

## RECOMMENDATION ITU-R SM.1132-2\*, \*\*

**General principles and methods for sharing between radiocommunication services or between radio stations**

(1995-2000-2001)

**Scope**

This Recommendation provides the general principles and methods for sharing of frequencies or frequency bands by different radiocommunication services or by stations to facilitate efficient and effective sharing of spectrum by multiple radiocommunication services or by radio stations.

**Keywords**

Radio spectrum, spectrum sharing, channel plans, bandwidth, signal processing

The ITU Radiocommunication Assembly,

*considering*

- a)* that efficient and effective use of the radio spectrum often requires the sharing of frequencies or frequency bands by different radiocommunication services or by radio stations;
- b)* that general principles are needed for considering spectrum sharing;
- c)* that methods to facilitate sharing need to be delineated;
- d)* that methods to apply in specific sharing cases are recommended in a variety of ITU-R Recommendations appropriate to the specific sharing situation,

*recommends*

**1** that administrations consider the general principles and methods described in Annex 1 for facilitating efficient and effective sharing of spectrum by multiple radiocommunication services or by radio stations.

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\* This Recommendation should be brought to the attention of Radiocommunication Study Groups 4, 5, 6 and 7 and Telecommunication Development Study Groups 1 and 2.

\*\* Radiocommunication Study Group 1 made editorial amendments to this Recommendation in the years 2018, 2019 and 2023 in accordance with Resolution ITU-R 1.

## ANNEX 1

**General principles and methods related to spectrum sharing**

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**1 Dimensions of allocation sharing**

Spectrum sharing holds the potential for increasing the efficiency and effectiveness of spectrum use. Interservice sharing exists when two or more radiocommunication services effectively use the same frequency band. Nos. **1.166** to **1.176** of the Radio Regulations (RR) define the parameters to be taken into account in frequency sharing. Interservice and intra-service sharing of spectrum are facilitated by application of sharing principles and methods that are considered on a general basis but also used in the assignment of frequencies on a station-by-station basis. Utilization of the radio spectrum is dependent on the dimensions of frequency, spatial location, time and signal separation. Any sharing of the spectrum will have to take into account one or more of these four dimensions. Sharing can be accomplished in a straightforward fashion when any two of these dimensions are in common and the third and/or fourth dimension differs by a degree sufficient to ensure that all the involved services or stations (two or more) can operate satisfactorily. Sharing can also be accomplished when services or stations have all four dimensions in common. In such cases, service sharing rules cannot ensure non-interference and individual assignments must be made on the basis of the totality of assignments already made in all of the overlapping services, so that combinations of factors can be found for individual assignments that will not interfere with each other. Generally speaking, multidimensional use of spectrum could obtain additional power/spectrum and/or orbit processing gain, even though it would make the system architecture or structure somewhat more complicated.

**2 Sharing methods**

Table 1 shows some of the methods which can be used to facilitate sharing, grouped in columns based on the four dimensions: frequency, spatial location, time and signal separation.

Within Table 1 some of the methods are new or innovative and may make more efficient use of the spectrum or provide flexibility. Many of these methods result from the introduction of new

equipment technologies, computerization of analysis and new ideas. Some of the methods are complex, involving real-time computer controlled frequency management.

Often, the specification of particular technical parameters for equipment is necessary to implement sharing methods shown in Table 1.

## **2.1 Frequency separation**

### **2.1.1 Channelling plans**

It is possible to arrange channels of operation on a homogeneous or inhomogeneous basis so as to interstitially configure one or more communications systems. This means of avoiding interference must be coordinated ahead of time so that the channels are appropriately separated to take advantage of the type of modulation FEC and/or coded modulation used, the frequency domain envelope shapes, the transmitted necessary bandwidth, and receiver bandpass characteristics. This technique is appropriate for use by adjacent satellites that do not use homogeneous transponders in the geostationary-satellite orbit (GSO).

The economics of channel plan coordination are often a necessary expense of coordination required between co-primary users of the same spectrum. The burden is shared between system operators and almost always gives satisfactory results.

TABLE 1

**Methods to facilitate sharing**

<b>Frequency separation</b>	<b>Spatial separation</b>	<b>Time separation</b>	<b>Signal separation<sup>(2)</sup></b>
Channelling plans Band segmentation Frequency agile systems Dynamic sharing: – dynamic real-time frequency assignment <sup>(1)</sup> Frequency division multiple access (FDMA) Control of emission spectrum characteristics Dynamic variable partitioning Frequency tolerance limitation Demand assignment multiple access (DAMA) Frequency diversity	Geographical shared allocations Site separation Antenna system characteristics: – adaptive antenna (smart antenna) – antenna polarization discrimination – antenna pattern discrimination – space diversity – antenna angle or pattern diversity Space division multiple access (SDMA) Physical barriers and site shielding	Duty cycle control Dynamic real-time <sup>(1)</sup> frequency assignment Time division multiple access (TDMA)	Signal coding and processing Forward error correction (FEC) Interference rejection Code division multiple access (CDMA) Spread spectrum: – direct sequence – frequency hopping – pulsed FM Interference power/bandwidth adjustments: – co-channel – dynamic transmitter level control – power flux-density (pfd) limitation and spectral power flux-density (spfd) limitation (energy dispersal) Modulation complexity Coded modulation Adaptive signal processing Antenna polarization

<sup>(1)</sup> Dynamic real-time frequency assignment facilitates sharing by simultaneously using frequency and time domains. Therefore, this method is shown in both columns.

