

On the use of unlicensed frequency spectrum, use rule evolution, and interference mitigation

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Abstract — This paper reviews the technical requirements of U-NII, ISM and U-PCS bands as well as use rules and constraints. Current market activity of product and service development indicates that the idea of unlicensed spectrum is successful. It is likely to continue. Further expansion of unlicensed band allocation by the FCC will be based on its continued success and should be considered together with a new set of use rules. Some constraint parameters to create a new set of use rules are discussed, and those use rules should be evolved to reflect the changes of technology and market needs. It is intended that this paper stimulates further discussion and research into this area.

ABBREVIATIONS

AMPS: advanced mobile phone service
BTA: basic trading area
DS: direct sequence
Eb/No [dB]: energy per bit/noise spectral density
EIRP: Equivalent isotropic radiated power
ETSI: European Telecommunication Standard Institute
FCC: Federal Communications Commission
FH: frequency hopping
IEEE: Institute of Electrical and Electronics Engineers
ISM: Instrument, Scientific, and Medical
LAN: local area network
MAN: metropolitan area network
MTA: major trading area
OFDM: orthogonal frequency division multiplexing
PAN: personal area network
U-NII: Unlicensed National Information Infrastructure
U-PCS: Unlicensed Personal Communications System
UWB: ultra wide band
WAN: wide area network

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INTRODUCTION TO LICENSED VS. UNLICENSED

Unlicensed spectrum is open to everyone. It has many advantages over licensed ones [1]. It allows spectrum sharing and reuse for variety of applications to serve the market with speed and flexibility. On the other hand, there is a potential problem of mutual interference which is amplified by the fear that there is no "guarantee" and control. It is possible that intolerable interference may result from the greedy use of the bands since it is free, or by simply too many active devices in a small area. The simplest approach to this problem of mutual interference is to have the government divides the spectrum and distributes licenses. As a result, a license recipient has an exclusive right to use the frequency spectrum and air space in a geographical area. By exclusive access to the frequency and air space, the problem of mutual interference may be solved. However, with this traditional spectrum licensing, spectrum often sits idle, and no one else can use it due to exclusivity. Clearly this is not efficient. The licensing by central planning does not solve the problem of spectral efficiency, i.e., how to use spectrum efficiently to serve many devices. The licensing process itself could be abused by greed just as the use of unlicensed

spectrum. If licensing fee is free or at a modest price, some may accumulate licenses in anticipation of demand before it is needed, or resell the licenses at a higher price, if it is allowed. When the licensing fee (or auction price) is high, a recipient will be motivated to buy less and use the frequency efficiently. However, the high price will deter competition and favors those few who can afford it. In other words, licensing is not the final solution to the efficient use of spectrum. There are different approaches possible. For further discussion of spectrum management policy options, see the reference [1].

When a frequency band is licensed, its use has to be specified with a particular air space which may be a geographical area or a line of sight air space defined by two end points. For example, when PCS spectrum was auctioned geographical areas defined by MTA or BTA were assigned to different auction winners. When Part 101 fixed service frequency is licensed through a frequency coordination house, a specific line of sight air space is licensed along with a frequency band. A licensee has an exclusive right to use the air space. For unlicensed spectrum, no one has exclusive right to use air space as it is open to everyone.

Given a frequency band and geographical area, an operator who holds a license and intends to provide service will be highly motivated to attain high spectral efficiency for economic benefits. Note that the spectral efficiency includes both efficient uses of bandwidth and space. Naturally the operator will try to use all the technologies available to attain the maximum spectral efficiency to be competitive in providing services. This problem is a subset of unlicensed case since there may be multiple operators in an area. It is conceivable that two operators try to do the same service with unlicensed bands. It is a possible scenario that generates fear and this must be resolved in one way or another. This is a challenge of unlicensed spectrum use. However, this challenge should not deter the use of unlicensed spectrum. Conflicts may be resolved through diversity of applications, spatial separation, market ingenuity and initiative, and technology advancement.

This paper focuses on technological considerations and suggestions on future policy directions and evolution of

the rules on the use of unlicensed spectrum. Its future evolution will be influenced by new technologies that use spectrum efficiently. This paper raises the question on how to generate a set of use rules in order to have continued success in using unlicensed bands. Rather than suggesting a concrete set of rules, which is beyond the scope of the paper, it will explore new possibilities of constraint parameters from the modern communications systems theory point of view – power efficiency, spectrum efficiency, and spatial efficiency and device intelligence suppressing greedy use without inhibiting innovations. These constraint parameters will be the basis for defining a new set of the rules on the use of unlicensed spectrum.

