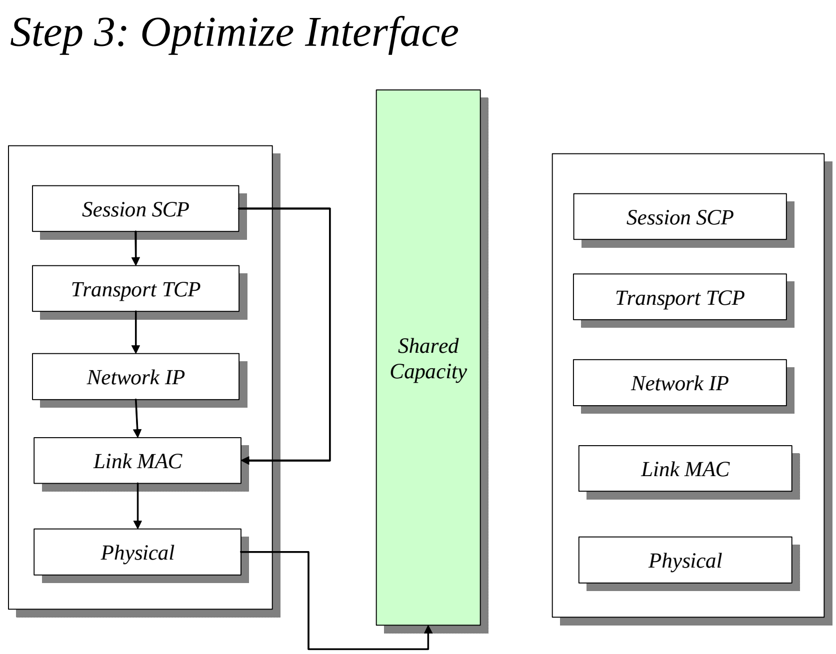


Step 2: This senses the interference on the channel. It uses a set of algorithms which can generally sense layer 1 and layer 2 signalling and uses the already existing signal and channel sensing elements of the standards sensed.

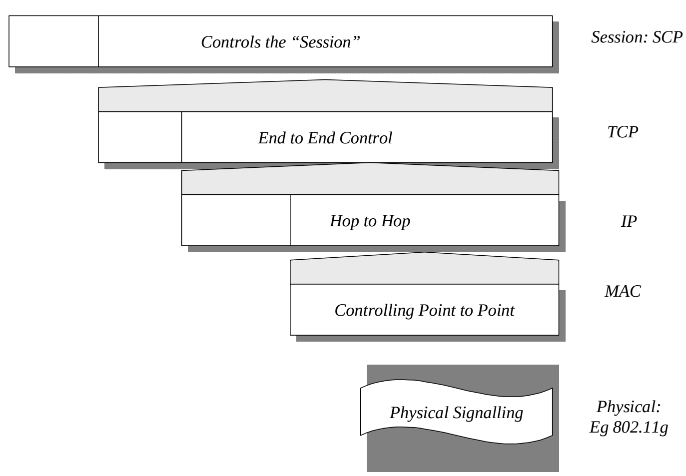
Step 2: Sense Interference



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:

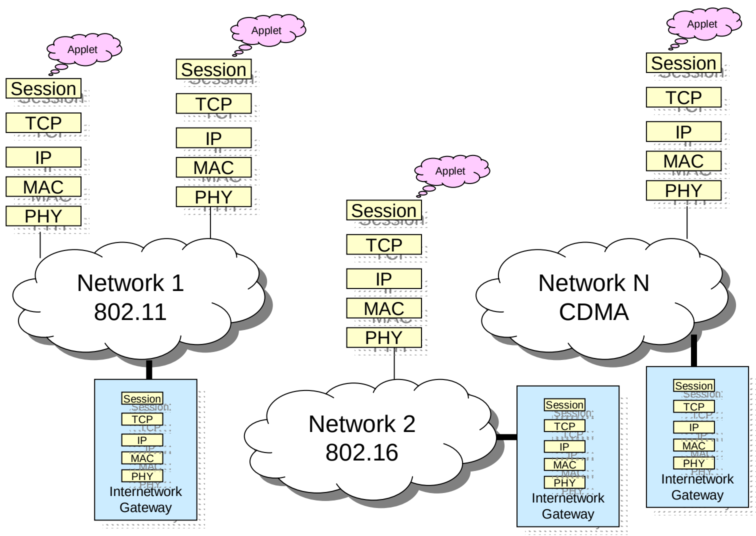


3.5 Architecture

The architecture of a sharaeble 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 anticipatedin such systems as 802.16.[13]

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

Architecture

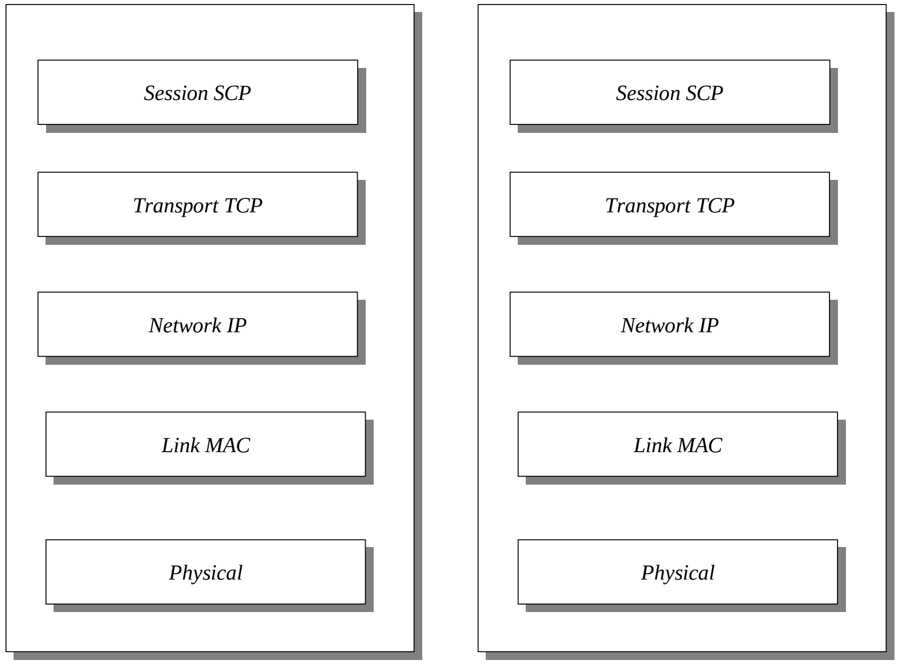


4. SESSION LAYER FUNCTIONAL STRUCTURE

This section provides a detailed discussion of the session based approach to spectrum markets vi micro transactions.

4.1 Overall Architectural Options

The first step is to understand where this function of capacity allocation best belongs. In the seven layer approach to communications protocols we have the configuration shown below:



4.2 Session Layer Functions

The OSI layered communications architecture has evolved to manage and support the distributed communications environment across error prone communications channels. It is presented in detail in either Tannenbaum or Stallings. A great deal of effort has been spent on developing and implementing protocols to support these channel requirements. Layer 7 provides for the applications interface and generally support such applications as file, mail and directory. The requirements of a capacity allocation environment are best met by focusing on layer 5, the session layer whose overall function is to ensure the end to end integrity of the applications that are being supported.

Some authors indicate that the session function is merely to support virtual connections between pairs of processes.[14] Mullender specifically deals with the session function in the context of the inter-process communications (IPC). In the context of the capacity allocation object requirements of the previous section, we can further extend the concept of the session service to provide for IPC functionality at the applications layer and specifically with regards to capacity allocation applications and their imbedded objects.

We discuss the generally accepted services of the session layer and then we will show how they can be used as a micro transaction layer in support of the enhanced spectrum utilization goal presented herein. The services provided by the session layer fall into four categories:

1. **Dialog Management:** This function provides all of the users with the ability to control, on a local basis as well as global basis, the overall interaction in the session. Specifically, dialog management determines the protocol of who talks when and how this control of talking is passed from one user to another.