<sup>(2)</sup> These techniques for signal separation may also be applied to frequency, space and time separation technology.

### 2.1.2 Band segmentation (see Note 1)

The grouping of a number of channels, or the creation of a sub-band for non-channelized systems, for different users or uses of the spectrum is similar to the use of channel plans. In some situations this will be desirable because it has the advantage of minimizing or avoiding the need for coordination, while enabling multiple uses of a band. It encourages efficient use of the spectrum if additional spectrum is not available. It enables the full development of the respective services,

rather than having the early or unexpected growth of one service or type of system curtail the growth of another desired service or system.

NOTE 1 – Band segmentation between radiocommunication services can be viewed as actually eliminating sharing by creating sub-allocations. In light of the fact that administrations take internationally shared allocations and segment those bands for national uses, the material is appropriate for discussion as a sharing method.

### **2.1.3 Frequency agile systems**

Frequency agile systems select frequencies of operation anywhere within a specified band on a real-time basis, using the techniques of listening before transmitting. These are systems that do not rely on a mutual coordination process or on another systems operator's decision. Frequency agile systems seek out unused spectrum for a communication. These types of systems may not be suitable for public telecommunications or for transfer of critical data because of a higher possibility for interference.

Technology has made some types of frequency agile radio systems quite feasible and relatively inexpensive today. If a system can tolerate the time necessary to often change frequencies and synchronize terminals, the technique can prove cost effective.

### **2.1.4 Dynamic sharing**

Using advanced computer techniques, spectrum managers have greater opportunities to share frequencies, and thus greater opportunities to reduce inefficiencies created by rigid service boundaries. Dynamic sharing of frequencies between different systems in the same similar services allows more than one system to use the same frequencies but at different times, in the same geographic region. Traditionally, sharing the same frequencies at similar, high power in the same geographic area required adoption of discrete time periods for use by each service. Dynamic sharing techniques permit such sharing on an as-needed basis. Dynamic sharing requires reliance on sophisticated technologies and methodologies.

Trunking is an example of dynamic sharing. In a trunked system, channels that might otherwise be assigned to individual users are joined in a single system, and frequencies are automatically assigned to individual users on an as-needed basis. Trunked systems allow disparate users to share spectrum, and generally provide a significant increase in efficiency over conventional assignment methods.

Another type of dynamic sharing occurs between cellular providers and other users in the 900 MHz band. Access to these frequencies has greatly expanded the pool of available channels for cellular use. In this arrangement, the priority users have pre-emptive access to these frequencies, and as they need them, computer software programs automatically reclaim the frequencies for the priority use, excluding them from cellular access. In such instances, cellular users would experience graceful degradation, rather than a complete loss of service.

Dynamic sharing is a possible means to improve efficiency in radio spectrum use in cases where it is feasible to merge services, and thus broaden radio service definitions. The effect of such sharing would be similar to reducing distinctions among subclasses of users. For example, in the 2 GHz band, mobile-satellite services (MSSs) were divided into three radio services: aeronautical, maritime and land-mobile satellite. At WRC-97 they were combined into a generic MSS. While the services are different, they have common aspects that could allow a sharing of the services under a broader classification, MSSs.

#### **2.1.4.1 Dynamic real-time frequency assignment**

The system now proposed for sharing among the MSSs is quite complex. It would involve a process of dynamic allocation, where each of the MSSs would be allocated spectrum on an as-needed basis, requiring a mechanism to implement priority and pre-emptive access, as necessary. Such systems serve a variety of users with diverse needs, including different and continuously changing requirements for channel bandwidth, signal power, priorities and network interfaces. The replacement of analogue with digital transmission technology may increase the potential for dynamic sharing.

#### **2.1.5 FDMA**

The FDMA technique consists of assigning to each user a fraction of the bandwidth and confining its access to the allocated sub-band. Orthogonality is achieved in the frequency domain.

#### **2.1.6 Control of emission spectrum characteristics**

The control of emission spectrum characteristics increases the amount of spectrum available to radiocommunications by limiting the amount of spectrum wasted to unwanted emissions (both spurious and out-of-band emissions). Sharing of spectrum is facilitated by increasing the efficient use of the spectrum. Control of unwanted emissions generally comes at a cost since methods such as filtering must be employed in system design to control these characteristics. Spectrum shaping through changing the RF and/or IF, baseband filtering to the transmitter or receiver transmission line, are the ways to improve spectrum efficiency by minimizing either transmitted energy or received voltage that are not necessary to recover desired information. Vestigial sideband filters on television transmission lines is one example.

#### **2.1.7 Dynamic variable partitioning**

Another sharing method which results in a flexible use of the spectrum is dynamic variable partitioning, which is real-time sharing of a block of spectrum among two services for which one service has priority over the other. In dynamic variable partitioning there is a partition that divides the channels contained in a block of spectrum into two portions, one for service A and the other for service B. The partition moves in real time in response to actual or perceived demand from service A. A network operation centre is required to respond immediately to provide the channels necessary for service A. The method is based upon the establishment of a buffer of channels to respond immediately to requests. This method of sharing has been simulated using a Monte Carlo simulation but has not, as yet, been validated operationally.