UNLICENSED FREQUENCY SPECTRUM AND FCC PART 1

Table 1. Unlicensed Frequency Bands

	Name	Frequency Bandwidth
Part 15.247	ISM band	902 – 928 MHz (26MHz) 2400 – 2483.5 MHz (83.5MHz) 5725 – 5850 MHz (125MHz)
Part 15 Subpart E	U-NII band	5150 – 5250 MHz (100MHz) 5250 – 5350 MHz (100MHz) 5725 – 5825 MHz (100MHz)
Part 15 Subpart D	U-PCS band	1910 – 1920 MHz (10MHz) pair 2390 – 2400 MHz (10MHz) for data 1920 – 1930 MHz (10MHz) voice
Part 15.255		59 – 64GHz

ISM BAND

FCC allocated Part 15.247 (ISM band) in the late 80's with the continued pioneering spirit of effective spectrum utilization for public communication services. This was a bold experiment with tremendous success. It spurred enormous development activities of numerous and diversified products and applications. This experiment was the continuation of the pioneering spirit of the FCC with the introduction of Part 15 in 1938, which in general permits the operation of very low power radio frequency devices without license. It is bold since, in other countries, the frequency spectrum management is still under strict government control and regulation. This innovation is in line with the worldwide telecommunication deregulation. The initial rule of using spread

spectrum in ISM band has evolved to accommodate new applications in the market. For example it now allows point-to-point application with highly directive antenna where initially it was possible only through a special waiver. The processing gain requirement is relaxed by using CW based measurement method. Most recently it allows 5MHz bandwidth frequency hopping proposed by Wireless Home Network for 2.4GHz whereas it was up to 1MHz before. Appendix II: ISM band Summary of General technical requirements (on page 9) summarizes the rules to use the band. It is expected that these rules will evolve further by market forces along with the FCC progressive attitude. For example, there is a lively debate on the application for certification by Wi-LAN whether OFDM should be allowed in ISM band. Despite FCC initial rejection (See FCC ID K4BAP01 for details.), it is likely that it will continue. The applications are diverse and include cordless telephone, wireless LAN, alternative to a dialup modem to Internet access like Ricochet, and mesh network based Internet access, PAN like Bluetooth and point-to-point digital microwave radios.

this would “facilitate rapid and inexpensive wireless access to information resources by educational institutions, business, industry and consumers.” Currently there are a lot of activities of developing new products and applications using this license free bands and commercial products are already available particularly for the application of broadband Internet access solutions. Appendix I U-NII Summary of General technical requirements summarizes the rules to use the band. The 5150 – 5250MHz band is allowed for only in-door uses with transmit power +4dBm per 1MHz and 6dBi antenna gain. The 5725-5825MHz band is allowed to use for point-to-point use with up to 23dBi antenna gain without antenna directivity power penalty. Note that this band overlaps with ISM band of 5.8GHz. The 5250-5350MHz band can use up to 11dBm per 1MHz power with dB by dB antenna directivity penalty after 6dBi, i.e., transmit power should be reduced by the same dB of antenna gain in dB over 6dBi. It appears that the bands have a three tier architecture in mind to provide a full wireless access solution; the 1st tier is in-building wireless LAN, 2nd is building to building campus wide wireless point-

Table 2. Application Limit and Examples

Devices	ISM operation devices	U-NII devices	UPCS devices
Application limit and examples	Frequency hopping and direct sequence.	Provide a wide array of high data rate mobile and fixed communications for individuals, businesses and institutions.	A wide variety of mobile and fixed communication services to individuals and businesses.
	Cordless Phone Wireless LAN- IEEE 802.11b, Bluetooth, Wireless Home Network Wide band access – Ricochet Point-to-point digital radio.	Broadband Internet Access – IEEE 802.16 Wireless LAN- 802.11a, HIPERLAN Point-to-point digital radio.	Wireless PBX – Lucent, Ericson 1900 Freeset.
Comments	No digital modulation is imposed.	Use wide band digital modulation.	Digital modulation only.
	<ul style="list-style-type: none"> • Antenna directivity penalty except for point-to-point applications. • No requirements of power efficiency (Eb/No) or bandwidth efficiency (bps/Hz). • Often a band is subdivided into a number of sub-channels for duplex operation, and multiple channels and dynamic selection for interference avoidance. 		

As shown in the table, the unlicensed band use rules are general enough but sometimes a limit is imposed.

For example, in the ISM band, FH and DS operation is clearly specified.