2. **Activity Management:** An activity can be defined as the totality of sequences of events that may be within a session or may encompass several sessions. From the applications perspective, the application can define a sequence of events called an activity and the session service will ensure

[14] See Couloris and Dollimore or Mullender

that it will monitor and report back if the activity is completed or if it has been aborted that such is the fact. For example, in a medical application, we can define an activity called "diagnosis" and it may consist of a multiple set of session between several consulting physicians. We define a beginning of the activity when the patient arrives for the first visit and the end when the primary physician writes the diagnosis. The session service will be responsible for ensuring that all patients have a "diagnosis".

3. **Synchronization**: We have seen that at the heart of a capacity allocation system is a capacity allocation data object. Each of the objects has its own synchronization or timing requirements and more importantly, a compound object has the orchestration requirement. The session service of synchronization must then ensure that the end to end timing between users and objects is maintained throughout.

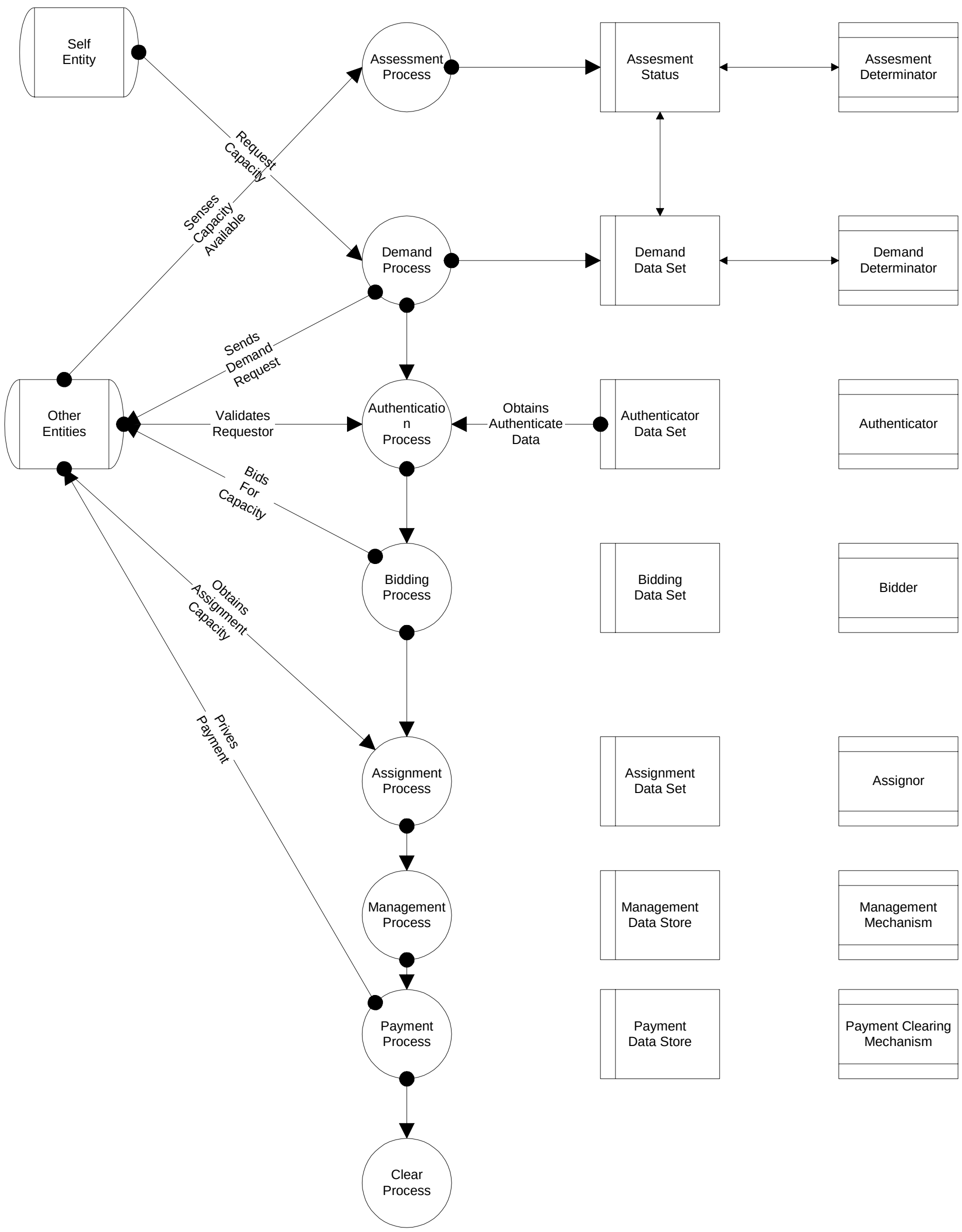
4. **Event Management:** The monitoring of performance, isolation of problems, and restoration of service is a key element of the session service. Full end to end network management requires not only the management of transport and sub network, but requires that across all seven OSI layers, that overall end to and management be maintained[15] .

4.3 State Model

The overall state model for the session layer process is shown below. It consists of eight processes which perform eight distinct but related functions. The processes all reside at the session layer and can be implemented by session layer primitives as will be shown latter. We will relate each of the four session primitive functions; dialog, activity, synchronization, and event; to each of these eight processes. The processes may be viewed as applets which can be real time downloaded to each and every agreeing participant in the network mesh or grid. This session layer approach is fundamentally different from all other approaches which try and put this functionality at lower layers. We argue herein that the session layer is the optimal location, especially in networks deploying TCP/IP.[16]

[15] See McGarty and Ball

[16] See Stallings for a detailed discussion of the Session layer. Recently there has been a de-emphasis on session with a stronger focus on PHY and MAC. Our argument is that this new emphasis is essential.

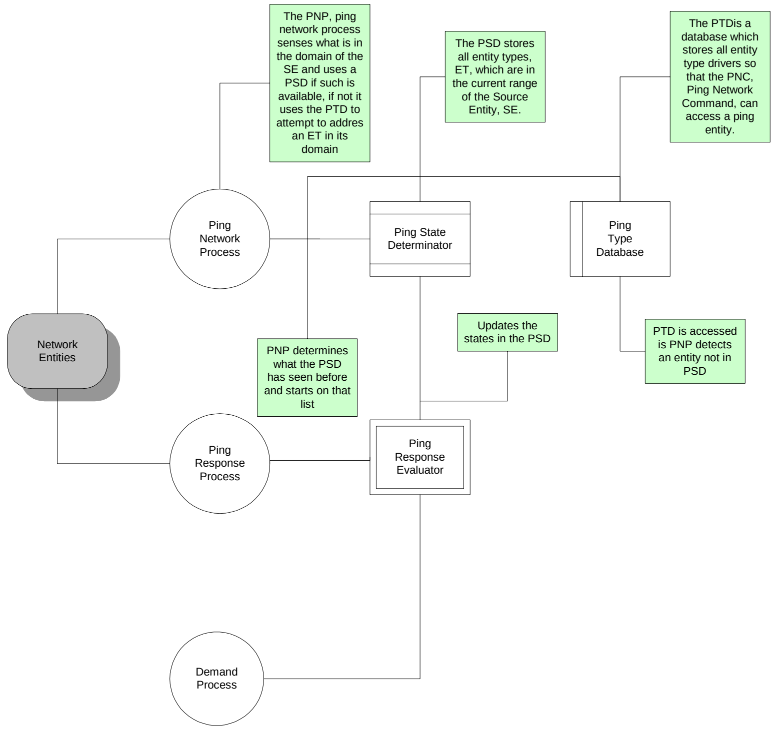


4.4 Element Functionalities

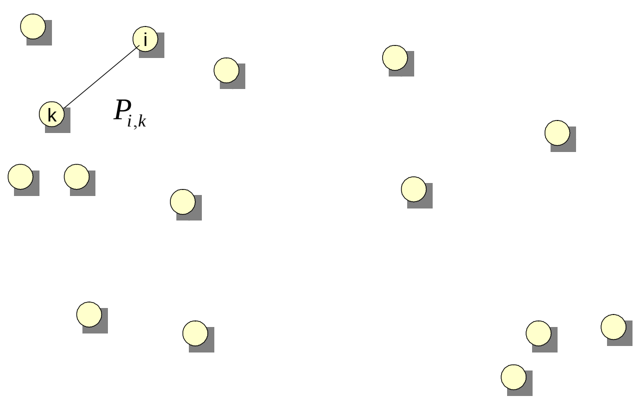
4.4.1 Assessment

Assessment is the process of scanning what is out there and reporting it to the common data file at each user.[17] The assessment function must be able to tap into the various layers of other air interface standards and transfer the sensing of their status to each other entity in a fully distributed manner. The assessment function must be able to accomplish the following flows.