#### **2.1.8 Frequency tolerance limitation**

Frequency tolerance is defined as the maximum permissible departure by the centre frequency of the frequency band occupied by an emission from the assigned frequency or by the characteristic frequency of an emission from the reference frequency. The limitation of frequency tolerance cuts down the wasting of spectrum by controlling the wandering in frequency of the transmission signal increasing the number of systems that can operate within a portion of the spectrum.

At the same time, for the frequency converter purpose the frequency tolerance of the transmitter and receiver oscillators should also be limited to avoid the degradation of system performance and increased interference.

#### **2.1.9 DAMA**

The main disadvantage for pre-fixed assignment of channels is that it is hard to match the traffic random variation. For the thin route case with little traffic for every station, where the network or system has a great number of stations, using DAMA technology is most suitable for increasing spectrum efficiency; DAMA single channel per carrier (SCPC) system and single channel per

carrier, pulse code modulation (PCM) multiple access, demand assignment equipment (SPADE) system are the typical examples of this type of application.

### **2.1.10 Frequency diversity**

When radio propagation fading varies with frequency and the fading at different frequency location has a different level with small or negligible correlation, using the frequency diversity would obtain quite obvious diversity gain combined with the channel hitless (error-free) switching. The frequency diversity gain depends on the fading dispersion characteristics and the correlation factor between the frequency locations for diversity, as well as the performance of hitless (error-free) switching.

## **2.2 Spatial separation**

### **2.2.1 Geographical shared allocations**

Users in different geographical areas can reuse the same frequency if separated by sufficiently large distances. Geographical or area sharing of frequencies is a technique that speaks for itself and has long been considered of practical application. This type of sharing has been used for many years on a global basis in the HF broadcast band, for example. It is useful in any band depending on the requirement for service links and geographical coverage. It can take into account the characteristics of propagation to facilitate its use. This is also a technique that can use, to advantage, specific antenna system characteristics. In space service bands, where antennas point to the GSO, and depending on the latitude of operation which in turn determines the elevation angle and boresight direction in three dimensions, it may be possible to share spectrum around a terrestrial terminal. Antenna diversity and antenna pattern shaping can be an aid to geographic sharing either through automatic or manual switching between sites.

Another possible sharing method is to allocate a block of spectrum to two or more services and then implement the sharing within administrations by geographically separating users in the different allocated services. This utilizes sharing by separation in the spatial coordinate of spectrum. An example is the sharing between television broadcasting and terrestrial mobile services where geographical separation has facilitated sharing. The allocation tables contain a number of country footnotes, which define a different service for use within a particular administration. These footnotes provide flexibility for countries to utilize an allocated service differently from the world or regional allocation. These footnotes define a *de facto* sharing arrangement among users who utilize the RR Article 5 Table of Frequency Allocations and the administrations utilizing a service defined by the footnote. This type of sharing is most useful for terrestrial services on the surface of the Earth. It is more difficult to effect the sharing when one or both of the services involve an airborne or a space or satellite communication service.

### **2.2.2 Site separation**

Site selection primarily involves the determination of an operating location that provides adequate distance separation from other operating stations at the same frequency. An extended case of site separation is the route separation that is the important countermeasure against the high rain attenuation due to the heavy raining for frequency bands above 10 GHz or several 10 GHz.

### **2.2.3 Antenna system characteristics**

Different possibilities exist for employing antenna system characteristics to facilitate frequency sharing or to minimize interference. The most obvious way is to use directional antennas to the extent that technology allows.

### 2.2.3.1 Adaptive antenna (smart antenna)

Actively adaptive antenna arrays (adaptive antennas) can quickly focus in real-time pattern nulls in the direction of a detected interference signal. Improved side-lobe control over current antenna designs can be a technique for further facilitating sharing.

Actively adaptive antenna arrays and side lobe cancellers are feasible, depending on the frequency of operation, but can be quite complex, and they require a significant amount of hardware. Active sidelobe cancellation does not decrease the amount of interference received through main beam coupling. Improved side lobe control on fixed antennas may also be possible, with its feasibility inversely proportional to the amount of additional side lobe suppression. Factors such as scattering from antenna mounts and other surrounding objects or structures may limit the amount of side lobe suppression that can be easily achieved. Mechanical and construction tolerances on antenna elements directly impact the achievable side lobe suppression of fixed phased array antennas.

The economic impact of side lobe cancellers and active antenna arrays is proportional to the complexity and additional amount of hardware required. Lobe suppression through use of absorbing material and/or shielding will result in more costly equipment and installation costs, but back lobe suppression should be more cost effective to implement from a design point of view than lobe suppression in other directions.

As digital signal processor (DSP) technology and software radio improve, the adaptive antenna is also improved as the smart antenna or intelligence antenna, widely used in mobile communications and satellite communications areas.

### 2.2.3.2 Antenna polarization discrimination

The orthogonal polarization performance of electromagnetic waves can be used for enhancing frequency reuse ability. For linear polarization, horizontal and vertical polarization are orthogonal to each other, while for circular polarization, right-hand and left-hand polarization are orthogonal. Using polarization discrimination between orthogonal polarization signals can increase spectrum utilization and improve satellite orbit capacity. Polarization discrimination performance is effected by several factors, such as antenna beam direction, frequency bands used, cross-polarization performance of transmitter and receiver equipment, depolarization discrimination effects of satellite radio propagation positioning stability, as well as polarization tracking and polarization correction performance, etc.