U-NII BAND

In January 1997, FCC decided that a new approach was needed to the nation wide information infrastructure using wireless solutions and provided 300MHz of spectrum named U-NII as in Table 1. According to FCC,

to-multi point solution and finally the 3rd for back-haul to fiber based nationwide backbone networks. New applications will be added in the future. IEEE initiated standardization of activities as part of 802.16 Broadband Wireless Access working group[4] in addition to IEEE 802.11a and ETSI HIPERLAN-2.

U-PCS

When FCC auctioned PCS frequency bands around 1.9GHz, some portion was set aside for unlicensed use, and its use rules are specified in Part 15 Subpart D as shown in Table 1 and summarized in Appendix III on page 11. This band introduced the concept of spectrum etiquette, i.e., monitoring before transmit or “listen before talk.” It provides details of monitoring and scanning rules; a device has to have a capability to measure other signal (potentially interference) power before transmitting. Further modifications were suggested in [2]. The idea is to impose transmission time penalty to the rule violators. This band has applications for wireless PBX or similar.

REVIEW OF THE BASIC IDEAS OF UNLICENSED SPECTRUM USE RULES

Transmit Power or Field Strength limit:

Before the advent of modern unlicensed bands listed in Table 1 (ISM, U-NII), Part 15 allows unlicensed use of spectrum by severely limiting transmit power and thus covering a very limited space. A main idea of interference mitigation is spatial separation by allowing a very limited transmit power (See the note 2 on page 15). For example Part 15.211 Tunnel radio systems allow to use any frequency if it is contained within the structure and specified power limit. For ISM band and U-NII band, there is transmitting power limit although it is much greater than that specified in Part 15.209. See Appendix I and Appendix II.

Spread Spectrum Processing Gain:

In ISM bands, the idea of spread spectrum of both FH (frequency hopping) and DS (direct sequence) has been introduced, again to mitigate mutual interference. Spread spectrum signals are distinguished by the characteristic that their bandwidth is much larger than information bit rate. The bandwidth expansion factor, called processing gain, is the margin against interference. For ISM it is specified as about 10dB for DS, 12 dB (15hops) to 18dB (75hops) for FH. See Appendix II on page 10 for details. A digital transmission system requires the signal energy per bit, $E_b = P_{av} * t_b$ where P_{av} is the average power and t_b is bit duration and $R=1/t_b$ is bit rate. The power spectral density of interfering (jamming) signal may be expressed as $J_o = J_{av} / W$ where W is the chip rate or the

bandwidth to be used. Then $E_b/J_o = P_{av}/J_{av} * W/R$. (1)

Or in dB

$$(E_b/J_o) \text{ dB} = (P_{av}/J_{av}) \text{ dB} + (W/R) \text{ dB} \quad (2),$$

where (E_b/J_o) dB is the signal to interference (noise) ratio measured needed by the receiver to achieve a specified level of error rate performance, (W / R) dB is the processing gain, and (P_{av}/J_{av}) dB is the signal power to jamming (interfering) signal power ratio. From the above equation, any amount of jamming can be nullified by increasing processing gain. In addition, once bandwidth is expanded, a powerful coding can be added without further expanding the bandwidth. When there is no coding the spread spectrum can be interpreted as repetition code which has no net coding gain. Coding gain reduces the required (E_b/J_o) dB for a given error rate. Another interpretation of the above equation is that given J_{av} (interference power), the signal power (corresponding transmit power) can be reduced by increasing processing gain and coding gain. The evolution of the ISM band indicates that processing gain requirement seems to be relaxed by using CW margin method if the vendor uses a system less than 10 chips per symbol. For example see the reference [6]. The method is using essentially Eq.2 in the above. By knowing and measuring (E_b/J_o) dB and (P_{av}/J_{av}) dB, one can find (W/R) dB, processing gain. In the proposed method of [6], J_{av} is CW and (E_b/J_o) dB allows a 2dB implementation loss. Any receiver improvement of coding and narrow band cancellation can be used as processing gain in this method. For FH case, up to 5MHz bandwidth with 15 hopping frequency is allowed compared to the maximum 1MHz with 75 hops before. A major drawback to processing gain is the reduction of bps /Hz spectral efficiency, i.e., data rate is reduced by the same factor.

Transmit power spectral density & Antenna gain limit:

In U-NII band, transmit power is limited but it is not required to have processing gain as in ISM band. The transmit power limit is specified by defining power spectral density rather than a total power, i.e., the more the bandwidth the more the total power. This is another contrast to ISM band where a total power is specified. By limiting antenna gain, EIRP is specified there is dB to dB power reduction when the antenna gain is above 6dBi. The exception is 5.725 – 5.825GHz band where it allows 23dBi antenna gain without penalty for point-to-

point applications. 5.15 –5.25GHz have to be indoor only with integrated antenna. As the name implied, when the U-NII band was conceived, it appears that a total wireless broadband access was in mind – wireless LAN, wireless MAN and point-to-point backhaul links.