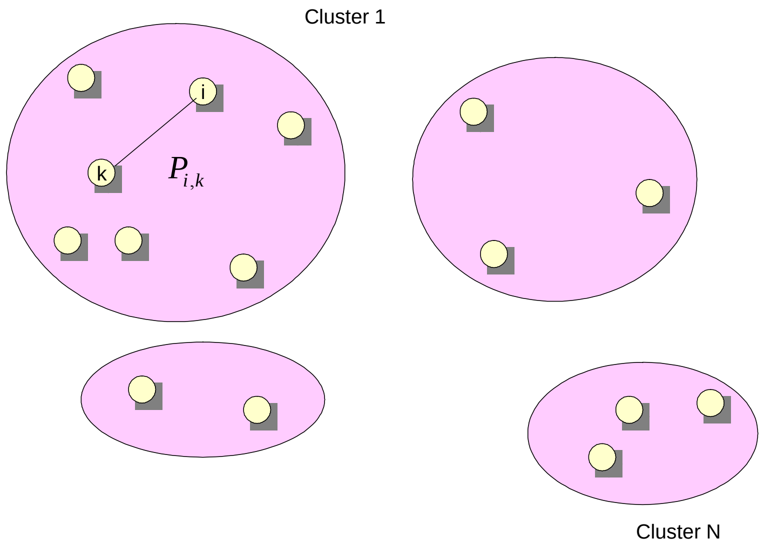
[17] See materials from Meshnetworks as example of self managing systems over disparate air interfaces.



The assessment process may be very simple or it can be quite complex. For example, consider a set of users and consider that each user pair can have a determinable power between each, $P_{i,k}$. Then the users would appear as follows:



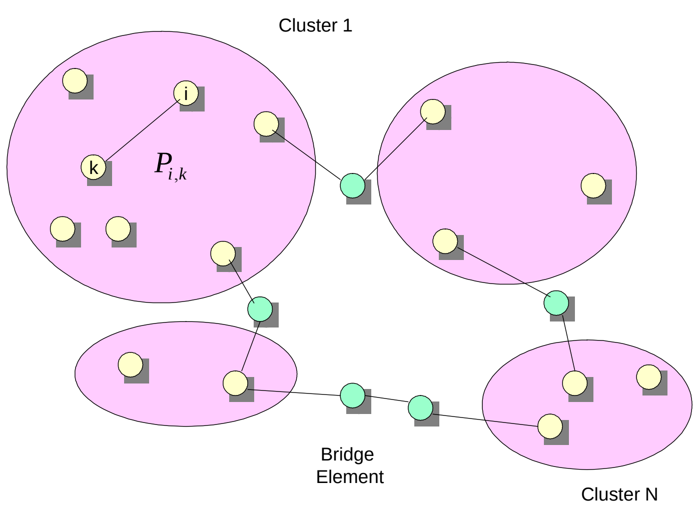
Now assume that there were some algorithm which allowed sets of these users to talk with one another and just determine their presence, relative to each other. Namely we collect cluster of users whose inter-user power is always greater than some value, say a threshold. This would result in some cluster set of users, namely those who could in some way "talk" with each other. This is shown below:



We need to solve two problems:

First, we then need some algorithm to create the clusters and to manage them;

Second, we need some mechanism to allow for the introduction of cluster bridges to allow for the interconnection of the clusters. This is shown below:



The bridge elements are to be provided by some centralized or distributed control entity and are used to create bridges between the clusters. The bridges may most likely but not necessarily be the user elements themselves.

Thus the assessment function must satisfy the following processes:

Determination of neighbors: this is effectively an RF sensing mechanism.

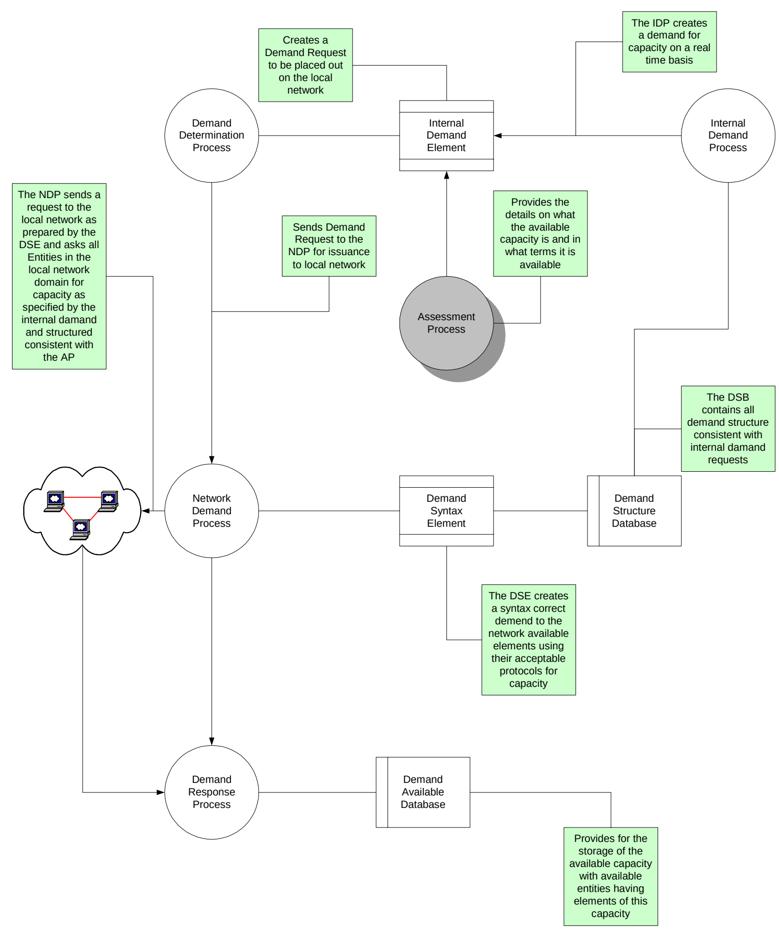
Construction of Clusters: this is a power based clustering process. Cluster analysis can be performed using power as the distance metric.[18]

Bridge Construction: this process must be facilitated by some overseeing entity which can work between clusters. The clusters may never know the existence of other clusters, thus the bridge builder must transcend that.

4.4.2 Demand

The demand function is potentially a complex function. It may demand not just a single link but a collection of links as may be required to meet the desired service level. For example in the assessment function the function scans what is available and then provides a data base to present to the demand function. The demand function looks at what is required for the service delivery and looks at what is available and creates an amalgam demand. For example, to ensure adequate service quality the demand function may select multiple paths between the entities communicating, not just a single path. These multiple paths may all be used simultaneously and the results processed from one extreme of selecting the best to the other extreme of using all in some optimally weighted process.

The demand process must be capable of accomplishing the following:

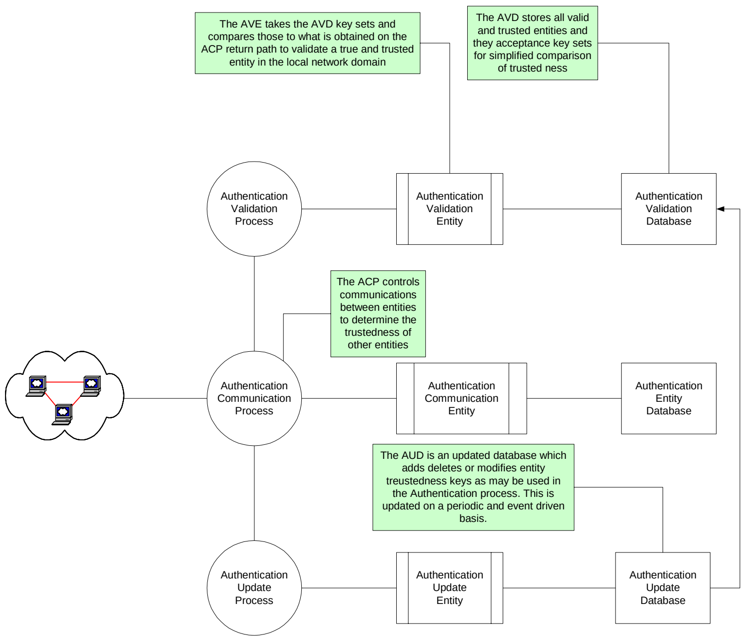


4.4.3 Authenticate

[18] See Cover, Nearest Neighbor Algorithms, IEEE Information Theory, 1968.