When linearly polarized radio waves travel through the ionosphere, their polarization plane undergoes a rotation due to the Faraday effect. As indicated by analysis and computation, the Faraday rotation is inversely proportional to the square of the frequency, for example, the peak of angle due to Faraday rotation at about 1 GHz band could be up to several  $10^\circ$ , while at 4, 6 and 12 GHz bands the rotation angles are up to  $9^\circ$ ,  $4^\circ$  and  $1^\circ$ , respectively. It presents no problem at frequencies larger than 10 GHz. On the other hand, at frequency bands above 10 GHz or several 10 GHz, the scintillation materials like rain, etc. have big depolarization effects especially for circular polarization, therefore, for frequencies lower or equal to 1 GHz, circular polarization is usually used, while for frequencies higher than 10 GHz, linear polarization is normally used; at the 4 and 6 GHz bands, the effects due to Faraday rotation and rain depolarization are not so obvious, linear and/or circular polarization can be used. To increase the frequency reuse times for trans-ocean satellite systems, the circular polarization is always used; however, for national and/or regional applications, the coverage is usually smaller, and there is no need to use multibeam and multi-times frequency reuse, linear polarization can still be used, as it is simple and inexpensive.



### 2.2.3.3 Antenna pattern discrimination

The antenna associated with each radio transmitter takes the output power of the system and translates that into radiated power. The resulting radiated power has a pattern based on the design of the antenna. The signals radiated by omnidirectional or nearly omnidirectional antennas spread equally along all azimuths with little or no gain. Therefore, their signals may deny spectrum to others in all directions but over a distance only limited by the transmitter power. Highly directional antennas focus and amplify the radiated power in a specific direction. These signals deny spectrum along a specific line but possibly for longer distances due to the gain of the antenna. However, some directional antennas rotate combining the characteristics of high gain and omnidirectional pattern. These patterns determine how systems can fit together geographically. Receive antenna patterns also impact sharing by increasing or decreasing the receiver's ability to pick up the desired signal over others in the same geographic areas. Highly directional antennas are not receptive to signals away from the intended direction of reception.

Antenna patterns can be measured and gain determined along each azimuth. For spectrum planning purposes, patterns are usually considered in terms of a separate gain value for the main beam, back lobe and side lobes.

### 2.2.3.4 Space diversity

Space diversity (usually it means vertical space diversity) is a simple and powerful countermeasure against frequency selective fading, the principle of using space diversity to improve system performance in a selective fading environment is based on the small or negligible correlation between or among the main signal and sub-signals by main antenna and diversity antennas, which must have enough vertical antenna-space separation. In this case, using the adaptive combiner to combine the different signals by the different antennas that form the small or negligible received signals can obtain the good system gain improvement of power utilization. The performance improvement depends on the combiner scheme with a specific adaptive control algorithm. Maximum power combiner, maximum ratio combiner, minimum dispersion combiner, as well as both optimized amplitude and phase combiner, etc. are the typical adaptive combiners.

### 2.2.3.5 Antenna angle or pattern diversity

The main disadvantage of vertical space diversity is that it needs two or more antennas, placed in such a way that they have enough vertical space separation to get the necessary radiowave propagation clearance for the sub-antennas compared to the main antenna, which increases the construction cost. On the other hand, so-called angle or pattern diversity is in fact also a type of space diversity (usually it is called horizontal space diversity), but using horizontal separation rather than vertical space separation to reduce the radiation angles and obtain the receive diversity performance improvement, especially in terms of the construction cost. Using sub-antennas or antenna beams with different size of beam dispersion performance improvement, some experimental data shows that a quadrature amplitude modulation (QAM) 64-QAM system, using those type of diversity, can obtain about a 400-time diversity gain. Generally speaking, the diversity gain however would be quite dependent on the system fade margin and the propagation path environment, including the reflected beam sizes, the angle between the main-signal beam and reflected beams, etc. The antenna angle or pattern diversity is an economically important approach against frequency selective fading, which can also combine with two-antenna space diversity in a suitable vertical space separation to form a strong multi-diversity scheme with big diversity gain and a good performance-cost compromise.

## 2.2.4 SDMA

Techniques have been developed to allow transmission discrimination based on spatial orientation according to a controlled variation of antenna patterns. This technique has particular importance for

new satellite, wireless local loop and cellular mobile radio applications. Smart antennas combined with software radio technology could be an important and effective approach for realizing SDMA, because it is easy to separate the beam direction.

### **2.2.5 Physical barriers and site shielding**

Shielding can limit the direction in which a transmitter can radiate and therefore interfere with other systems and the direction in which a receiver can receive interference. Such limitations allow greater sharing by fitting systems together geographically that might otherwise interfere with each other. Site shielding can be accomplished naturally through vegetation, terrain or buildings. Site shielding can also be constructed by building beams, or metal shielding. For example, site shielding would be important for sharing between the fixed service (wireless access) and the fixed-satellite service.

## **2.3 Time separation**

Users can share spectrum in time, as when taxicabs alternately use the same frequencies or citizen band radio operators share frequencies.