Spectrum use etiquette or use time limit:

UPCS band uses the idea of spectrum etiquette which is simply ‘monitoring before transmission.’ Part 15.321 and 15.323 specify the details of how to monitor the spectrum to use – monitoring duration, threshold, sequence and limit of total transmission, etc. The time to use the spectrum is shared among all the users around; when someone is talking do not interfere. It is an interference avoidance idea. A further modification was suggested in reference [2] where the violators of the rules are penalized in the use time of the spectrum. Further refinements of the spectrum etiquette are under discussion for the un-

censed use of 59-64GHz as Part 15.255. See FCC 00-161 ET Docket No. 94-124 dated May 17, 2000, Third Memorandum Opinion and Order.

Antenna gain Penalty & Spatial filtering/separation: In all of ISM, U-NII, and UPCS, transmit power should be reduced if antenna gain is above 6dBi for U-NII and ISM, above 3dBi for UPCS except for point-to-point applications. For 5725-5850GHz under ISM use rules, there is no antenna gain limit for point-to-point applications. On the other hand, the frequency under U-NII, it allows 23dBi antenna gain without reducing power.

Future Evolution of Use Rules of Unlicensed bands:

The use rules will evolve to reflect the need of markets and to utilize the available technologies. A futurist predicts that the spectrum will be made abundant by future technology innovation [9], and therefore further expansion of unlicensed bands beyond auction [10]. Certainly

Table 3. List of Constraint Parameters and Possible future use

Constraint Parameters	Current Constraints	Comments
Power	U-NII band constraints only maximum power. No information, no transmission.	<ul style="list-style-type: none"> • Appropriate maximum power depends on application and propagation channel • Devices tend to transmit maximum power regardless of need • Power control requirement, C/I measurement • Eb/No constraint close to Shannon limit
Time	UPCS spectrum etiquette shares time after monitoring and transmission time limit and sharing.	<ul style="list-style-type: none"> • Further refinements suggested [2].
Signal Type	ISM – FH, DS but no modulation type. Digital modulation.	<ul style="list-style-type: none"> • New innovations should be encouraged • A large processing gain with very low power (e.g., UWB)
Frequency Bandwidth	There is no bandwidth efficiency constraint.	<ul style="list-style-type: none"> • Devices tend to use maximum possible • Bps/Hz constraint depending on application and propagation channel • Adaptive modulation • Frequency selection/hopping
Space	Antenna gain penalty.	<ul style="list-style-type: none"> • Sectorized antenna use not encouraged from power point of view • Distance constraint may be imposed • Smart antenna technology • Polarization use
Device intelligence	Interference monitoring for UPCS.	<ul style="list-style-type: none"> • C/I monitoring • User ID broadcasting • Frequency selection
Applications	Generic enough for mobile and fixed.	<ul style="list-style-type: none"> • Determine other parameters

policies and standards should not inhibit innovation, but the policy direction should encourage innovation and efficient use of spectrum. The evolution of the use rules should include experiment with the new ideas of making the rules. In order to experiment, with a new set of use rules, a new unlicensed band is allocated.

A combination of the parameters is needed to make up a set of rules. No constraints on spectrum use were experimented as in [11], with a mixed result. It does not necessarily encourage efficient use of spectrum. The comments in the above table suggest the ideas without much elaboration for future discussions.

With the existing rules of unlicensed spectrum, they do not motivate to use it efficiently. A device may transmit maximum allowed power regardless of need. There is no provision of bps/Hz requirement, and therefore it is likely to use the maximum bandwidth to make a design "cheap." The use of the sectored antenna is discouraged by antenna gain penalty, rather omni-directional one is encouraged to use. Appendix IV Appendix IV. Frequency Reuse and Spatial Filtering Technologies discusses the spatial reuse of frequency and it is dramatically improve the cellular system, and Appendix V. Spectral efficiency definition and future evolution. By designing the use rules to stimulate the spectral and power efficiency which may require sophistication, it seems to be possible to encourage innovations of technology and diversified applications. Modern communication systems theory should be applied to the problem of spectrum sharing and efficient use.

Suggesting a concrete set of unlicensed band rules is out of the scope of this paper and will be the subject of a future one. Some "seed" ideas were discussed by categorizing constraint parameters. See Table 3. List of Constraint Parameters and Possible future use and Appendix IV and Appendix V for details.