The authenticate function requires that the entitles be capable of determining that they are sharing resources with accredited and trusted entities. Thus authentication must be capable of various authentication processes between each other in a fully trusted and distributed real time environment.

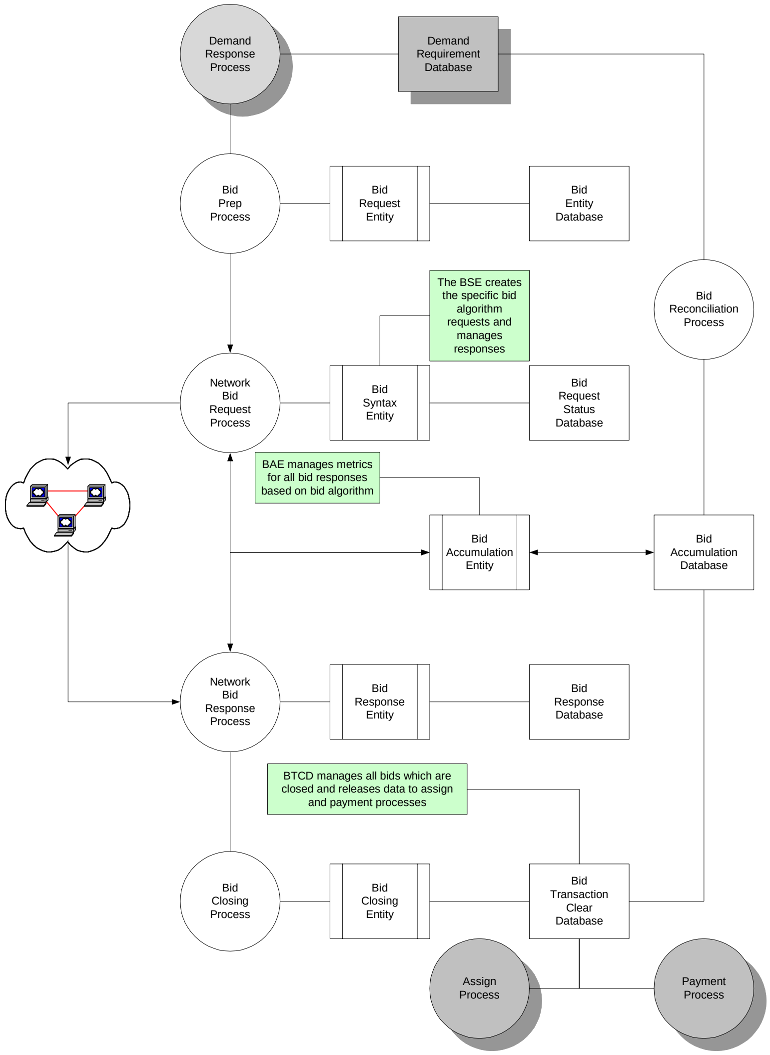
The authentication process is shown below.



4.4.4 Bidding

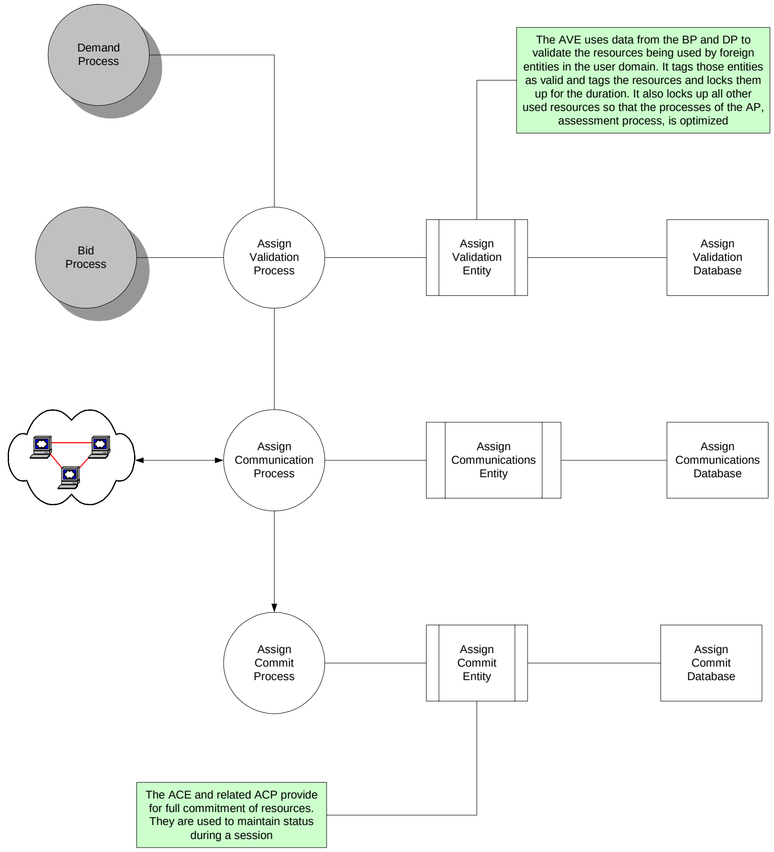
All spectrum from participants agreeing to participate in the grid is fungible and can be sold or transacted with any other user, a buyer. This is based upon micro-transaction technology. Micro-transaction technology requires a very low overhead, fast, highly distributed and low transaction cost technology for bidding on and closing on bids between multiple parties in real time. Micro transactions may accumulate fees and the “clearing” of the market transactions may take place on a non real time basis.

Many different algorithms have been developed for micro transactions but they are generally for small real transactions such as those in banking, telecommunications, and retail. The level of micro herein is substantially by orders of magnitude smaller than what is found in most state of the art transactions. The costs of the transaction must be de minimis.



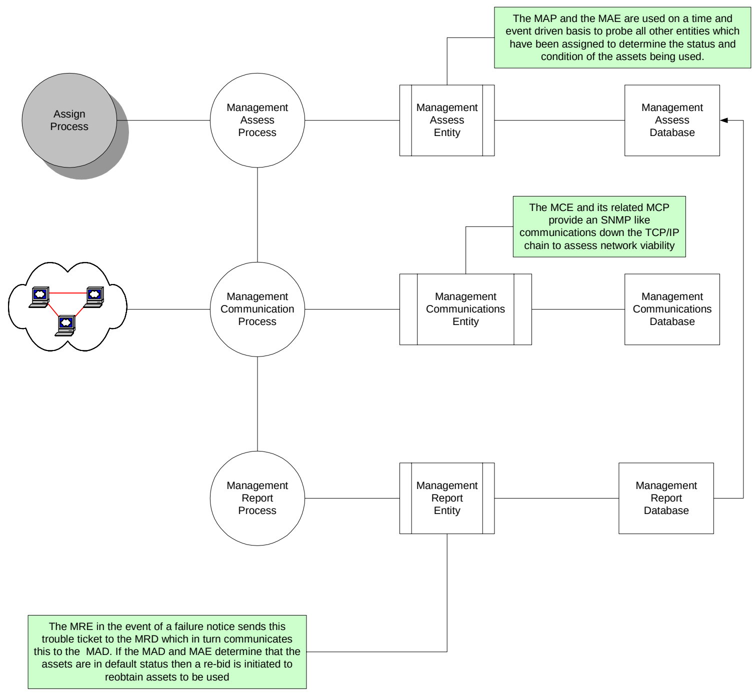
4.4.5 Assignment

Assignment is the process whereby the actual resources are assigned to each entity. Assignment may be a real time process under the control of the management process. The overall structure is shown below.