### **2.3.1 Duty cycle control**

Duty cycle is the product of the pulse duration and the pulse repetition rate. It is also the ratio of the average power output to the peak power output.

### **2.3.2 Dynamic real-time frequency assignment**

Another sharing method which results in a flexible use of the spectrum is dynamic variable partitioning which is real-time sharing of a block of spectrum among two services for which one service has priority over the other. In dynamic variable partitioning there is a partition that divides the channels contained in a block of spectrum into two portions, one for service A and the other for service B. The partition moves in real time in response to actual or perceived demand from service A. A network operation centre is required to respond immediately to provide the channels necessary for service A. The method is based upon the establishment of a buffer of channels to respond immediately to requests. This method of sharing has been simulated using a Monte Carlo simulation but has not, as yet, been validated operationally.

### **2.3.3 TDMA**

The TDMA technique consists of assigning fixed predetermined channel time slots to each user; the user has access to the entire bandwidth, but only during its allocated slots. Here, signalling waveforms are orthogonal in time. The TDMA approach is more complex to implement than FDMA, but an important advantage is the connectivity that results from the fact that all receivers listen to the same channel while senders transmit on the same common channel at different times. Accordingly with TDMA, many network realizations, both in ground and satellite environments, are easier to accomplish. With digital modulation, coordinated time sharing such as with appropriately synchronized time-division multiplexed signals could allow simultaneous use of the same frequency band by two or more systems. With analogue FM, certain types of bursty interference may be more tolerable than others due to the well-known FM capture phenomena providing improvement, and discrimination against unwanted signals with low duty cycles. Dynamic, real-time frequency assignment can be managed by a control station in some cases where one frequency band is used for more than one purpose and sub-bands are shifted in width to meet demands. Usually, shifts will occur in blocks of spectrum for substantial blocks of time.

Analogue FM can provide an improvement on the order of up to 10 dB of interference rejection when there is a frequency separation between the desired and interference carriers, with greater improvements for large carrier separation within the total signal bandwidth. Digital time sharing

between transmitters in the same system (TDMA) must overcome the difficulty of synchronizing transmissions from different locations.

There is no additional economic impact for analogue FM improvements for systems using this type of modulation. The economic impact of digital time-sharing is proportional to the difficulty in solving the synchronization issue.

For satellite communication, the satellite switched TDMA (SS-TDMA) and sweep spot beam TDMA are the important approaches of the high efficiency TDMA applications.

## **2.4 Signal separation**

Transmission of communication signals using digital radio also promises improvements in spectrum efficiency. Since many signals (such as audio and video) originate as analogue signals, they must be converted to digital format prior to transmission to exploit this technology. Ironically, the bandwidth of the digital signal is greater than the analogue version. The spectrum efficiency benefit of digital technology is derived from different factors, including compression techniques. Digital communication systems often employ error detection and FEC algorithms to improve system performance in the presence of interference sources, thus enhancing sharing possibilities.

### **2.4.1 Signal coding and processing**

Several techniques generally classed under signal coding (or coded modulation) and processing are available. The coding may occur as part of the modulation process (channel coding, as with CDMA) and it may also occur in the original signal prior to transmission (source coding, as when data strings are compressed).

### **2.4.2 FEC**

One method is the use of FEC on digital links to reduce the required  $C/(N + I)$  ratio. The FEC design allows for decreased power margins at the expense of either throughput or bandwidth. In this case, source coding techniques are used to detect errors and control the transmitter to require retransmission of erroneous data blocks.

### **2.4.3 Interference rejection**

An advanced interference mitigation technique is non-linear interference rejection using powerful signal processing algorithms that exploit the spectral correlation properties of both the desired signal and the interference signal.

### **2.4.4 CDMA**

Spread spectrum modulation or CDMA offers significant advantages for uniformly sharing in either the same system or in several systems.

The CDMA technique allows overlap in transmission both in frequency and time. It achieves signal separation by the use of different signalling codes in conjunction with matched filters (or equivalently, correlation detection) at the intended receivers. Each user is assigned a particular code sequence, which is modulated on the carrier with the digital data modulated on top of that. Two common forms exist: the frequency-hopped and the phase-coded. In the former, the frequency is periodically changing according to some known pattern; in the latter, the carrier is phase modulated by the digital data sequence and the code sequence. Multiple orthogonal codes are obtained at the

expense of increased bandwidth requirements (in order to spread the waveforms). With CDMA, there is also a lack of flexibility in interconnecting all users (unless, of course, matched filters corresponding to all codes are provided at all receivers). However, CDMA has the advantage of allowing the coexistence of several systems in the same band, as long as different codes are used for different systems.

CDMA has become a key technology in International Mobile Telecommunications-2000 (IMT-2000) wideband multimedia cellular mobile communication systems. In these wideband CDMA systems a number of sophisticated technologies have been introduced such as adaptive transmitter control, high efficiency Turbo coding, multi-mode and multi-rate operations, various diversity receptions, interference cancellation, multi-user joint detection, smart antenna, as well as software defined radio, etc.

#### **2.4.5 Spread spectrum**

Transmitters using spread spectrum techniques spread the signal over a bandwidth many times larger than the original signal bandwidth, using a predetermined repeating code. The receiver uses the same code to disperse the signal back into its original form.

A benefit of spread spectrum is interference suppression. Commercial applications include personal communications, cellular telephones, wireless alarm systems, local area networks and paging systems.