- Power control with E_s/N_0 requirement
- Efficient spatial use (high directivity antenna, smart antenna) with possible distance limit
- bps/Hz requirement for a given signal to noise ratio, e.g., fixed point-to-point applications with FCC part 101 it should be 4 or more bps/Hz.
- Interference monitoring capability during normal operation

CONCLUSION

This paper reviewed the use rules of unlicensed bands and pointed out that further evolution of those should encourage to use spectrum more efficiently. In addition to technology ideas, in order to resolve possible conflicts and to develop a concrete set of use rules, it is conceivable to have:

- Public data base deployment
- Formation of unlicensed band user group
- Part 15 certification process as enforcing rules
- Conflict resolution criteria: communication systems efficiency (power, spectrum, and space) as guiding principles perhaps in addition to precedence rules

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Example1: B=1MHz measured with 26dB emission bandwidth, i.e., attenuated by 26 dB from the peak of carrier frequency, and 6dBi antenna gain. Antenna port total peak power equals to 4 dBm for LB, 11dBm for MB and 17 dBm for UB where the antenna port is defined where the antenna is attached.

Example 2: B=10MHz and antenna gain 18dBi. Antenna port total peak power equals to +2dBm for LB (4+10-18 +6), +9dBm for MB. For UB, there two cases one for point-to-point and point-to-multi point. Antenna port total peak power equals +15dBm for point-to-multipoint, +27dBm for point-to-point case.

Band	Peak transmit power at antenna port (B=10MHz, 18dBi antenna gain)	Power spectral density in 1 MHz measured at antenna port
(LB) 5.15 – 5.25GHz	+2dBm	-8dBm/MHz
(MB) 5.25 – 5.35GHz	+9dBm	-1dBm/MHz
(UB) 5.725 – 5.825GHz	+15dBm or +27dBm for PTP	+5dBm or +17dBm/MHz

APPENDIX I U-NII SUMMARY OF GENERAL TECHNICAL REQUIREMENTS

Part 15 subpart E – Unlicensed National Information Infrastructure Devices §15.401 – 15.407

For this particular document see

http://www.fcc.gov/Bureaus/Engineering_Technology/Documents/cfr/1998/index2.html

Power Limits

Band	Peak Transmit Power at EIRP = power spectral density/MHz + bandwidth in MHz (log) + antenna gain	Remarks
5.15 – 5.25GHz (LB)	4 dBm + 10 log B/MHz + 6dBi (antenna gain)	In-door only with integrated antenna
5.25 – 5.35GHz (MB)	11 dBm + 10 log B/MHz + 6dBi (antenna gain)	In-door only with integrated antenna
5.725 – 5.825GHz (UB)	17 dBm + 10 log B/MHz + 6dBi (antenna gain)	Point-to-point use allows 23dBi antenna gain without reducing power

Emission bandwidth is determined by measuring the width of the frequency spectrum of the signal between two points, one below the carrier frequency and on above the carrier frequency, that are 26dB down relative to the maximum level of modulated carrier. The measurement resolution band width is about 1% of the emission band width.

Peak Transmit power. The maximum transmit power as measured over an interval 30/B or the transmission pulse duration of the device, which ever is less, under all modulation conditions. For example, for burst transmission case, the power measurement is done during the burst, but not averaging through no burst time. The 'peak' here means that the measurement is done over any interval of continuous transmission, but the power is measured as a true rms value. Any instrument limitation, not measuring a true rms over any interval of transmission, should be adjusted accordingly.

Power spectral density. This measurement must be done with 1MHz bandwidth or 26dB emission band-

width, whichever is less. For example for nominal 10MHz signal bandwidth the measurement must be done in 1MHz. If the resolution bandwidth of the instrument is less than 1MHz, the power spectral density should be scaled properly.

The peak excursion of modulation envelop.

This is commonly called peak to average or crest factor. The ratio of the peak excursion of the modulation envelope, measured using a peak hold function, to the peak transmit power, measured as a true rms with 1MHz resolution bandwidth, shall not exceed 13dB across 1MHz or the emission bandwidth. This 13 dB is enough margins for most practical modulation including 256QAM. Other signals like OFDM can exceed this limit, but the probability is ver low. Another aspect is that when the emission bandwidth, or roughly signal bandwidth, is less than 1MHz, the spectral density cannot increase beyond the specified limit 4dBm, 11dBm, 17dBm.

Automatic discontinuation of transmission.

The device shall automatically discontinue transmission in case of either absence of information to transmit or operational failure. The application for equipment authorization should include a description of how this requirement is met.