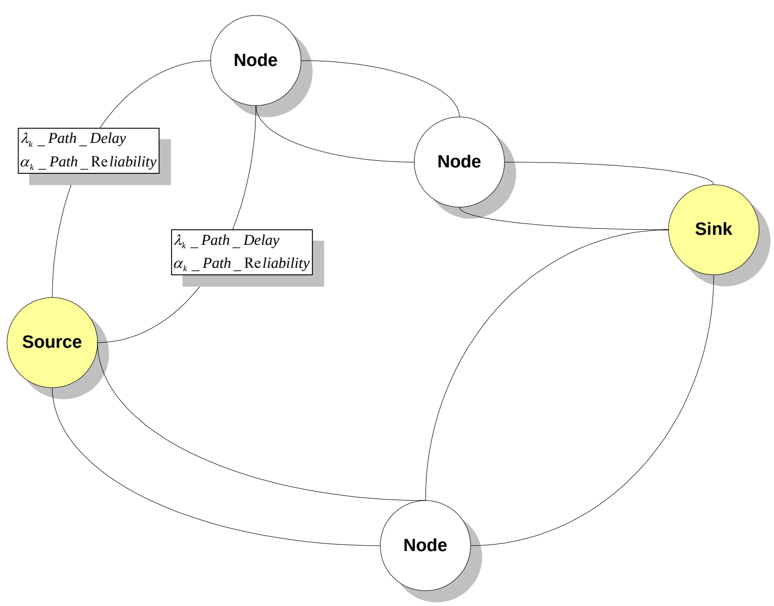


4.4.6 Management

The management function process performs two distinct functions: management of the ordinary functions of the network when set up and optimization in a real time manner of network assets. He latter is a critical function which is essential for the overall QoS of the network connection.

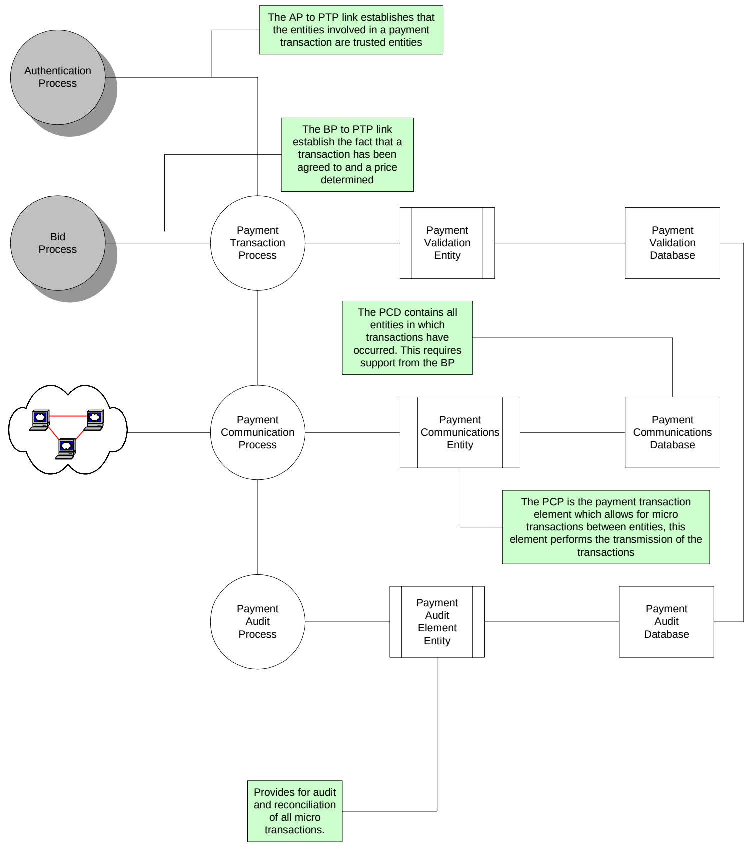


The management process also has several key elements of link optimization and utilization. Consider the following figure with a source and sink and a set of intermediate nodes with links to all. In fact there may be multiple links to all. The management process may then use some form of optimized link utilization sub process to select the best link or best weighted combination of links. The links may have a delay λ and a reliability α. The factors may be random processes as well. Then the management process must be dynamically utilizing all available assets in order to ensure the quality of service desired by the using application.



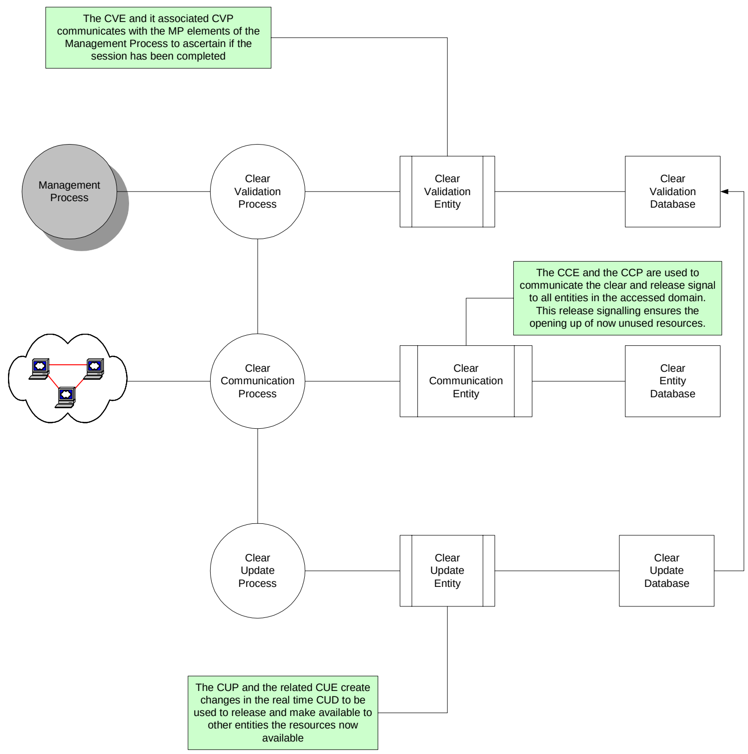
4.4.7 Payment

The payment function process is a non-real time true up of all transaction costs. It may be run on a time driven or event driven basis depending on the design parameters. The payment generally is a "credits" based system wherein credits are built up or traded and that at some time any user exceeding some credit level will have to true up with a cash based payment as well. Generally however it is anticipated that if there is balanced and non-discriminatory use there may only infrequently be a money based true up.



4.4.8 Clear

The clear function process is the simplest. It just releases all assets and ensures that the assets are made available again in a real time manner.



4.5 Session Layer Functions and Spectrum Allocation Processes

The following depicts the correlation of the elements with the Session layer functions.

	Dialog Management	*Activity Management*	*Synchronization*	*Event Management*
Assessment		X		
Demand	X		X	
Authenticate	X		X	
Bidding	X	X		X
Assignment	X	X		
Management				
Payment		X		X
Clear			X	X

The above shows that one can create and operate the processes using the primitives available within the session layer set of protocols. The detailed implementation of these processes will be discussed in the following section.

5. SESSION LAYER PRIMITIVES AND OPERATIONS

This section discusses the overall architecture of the proposed system.

5.1 Detailed Session Functionality

Here we have shown the session entity which is effectively a session service server. The entity is accesses from above by a Session_Service Access Point (S_SAP). The session entities communicate through a Protocol Data Unit (PDU) that is passed along from location to location. Logically the session server sits atop the transport server at each location.

The servers are conceptually at a level above the transport level. We typically view the transport servers as communicating distributed processes that are locally resident in each of the transmitting entities. This then begs the question as to where does one place the session servers. Are they local and fully distributed, can they be centralized, and if so what is their relationship to the Transport servers. Before answering these questions, let us first review how the session services are accessed and how they are communicated.

Session services are accessed by the higher layer protocols by invoking session service primitives. These primitives can invoke a dialog function such as Token_Give. The application may make the call to the S_SAP and this request may be answered. There are typically four steps in such a request, and these are listed in Stallings who shows that the requests are made of the session server by entity one and are responded to by entity two. The model does no however say where the session server is nor even if it is a single centralized server, a shared distributed server, or a fully distributed server per entity design. We shall discuss some of the advantages of these architectural advantages as we develop the synchronization service.

5.1.1 Dialogue Management

Dialog management concerns the control of the end user session interaction. Specifically, who has permission to speak and when, who can pass the control and how is that implemented. In this section we shall describe the environment for the dialogue management function and develop several possible options for implementing this function.