While overlaying spread spectrum systems on frequency bands could improve spectrum efficiency (as with unlicensed low-power devices), the possibility of interference increases with an increasing number of spread spectrum systems. The proliferation of direct sequence systems may substantially raise the noise floor, degrading the operation of all narrow-band systems. If the number of frequency hopping systems increases dramatically, the occurrences of interference, though brief, may become so frequent as to degrade operation.

Spread spectrum systems can be defined as ones in which the average energy of the transmitted signal is spread over a bandwidth that is much wider than the information bandwidth. These systems usually trade the wider transmission bandwidth for a lower average psd and increased rejection to interfering signals operating in the same frequency band. They therefore have the potential of sharing the spectrum with conventional narrow-band systems because of the potentially low power that is transmitted in the narrow-band receiver passband. In addition the spread spectrum systems are capable of rejecting the narrow-band interference.

Another factor which affects sharing of spread spectrum systems is the near-far problem which results when an interfering spread spectrum system is geographically nearby and the wanted signal is from a source spatially some distance away. When, because of the near-far problem, interference occurs between equipment in different services, sharing is difficult to accomplish.

A number of new technologies such as mobile data systems and low-Earth orbit (LEO) satellites may transmit their information as low duty cycle packet communications. These types of communications are candidates for overlay sharing. However, studies must be undertaken to determine the probability of interference and to define applicable performance protection criteria.

Both spread spectrum and packet radio systems are multiple access communication systems and sharing can best take place when the number of active equipment in the overlay is small. The limitation to any sharing of these schemes is dependent upon the number of active users in any particular frequency band. Each overlay increases the noise level slightly and therefore increases the probability of interference. The important issue is how to control the use of a block of spectrum that contains spread spectrum or intermittent packet users. When an overlay sharing is effected among services, it may be necessary to regulate the number of users that are present in the overlay to be sure that the interference level is below a predefined level. This is similar to present procedures

where, by assignment methods, there is a limit to the number of users and their bandwidth. New systems such as intelligent frequency agile radios also operate as an overlay and could facilitate frequency sharing. These devices are intelligent enough to determine in real time if the spectrum is occupied. Intelligent radios could find and utilize unused spectrum in the allocated shared spectrum block.

#### **2.4.5.1 Direct sequence**

One technique, known as direct sequence spread spectrum, expands the signal's frequency spectrum over a wider bandwidth. A direct sequence modulated system is one where the carrier is modulated by a digital code sequence whose bit rate is much higher than the information signal bandwidth. Interference from a direct sequence system to a narrow-band receiver will appear similar to random electrical noise.

#### **2.4.5.2 Frequency hopping**

Frequency hopping, the other primary spread spectrum technique, alternates frequencies over the spread bandwidth in a seemingly random manner. Frequency hoppers use carrier frequency shifting in discrete increments in a pattern dictated by a code sequence. The transmitter jumps from frequency to frequency within some predetermined set; the order of the frequency usage is determined by a code sequence. Interference from a hopped system, although of the same power as a conventional system, is so brief that it does not adversely affect many types of systems.

Frequency hopping is the repeated switching of frequencies during radio transmission according to a specified algorithm, to minimize unauthorized interception or jamming of telecommunications. The overall bandwidth required for frequency hopping is much wider than that required to transmit the same information using only one carrier frequency.

The time of transmission for time hoppers and time-frequency hoppers (usually of low duty cycle and short duration) is governed by a code sequence. The code sequence determines both the transmitted frequency and the time of transmission.

#### **2.4.5.3 Pulsed FM**

Pulsed FM or chirp modulation is where a carrier is swept over a wide band during a given pulse interval.

#### **2.4.6 Interference power/bandwidth adjustments**

If it can be assumed that noise and interference affect receiver performance equally, as is the case in some systems, the technique of power or bandwidth adjustment may be used to exploit the non-linear nature of acceptable carrier-to-interference ( $C/I$ ) ratio, as a function of carrier-to-noise ( $C/N$ ) for a constant  $C/(N + I)$ . The technique is employed by increasing the transmitter power in the system being interfered with. By increasing the transmitter power of a noise limited system by a small amount, e.g. < 3 dB, the amount of interference that can be tolerated at the receiver is increased by a much larger amount, e.g. 10 dB.

Satellite uplinks are often noise limited due to the amount of transmitter power required to overcome path loss over the large distance involved. Under this limiting condition, very little margin is left for interference. Increasing the transmitter power of satellite uplinks is difficult when the required uplink power is close either to the state-of-the-art limit or to the maximum authorized limit. An alternative to increasing maximum transmitter power is to reduce the amount of power control allocated to overcome rain fades. This leads to a decrease in system availability that may not be acceptable depending upon system service objectives. An increase in satellite uplink power may create interference into terrestrial receivers, but terrestrial systems that share frequencies with satellite uplinks could be self-interference limited and not noise limited. Hence, an increase in

uplink transmitter power does not lead to a comparable increase in the amount of interference power that can be tolerated in some terrestrial systems. The feasibility of increased power and the impact on satellite uplinks must be agreeable before this technique can be used.