Frequency stability. Manufacturers are responsible for ensuring frequency stability is maintained within the band of operation under all conditions of normal operation as specified in user’s manual.

Undesirable emission limits.

The out band emission requirement is simply put as it shall not exceed an EIRP of –27dBm/MHz. An exception to this is for 5.725 – 5.825GHz case. From the band edge to 10MHz above or below the band edge shall not exceed an EIRP of –17dBm.

Appendix II: ISM band Summary of General technical requirements

Part 15.247– Operations within the bands –frequency hopping and direct sequence. For this particular document see http://www.fcc.gov/Bureaus/Engineering_Technology/Documents/cfr/1998/47cfr15.pdf

Frequency	Bandwidth	Frequency Hopping		Direct Sequence	Antenna Gain
		Hopping	Power Limit		
902 – 928 MHz (900MHz)	26 MHz	50 hops more, less than 250kHz, 20 sec/0.4sec	1 Watt	1 watt total power 1. Peak power spectral density = 8dBm /3kHz 2. Processing gain = 10dB or more 3. 3. chip rate GT 500 kHz	6dBi limit except for PTP applications
		LT 50 hops more than 25 hops, greater than 250kHz 10 sec/0.4 sec	0.25 Watt		
2400 – 2483.5 MHz (2.4GHz)	83.5 MHz	75 hops LE 1 MHz	1 Watt		No limit for PTP, not for PMP
		15 hops GT 1 MHz (recent addition due to HomeRF)	0.125 Watt		
5725 – 5850 MHz (5.8GHz)	125 MHz	75 hops LE 1 MHz	1 Watt		

PMP: point to multi point

PTP : point to point

LE: less than equal

GT: greater than

NOTES.

1. 5.8 GHz is allocated overlap with U-NII band of 5725 – 5825MHz.
 2. Greater than 1MHz bandwidth for frequency hopping of 2.4GHz is added recently (September 2000).
 3. Direct sequence processing gain 10dB requirement is relaxed by adding CW based measurement method.
 4. By using frequency hopping and direct sequence together, processing gain requires to be 17dB.
 5. For PTP applications, antenna gain is allowed unlimited for 5.8GHz case, limited amount for 2.4GHz.
 6. The out-band rejection requirement is 20dB down from the peak measured with 100kHz bandwidth.
- For terminology like peak transmission spectral

NOTE.

1. UTAM coordination company designated by FCC
2. Transmit power: examples 2.5MHz bandwidth 158milliwatt (+22dBm), 1.25MHz : 111mWatt (+20dBm)
3. “Listen before talk” monitoring before transmission or spectrum use etiquette: See the web site for details.
4. The time to use is restricted to avoid interference in the band. Further modification idea of penalizing the violators of the etiquette (see the reference)

APPENDIX IV: FREQUENCY REUSE AND SPATIAL FILTERING TECHNOLOGIES

Frequency Reuse in Cellular Example

A major spectral efficiency improvement was achieved by frequency reuse in spatial separation. By design, cellular/ PCS systems are limited by co-channel interference. A hexagonal geometry gives mathematically simple relationship and provides a basis for system capacity computation. As shown in the table below, by using sectored antenna rather than omni-directional antenna at a base station, S/I improves. As explained in the table, the interference is reduced since a number of interferers are reduced from 6 to 2 when 120 degree sectored antenna is used.

Current cellular (AMPS) system is based on cluster size (N) 7. By using the system that requires less S/I (or equivalently Eb/No), the cluster size can be made smaller. A cellular system capacity is a function of S/I that it needs to meet performance requirement. From the table, if S/I requirement is 11.3 dB or less then the cluster size N=3 is enough compared to 7 when S/I needs 18.6dB. The spectral efficiency is improved by 2.3 (=7/3). A major capacity improvement (a number of voice channels) from AMPS to 2nd generation (2G) digital is due to the reduced requirement of S/I; AMPS 18dB and CDMA 6 - 8dB. The frequency reuse is a spatial separation by distance and signal attenuation. By making the system S/I (or Eb/No) requirement smaller using a powerful coding and diversity, the system capacity improves or a more voice channels for a given amount of spectrum.