Dialog management requires that each of the virtual users have a token or have access to a baton in order to seize control of the session. In the course of a typical session, the two virtual users fist establish the initial subsession that becomes the first part of the session. The addition or binding of other virtual users through subsessions to the session allows for the growth of the session. The baton or token may be a visible entity that is handed from one to the other or it may be hidden in the construct of the applications.

Consider the session level service called dialogue. The service can be implemented in four possible schemes. These schemes are:

(1) **Hierarchical:** In this scheme there is a single leader to the session and the leader starts as the creator of the session. The baton to control the session can be passed upon request from one user to another, while full control remains with the session leader. The session leader may relinquish control to another user upon request and only after the leader decides to do so. The leader passes the baton from users to user based upon a first come first serve basis. It is assumed that each users may issue a request to receive the baton, and that any requests that clash in time are rejected and the user must retransmit. There transmit protocol uses a random delay to reduce the probability of repeated clashing. The leader always acknowledges the receipt of the request as well as a measure of the delay expected until the baton is passed.

(2) **Round Robin:** In this scheme, the baton is passed sequentially from one user to another. Each user may hold the baton for up to Tbat sec and then must pass the baton. When the baton is held, this user controls the dialogue in the session.

(3) **Priority:** In this case, all of the users have a priority level defined as $P_k(t)$, where k is the user number and t is the time. We let the priority be;

$$P_k(t) = R_k(t) + T_k(t) + D_k(t)$$

Here R is the rank of the k th user, T is the time since the last transmission and D is the data in the buffer. We assume that some appropriate normalization has occurred with this measure.

Every T_{check} seconds, each users, in sequence sends out a small pulse to all other users, on a broadcast basis, and tells them their current priority. Each user calculates the difference between theirs and all the others. User k calculates a threshold number, TR_k, which is;

$TR_k = \max |P_k(T)-P_j(T)|$

If $TR_k > 0$, then user k transmits its packets for T_{send} seconds.

(4) **Random Access**: Each user has a control buffer that indicates who has control of the session, namely who has the baton. The session is broken up into segment T_{sess} in length, with T_{req} seconds being relegated to a baton ownership selection period and T_{sess}-T_{req} being left for the session operation. During T_{req} , all of the users transmit a request packet that is captured by all of the other users buffers. T_{req} is broken into two parts, T_{send} and T_{eval}. These requests are broadcast in T_{send}.

Now after the sent messages are received, one of two things can happen, the message is received or it collides with another message and is garbled. If the message is garbled, the buffer is not loaded and is left empty. If it is filled, then each buffer during T_{eval} sequentially broadcasts its contents and all of the users listen to the broadcast and record the counts, N_k where N_k is the number of votes for user k in that call period.

The choice of baton control is then;

Choose user k if $N_k = \max_j | N_j |$

else restart T_{req} again.

For each of the protocols we describe the advantages and disadvantages of each in Table 4.3.

Table 4.3 Dialog Protocol Comparison

Protocol	**Advantage**	**Disadvantage**
Hierarchical	Single Point of Control of the Session.	Lacks capability to have open discussion.
Priority	Establishes who is in charge by allocation.	Requires a scheme to give priority that may be open to compromise.
Round Robin	Everyone gets to talk. Egalitarian approach.	May be excessively time consuming.
Random	Strongest player wins.	May not permit dissent.

5.1.2 Activity Management

Activity management looks at the session as an ongoing activity that users may come and go to. This services provides an ability to easily add, delete and terminate the entire session.

An activity in the terms of the session is a total bounded event that can be compartmentalized in such a way that other events may be locked in suspension until that event is complete. Activity management is in the session layer a function similar to transaction management in a transaction processing system. It allows for the definition of demarcation points that permit suspension of activities in other areas until the activity managed transaction is complete. Activity management can also be developed to manage a set of events that can be combined into a single compound event.

There are several characteristics that are part of activity management:

1. **Activity Definition:** This allows for the defining of an activity as composed of several dialogue. It allows for the defining of the activity as a key element of a single session or even to expand over several sessions. Activity definition is the process of informing the session server of the beginning and end parts of an activity and in providing the session server with an identifiable name for the activity.

2. **Activity Integrity Management**: Activities are integral elements of action that cannot be segmented. The activity management system must ensure that once an activity is defined and initiated, hat no other activity that could interfere with the existing one is allowed to function.

3. **Activity Isolation:** The ability to provide integrity is one part of managing the activity. Another is the ability to isolate the activity from all others in the session. An activity must be uniquely separable from all other activities, and this separation in terms of all of its elements must be maintained throughout its process.

4. **Activity Destruction:** All activities must be destroyed at some point. This is a standard characterization.

There are several sets of activities that are definable in a capacity allocation environment. These are as follows:

1. Compound Capacity allocation Object Transfer

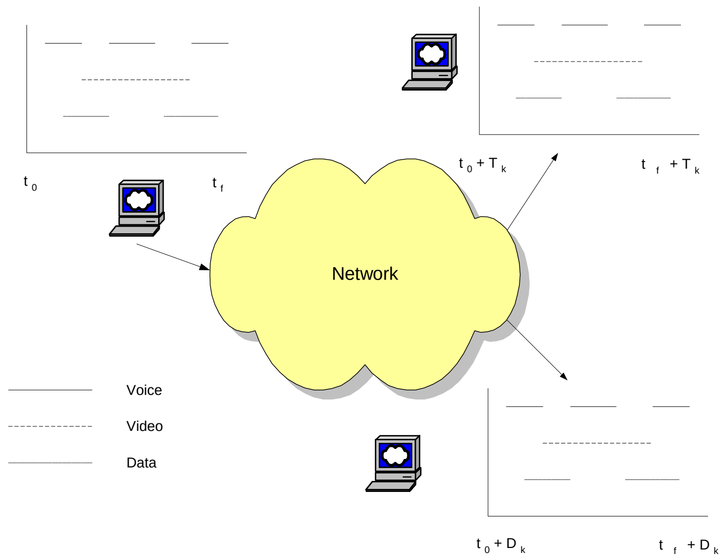
2. Subsession Management

3. Dialog Control

The algorithms to perform the activity management functions are developable consistent with the OSI standards. There are no significant special development necessary.

5.1.3 Synchronization Management

Synchronization is a session service that ensures that the overall temporal, spatial and logical structure of capacity allocation objects are retained. Consider the example shown below. In this case we have a source generating a set of Voice (VO), video (VI), and Image (IM) data objects that are part of a session. These objects are simple objects that combined together form a compound capacity allocation object. The object is part of an overall application process that is communicating with other processes at other locations. These locations are now to receive this compound object as show with the internal timing retained in tact and the absolute offset timing as shown for each of the other two users. The following figure depicts the synchronization concept for a session based system.



In this example, the synchronization function provided by the session server to the applications processes at the separate locations is to ensure both the relative and absolute timing of the objects. The location of the functionality can be centralized or distributed. Let us first see what the overall timing problem is. Consider a simple SMO synchronization problem. The network than transmits the packets and they arrive either in order or out of order at the second point. The session server must then ensure that there is a mechanism for the proper reordering of the packets at the receiving end of the transmission.

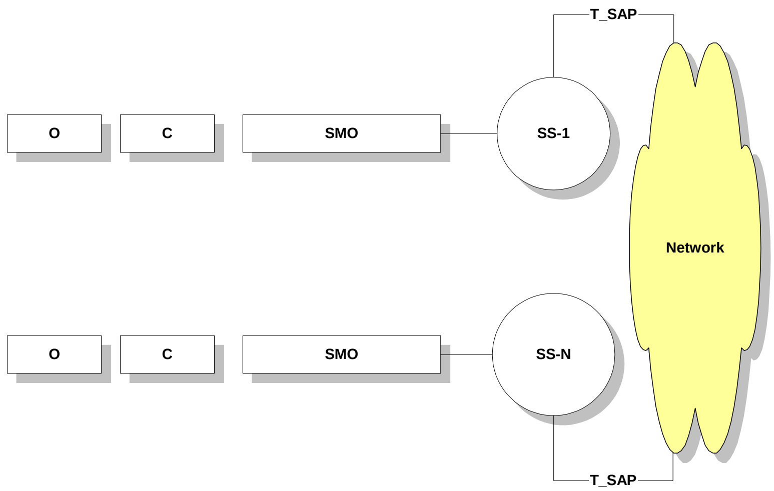
Let us consider what can happen in this simple example.