The economic impact of increased transmitter power depends on how close the designed transmitter power is to the state-of-the-art maximum. If the designed power is well below the currently achievable maximum, then an increase in transmitter power may not be too expensive. If the designed transmitter power is already relatively high, this increase could be costly, if applied to a large number of terminals. Reduced system availability, and the resultant deterioration of service, lead to a reduced ability to charge users for service. The magnitude of the reduction in system availability is related to the available excess margin and the rain rate statistics in the region where the earth station is located.

#### **2.4.6.1 Co-channel**

Co-channel frequency sharing is possible, as with low-power unlicensed devices, which have such low power that they can operate at the same time and on the same frequencies as licensed services.

#### **2.4.6.2 Dynamic transmitter level control**

Also known as automatic power control, this capability allows the power of a transmitter to be varied based on the environmental situation. For example, as rain increases, the power may be increased to compensate for the increased signal attenuation. This allows for greater sharing by eliminating or decreasing the amount of spectrum denied by systems that radiate more power than they need in order to accommodate situations where more power may be needed. This particularly works well where all systems in a geographic area can be expected to be experiencing the same variations in signal attenuation.

#### **2.4.6.3 pfd limitation and psd limitation (energy dispersal)**

The limitation of pfd or psd is an approach to setting limits on emissions at a potential receiver as opposed to the transmitter. This allows the operator to make a determination with respect to transmitter power, antenna gain and system location in order to comply with the limitation. This approach is often used in facilitating sharing between satellite systems and terrestrial systems.

#### **2.4.7 Modulation complexity**

The use of QAM with higher numbers of states ( $M$ -QAM) and advanced signal design provide the possibility of increasing the bit rate within a fixed channel bandwidth or decreasing the channel bandwidth for a fixed bit rate, as well also improving the power/spectrum utilization performance. Increasing the modulation complexity usually requires increased reliance on the use of error correcting codes and may require more complex dynamic channel processing to meet transmission performance objectives.

The typical  $M$ -QAM signal constellations are shown in Fig. 1, which includes the modified 256-QAM, named rounded square 256-QAM (RS 256-QAM) for improving the performance in the non-linear transmission environment, with a reduced signal peak factor (dB). Similarly, the constellation comparison for RS 64-QAM, RS 256-QAM and RS 1024-QAM in 1/4 quadrant description is shown in Fig. 2, while the corresponding relationship between  $r_p$  (dB) and required relative  $C/N$  (dB) for typical  $M$ -QAM and RS  $M$ -QAM is shown in Fig. 3. It is not so difficult to realize the modified RS type constellation structure by arranging some ROM technology to do the relevant signal processing.

FIGURE 1  
Some typical constellation structures for  $M$ -QAM signals

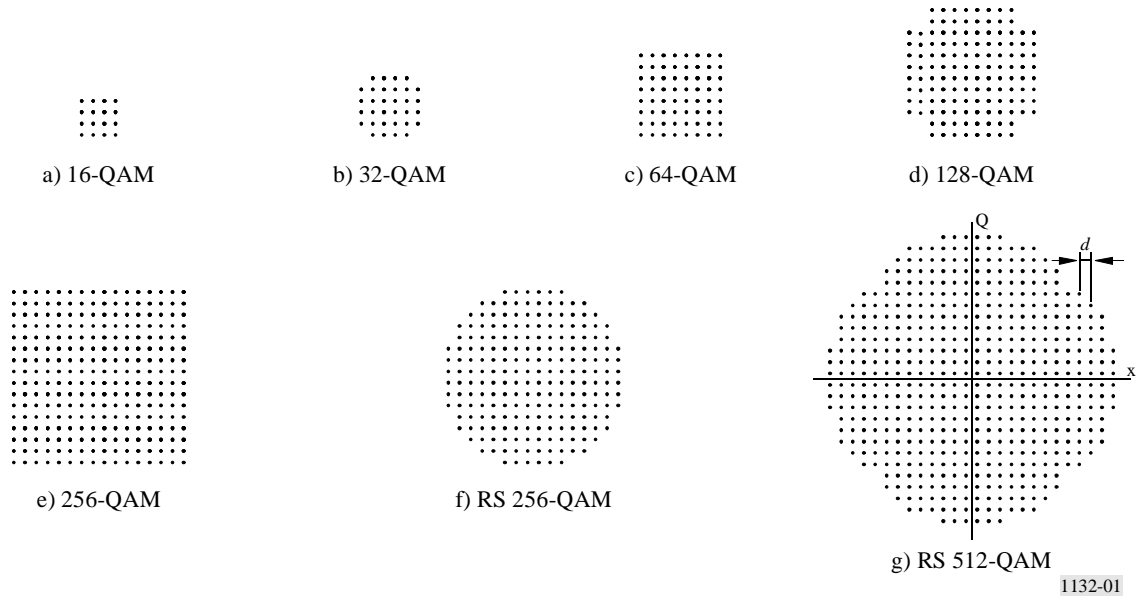


FIGURE 2  
The modified constellation comparison in 1/4 quadrant for RS 64-QAM, RS 256-QAM and RS 1024-QAM signals