APPENDIX III: UPCS BAND SUMMARY OF GENERAL TECHNICAL REQUIREMENTS

Part 15. Subpart D – Unlicensed Personal Communications Devices. For this particular document, see http://www.fcc.gov/Bureaus/Engineering_Technology/Documents/cfr/1998/47cfr15.pdf

Purpose: mobile and ancillary fixed communication service, digital modulation only

Band	Transmit Power	Mode	Channel Partition	Monitoring Before Transmit Rule
1910 – 1920 MHz 2390 – 2400 MHz	100* SQRT (Hz) u-watt	Asynchronous, data service	4*2.5 MHz pair	Monitoring threshold less than 32dB from thermal noise power. Scan range from low to high, high to low frequency.
1920 – 1930 MHz		Directional antenna gain penalty after 3dBi, dB by dB		
		Isochronous voice service	8*1.25MHz	Maximum 8 hours after initial monitoring.

Table for Cellular Frequency Reuse. See Reference [8]

Index	Cluster Size=N	Co-channel cell distance D to cell radius R, $D/R = \sqrt{3N}$. Omni directional antenna, 6 equidistant cells in hexagonal geometry.	S/I signal to co-channel interference dB. Interferers=6 $S/I=(D/R)n/6$		Antenna directivity improvement.
			Exponent n=4	Exponent n=3	
1, 1	3	3	11.3 dB	6.5 dB	120° sectored antenna reduces number of interferes to 2 S/I improves by 4.8dB. Further improvement possible by using smaller angle sectors.
1, 2	7	4.58	18.6	12.0	
2, 2	12	6	23.3	15.6	
1, 3	13	6.25	24.1	16.1	
2, 3	19	7.55	27.3	18.6	
1, 4	21	7.94	28.2	19.2	

Smart Antenna: Additional capacity improvement (or equivalently spectral efficiency improvement) is suggested by using arrays of antennas at base stations. It requires sophisticated spatial signal processing. See Reference [12, 13, 17] for details.

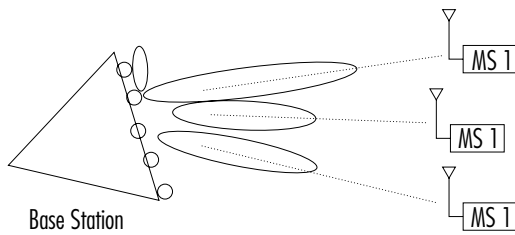


Figure :
Smart Antenna systems can form a different beam for each subscriber.
MS: mobile station with omni-directional.
BS: base station with antenna arrays.

For up link a spatial signal combining at base band will "effectively" form antenna beam pattern. For down link, it will physically generate a beam pattern, i.e., increasing antenna gain and EIRP with the same transmit power. Note that it affects down link (transmit) but not up link (receive) if there is antenna gain penalty as in unlicensed spectrums. Actual gain of using antenna arrays depends on temporal/spatial propagation channels, signal combining method, and the details of the algorithms. This may be complex and out of the scope of this paper.

However, there are three basic gains; array gain, diversity

gain, and antenna pattern gain. The array gain improves signal to noise ratio with multiple antennas combing the signal energy coherently. It is proportional to the number of antennas. Diversity gain helps to combat fading. Multiple antennas can adaptively form a spatial pattern to suppress interference and enhance the signal simultaneously. The multiple antennas can be used to create spatial channels, called spatial multiplexing [14].

For unlicensed bands, there is antenna gain penalty. What type of constraint parameters will motivate the efficient use of "space?" Smart antenna (adaptive beam forming) for down link will be considered point-to-point or point-to-multi-point? Is antenna gain penalty useful for spectral efficiency? For convenience, antenna gain related formulas are collect in the table below.

APPENDIX V: SPECTRAL EFFICIENCY DEFINITION AND FUTURE EVOLUTION

E_b/N_o [dB] vs. spectral efficiency

The channel capacity, C [bits/second], for the bandwidth limited additive white Gaussian noise (AWGN) channel is given by,

$$C = W \log (1 + C/W * E_b/N_o)$$

where the bandwidth is W[Hz], N_o [Watts/Hz] the noise power density, E_b energy per bit, and log has base 2. Or another way of presenting the same formula as,

$$E_b/N_o = 2(C/W) - 1/(C/W)$$

Shannon has derived this capacity formula originally, and a textbook presentation is in the reference [15] and [16].