- First, if the BMO of the SMO is very lengthy, then as we packetize the message, we must reassemble it in sequence for presentation. Let us assume that the BMO is an image of 100 Mbits. Then let us assume that the packet network has a packet delay that will be low if there is no traffic and grows as traffic increases. Now let us assume that the network provides 500 bit packets transmitting at 50 Mbps.

- Second, let us note that there are 200,000 packets necessary to transmit the data. Each packet takes 10 microseconds to transmit. If we assume that there is a load delay of 5 microseconds per packet, then the total transmit time goes from 2 to 3 seconds.

We can also do the same with a compound object. In this case, we take the CMO and note that it is composed of SMOs. The SMOs must then be time interleaved over the transmission path to ensure their relative timing. It is the function of the session service to do this. The application merely passes the CMO and its header information as a request to the session server to ensure the relative timing is maintained.

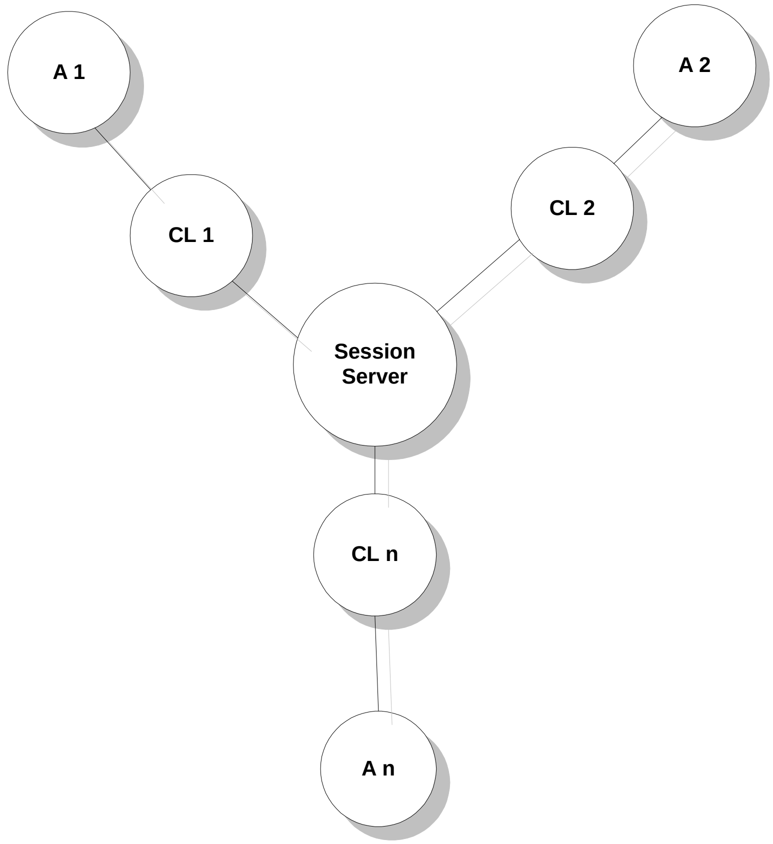
The architecture for the session synchronization problem is shown below. Here we have a CMO entering the network, knowing that the session server at Server 1 must not only do the appropriate interleaving but it must also communicate with the other servers (in this case K and N) to ensure that de-interleaving is accomplished. We show the session servers communicating with the network through the T_SAP and that in turn takes care of the packetizing. However, we also show that the session server, 1 and N, communicate in a out of band fashion, using some inter process communications (IPC) scheme, to ensure that the relative actions are all synchronized amongst each other. The following figure depicts the synchronization architecture.



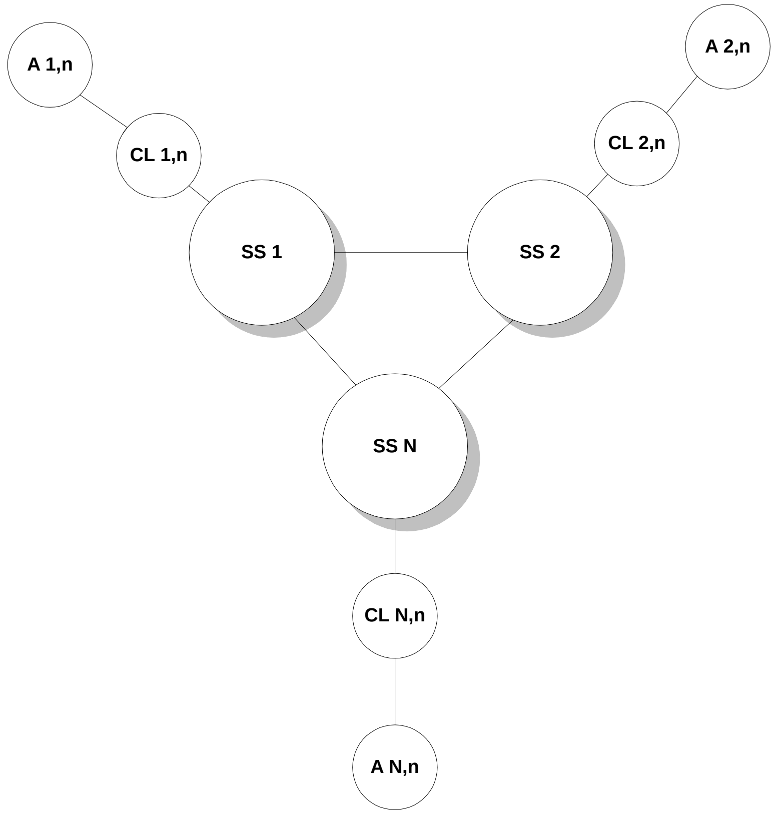
We can now envision how the architecture for this can be accomplished. There are two schemes:

Centralized: Figure below depicts the centralized synch scheme for the session service. It assumes that each application (A) has a local client (CL). The application communicates with the local client (CL) to request the session service. The session server is centrally located and communicates with the application locally by means of a client at each location. This is a fully configured client server architecture and can employ many existing techniques for distributed processing ([19]). The centralized architecture is shown below.

[19] See Mullender or Coulouris et al



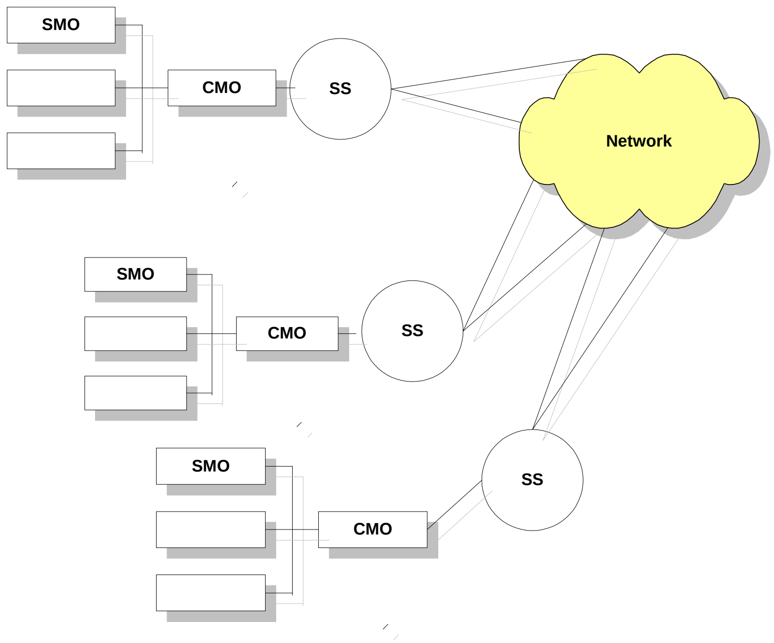
Distributed: In contrast to the centralized scheme, we can envision a fully distributed session server architecture as shown below. In this case we have a set of applications, and cluster several applications per session server. We again user local clients to communicate between the session server and the applications. The clients then provide local clusters of communications and the session servers allow for faster response and better cost efficiency. However, we have introduced a demand for a fully distributed environment for the session managers to work in a distributed operating system environment. As a further extreme, we could eliminate the clients altogether by attaching a session server per applications and allow for the distributed processing on a full scale. The distributed architecture is shown below.