Table for Antenna gain formula. See Reference [7]

	Directivity	Antenna Gain
$\lambda = c/f$ $A = \text{antenna aperture area}$ $\theta = \text{beam solid angle}$	$D = 4\pi A_e / \lambda^2 \approx 4\pi / \theta_{HP} \theta_{HP}$ where θ_{HP} is solid radian angle and $\theta_{HP} \approx \theta_{az} \theta_{el}$ where θ_{az} azimuth angle and θ_{el} elevation angle of half power. $D = 4\pi A_{em} / \lambda^2$	$G = kD$ Where $0 < k < 1$ antenna efficiency $k = 1$ with no loss and $k = A_e / A_{em}$ $A_e = \text{effective aperture}$ $A_{em} = \text{maximum aperture}$ $G = 4\pi A_e / \lambda^2$
Examples	Ex. 1. Half power beam width 20° both azimuth and elevation. $D = (180/\pi)^2 * 4\pi / (20 * 20) = 103 \Rightarrow 20\text{dBi}$ Ex 2. 5.8GHz 1 ft diameter dish with 60% efficiency. $G = 0.6 * 4\pi * (0.3/2)^2 \pi / (3.0e8/5.8e9)^2 = 198 \Rightarrow 23\text{dBi}$	

It is insightful to understand precise conditions that this capacity formula assumed. See Reference [16] for details of derivation. In the channel only interference is Gaussian noise and its power is given by variance σ_n , and the channel capacity is maximized by using Gaussian distributed input symbols where its power is given by variance σ_s . Then the bit per symbol, C' [bits per channel use], is given as $C' = \log(1 + \sigma_s^2 / \sigma_n^2)$. This is the case of time-discrete, amplitude-continuous symbols used at the input and output. Obviously more bits can be sent, i.e., C' can be increased by increasing SNR, σ_s^2 / σ_n^2 . But note that this channel capacity, C' , is attained, during the derivation of the formula, by forcing (or selecting) the statistics of the input to be Gaussian.

The spectral efficiency expressed by bit/sec/Hz is

A tabular form is shown below;

C/W [bit/sec/Hz]	E_b/N_0 [dB]	SNR [dB] E_s/N_0	Example Modulation	SNR [dB] 1E-10 BER	SNR [dB] 1E-6 BER
0.0	-1.6	- infinite	M-ary Orthogonal Signal M=32		
0.001	-1.58	- 31.58			
0.01	-1.58	- 21.58			
0.1	-1.44	- 11.44			
1.0	0.0 dB	0.0 dB	BPSK	13.0	10.5
2.0	1.8	4.8	QPSK	16.0	13.5
3.0	3.7	8.5	8 QAM	19.5	17.0
4.0	5.7	11.5	16 QAM	22.5	20.0
5.0	7.9	14.9	32 QAM	26.5	24.0
6.0	10.2	18.0	64 QAM	29.5	27.0
7.0	12.6	21.5	128 QAM	32.5	30.0
8.0	15.0	24.3	256 QAM	35.5	33.0
9.0	17.5	27.0	512 QAM	38.5	36.0
10.0	20.1	30.0	1024 QAM	41.5	39.0
11.0	22.7	33.0	2048 QAM	44.5	42.0
12.0	25.3	36.1	4096 QAM	47.5	45.0

related with E_b/N_0 [dB]. In AWGN channel, given an E_b/N_0 [dB], there is a limit for spectral efficiency or given a spectral efficiency, there is minimum need of energy E_b/N_0 [dB]. This is called a Shannon limit. For example, if SNR is 0.0 dB then the maximum attainable spectral efficiency is 1 bit/sec/Hz.

Spectral efficiency with spatial frequency reuse

Given a channel of point-to-point connection, a spectral efficiency can be expressed as in the above bit/second/Hz. One way to improve it uses a high order modulation where the higher the modulation order, the more signal to noise ratio as discussed in the above. Other way is to use spatial channels which require multiple antennas. In the past both horizontal and vertical

polarization were used as two channels to double the capacity. Usually antenna polarization discrimination is not enough, and additional one is possible by adding base band polarization cancellor. For the past several years, the idea of using space as additional has been advanced to dramatically improve the capacity [14], i.e., the wireless channel has considerably more capacity due to wave nature of propagation and sophisticated signal processing. This is in the early stage of development in terms of products in the market.

In a point-to-multi point situation, it can be explicitly expressed as bps/Hz/cell. As in a cellular case, the spectral efficiency will easily improve to use more sectors with proper antenna pattern. In [4], a Rosette cell is formed by placing highly directive antenna concentrically around a cell (hub). And this basic cell is replicated to make multi-cell systems to increase coverage and capacity.

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² Part 15.209 specifies radiated power limits as general requirements. For example frequency above 960MHz, it specifies field strength of 500uV/m at 3m, which translates into – 40dBm with 50ohm system.

³ For example, IEEE 802.11b uses this band with data rate 11Mbps. However its channel chip rate is effectively 22Mbps using so called CCK modulation.

⁴ Even further sophistication of spectrum etiquette was suggested for the unlicensed use of Par15.255 of 59 – 64GHz; a small portion of channel is allocated to broadcast the identification message. These are under debate.