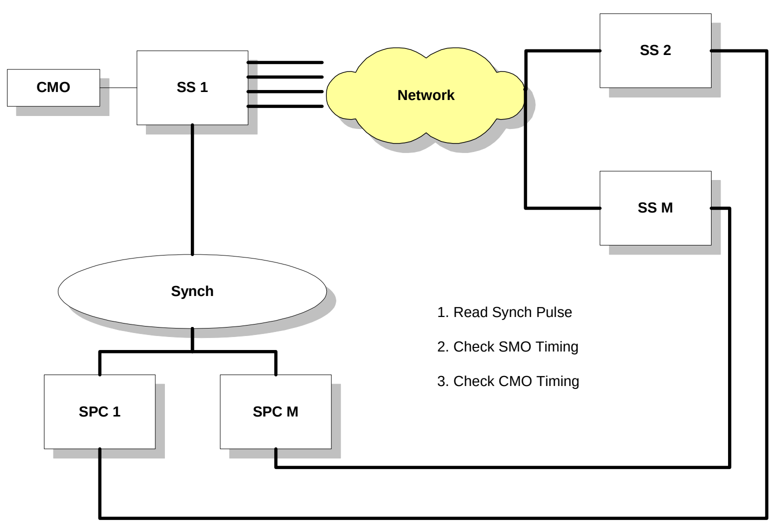
The major functions of the session server in its synch mode are:

1. To bind together simple objects into compound objects as requested by the application.
2. To provide intra object synchronization to ensure that all timing within each object is met.
3. To orchestrate amongst objects to provide inter object timing.
4. To minimize delay, slippage, between simple objects.
5. To minimize delay, latency, between different users.

To effect these requirements, we have developed and implemented a scheme that is based on a paradigm of the phased locked loop found in communications (See McGarty and Treves, McGarty). We show this configuration below. Here we have a distributed session server architecture receiving a CMO from an application. The session server passes the message over several paths to multiple users. On a reverse path, each server passes information on the relative and absolute timing of the CMO as it is received using the session services primitives found in the OSI model. Generally for segmented BMOs this is a simple problem but with streamed BMOs this becomes a real time synchronization problem. The details of synchronization is shown as follows.



The specific implementation is shown below. Here we show M session servers and at the sending server we do the pacing of the packets to the T_SAP and allow for the interleaving of the SMOs. Based on the commands from the feedback system we provide delay adjustment, through caching and resetting priorities to the T_SAP for quality of service adjustments for the lower layer protocols.



At the receiving session servers, the synch pulses are read by the server, the SMO timing errors are read, knowing the synch header, and an error message is generated. We also do the same for the inter object CMO timing error.

The information is sent back in an out of band fashion to the source session server which in turn controls the synch control pulses for the source session server.

We can provide further detail on the synchronization scheme as follows:

1. A CMO is generated by the applications program. This may be a totally new CMO or a result of a new SMO addition or deletion.

2. The Source Session Server (SSS) transmits the header of the CMO to the Receiver Session Servers (RSSs). They then respond with an acknowledgment and in turn set up their internal timing and sequencing tables for local control. They also use the CMO header to adjust their local clock for network timing references.

3. The SSS commences to interleave, sequence and pace the SMOs of the CMO down to the T_SAP for transport across the network. At this point, the Transport protocol must have certain requirements of either increasing bandwidth (e.g. local data rate requests and also controlling sequence order. This interaction between the SSS and the T_SAP will define what additional capabilities we will need at the Session layer.

4. At indicated instances, the SSS inserts local synch pulses in the interleaved CMO. The synch pulses are to be used as local timing reference point for global coordination.

5. The RSSs read the local synch pulses and relates them to both the SMO and the CMO and obtain offsets from the global system clock that has been updated in the RSS. It then send back the offset of the synch pulses on a periodic basis. The offset is a vector that is given by:

   $E(k,j) = [e(k,j,1),.....,e(k,j,n),e(k,j,M)]$

   where E(k,j) is the offset vector of RSS j at time instant k. The internal values of the vector are the offsets of each of the SMO elements and the last entry is the offset of the CMO.

6. The SSS uses the set of E(k,j) for j=1,..,N RSSs to calculate an overall error signal to control the SSS. There are two major control features. If the average error is low then the SSS can reduce the insertion of synch pulses and the lower the processing load. If the errors are large, then more synch pulses are inserted to obtain finer loop control. The second element is control over the lower layers. We use the magnitude of the delay offsets to send messages to the T_SAP to change the quality of service parameters for the system.

We have developed several performance models for these protocols and the architecture that has been developed to implement them.

5.1.4 Event Management

Event Management deals with the overall end to end management of the session. It is more typically viewed as a higher level network management tool for capacity allocation communications. In the current sate this service is merely a reporting mechanism. Although ISO has expanded the network management functionality of the seven layers, most of the functionality is still that of event reporting. In this section we discuss how that can be expended for the capacity allocation environment.

Event management at the session layer provides for the in band signaling of the performance of the various elements along the route in the session path as well as reporting on the status of the session server and the session clients. We note that each entity in the session path, which is limited to all involved clients and all involved servers provide in band information on the status of the session. In particular the in band elements report on the following:

1. Queue size at each client and server. The queue size can be determined on an element by element basis.

2. Element transit and waiting time. For each element involved in a session, the time it takes to transit the entire block as well as the time that the block has been in transit can be provided.

3. Session synchronization errors can be reported in this data slot. These errors can be compared to lower level errors and thus can be used as part of the overall network management schema.

The structure of the event management system has been effectively demonstrated. It is represented as a header imbedded in the transit of every data block. We can generate specific event management blocks that are also event driven and not data transit driven. These are generated by direct transmission of such blocks as overhead devoid of data content.

6. CONCLUSIONS

The session level approach to creating a bandwidth market across a disparate group of users provides a highly attractive solution to the currently highly inefficient methods of spectrum allocation. This is a software approach which is readily accessible to a wide user base and can be effected and spread across a wide domain of users is a short period of time.

This is a Session layer approach, lies above all other layers and is software based. Session layer is layer 5 and can be used to control multiple MAC/PHY layers (Layer 1&2) using TCP/IP (layers 3&4)
This is an architecture as well as element approach, taking control over an overall implementation. Architecture is modular based on functions, is intended as a platform enabling isolated solutions to knit together, like being an operating system that enables others to write applications. “Natural Location”: The Session layer sits above TCP which is a natural end to end layer and Session allows for control of multi user to multi user multi-media communications. Cannot readily be done at any lower layer. The implementation in the Session Layer requires no Standard or ASIC Development: This is a software approach which can readily be shared amongst users not requiring establishment of standard and production of ASICs.

The target market for this application is significant and includes:

- Target Market is composed of all users of wireless network applications and services.
- Target Market Size is predicted to exceed $20 Billion by 2010
- Consumer and commercial.
- The Target Market is all existing and to be designed air interface standards. This can be accomplished because the approach developed here sits on top of those standards.
- There is a great demand from vendors as well as system operators to expanding capacity and coverage. The Target Market thus includes vendors, system operators as well as major government users such as the Department of Defense as well as Homeland Security.

The key elements for implementation are the following processes each of which has multiple implementation possibilities but when structurally combined as we have done herein represent a unique way of effecting mesh or grid wireless networks:

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 comparison to other techniques is shown below:

	Physical Layer/MAC Layer	*Session Layer*
Implementation	Require silicon	Software
Rate of Market Penetration	Slow, uses standards process	Fast, can be “shared” in software platform, license
Advantages	Well understood, established constituencies	Simplicity of implementation, like TCP/IP
Disadvantages	Delays due to silicon costs	Less well known
Market Scope	Limited by where silicon works	Very expansive
Flexibility	Once in silicon and standard, takes time	Easily modified, like TCP/IP thru the IETF

This proposed technique should represent a viable and durable method to effect the networking in a fully shared and distributed manner and effectively alter the way one looks at spectrum management.

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