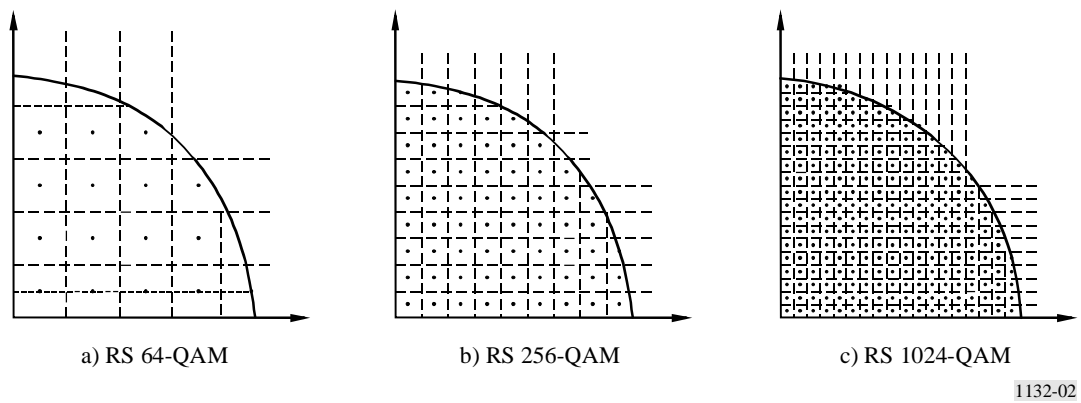
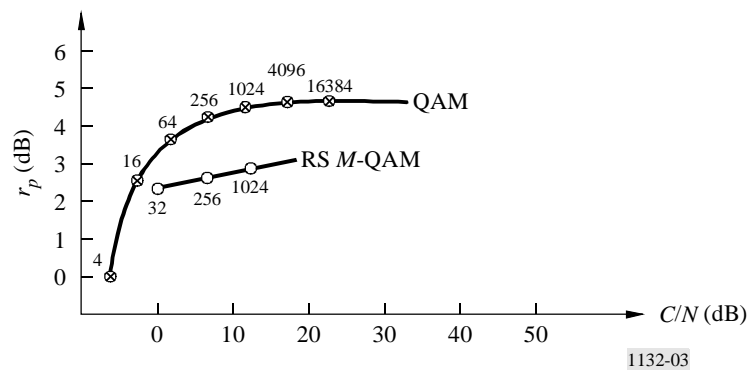


FIGURE 3  
 $r_p$  (dB) vs relative  $C/N$  (dB) for typical  $M$ -QAM and RS  $M$ -QAM signals



### 2.4.8 Coded modulation

FEC technology can improve power utilization. However it will reduce the spectrum efficiency due to inserting the redundancy in the time domain. An important technology to improve the power utilization while not reducing the spectrum efficiency is coded modulation, which combines the modulation with coding technology by mapping of redundancy into modulation signal parameters. For example, the signal vector number of the signal space can be increased, i.e. extending the number of signal constellations, or using the multidimensional signal structure. Therefore, the use of advanced coded modulation technology with multi-state and multidimensional design has already obtained the power/spectrum utilization quite close to the Shannon theoretical limit. There are some typical coded modulation schemes, such as trellis coded modulation, block coded modulation, constant envelope coded modulation, reduced modulation state-coded modulation, programmatic coded modulation, multiple trellis coded modulation, series concatenated coded modulation, parallel concatenated coded modulation, series plus parallel concatenated coded modulation, etc. As a special case of parallel coding technology, Turbo code has the outstanding performance very fast to approach the Shannon theoretical limit, it has been widely considered to be used in IMT-2000 terrestrial cellular mobile and advanced satellite communication systems. The relevant Turbo-coded modulation also has similar excellent performance. For signal design it is important to point out that the different type coded modulation could be matched to the different transmission environment.

### 2.4.9 Adaptive signal processing

Advanced adaptive signal processing technology is a key to realize the benefits of new generation high speed wireless digital transmission. By using:

- the adaptive equalization in frequency and/or time domain;
- the adaptive transmitter power control;
- antenna diversities including vertical space diversity and/or horizontal space diversity with various adaptive diversity combiners;
- frequency diversity including using hitless (error-free) switching against real time propagation delay variation;
- interference/echo cancellation or suppression and multi-user detection against real-time interference;
- (orthogonal) multiple carrier parallel transmission (or orthogonal frequency division multiplexing) against strong dispersion distortion for wideband signals;
- pre-distortion or non-linear equalization technologies against non-linear distortion, etc.

It will provide strong measures against the real-time transmission environment variation, such as the variation of received signal level and signal dispersion. To realize the good performance of a system with adaptive signal processing, the relevant signal design and signal detection are essential. The modem with adaptive estimation and equalization combined together can realize excellent modem performance with very small implementation degradation. The adaptive controls include IF signal level, local oscillators' orthogonality for quadrature modulation and detection, reducing the signal phase jitter, equalizing the signal waveform distortion and improving the signal eye pattern, keeping the optimum decision threshold, etc. The all-digital modem architecture is very easy and flexible to realize the whole adaptive controls as mentioned above. Also the control algorithm design will be very important to realize the good adaptive control performance. Among the algorithms the blind algorithm without the demodulation feedback control is usually very helpful for the estimation, equalization and joint detection processing, as well as for the adaptive control of smart antenna plus software (defined) radio operation.



#### **2.4.10 Antenna polarization**

As mentioned in § 2.2.3.2, the antenna polarization performance, such as the orthogonal polarization performance is very important for enhancing the frequency reuse ability of terrestrial digital radio communications, satellite communications, narrow-band/broadband wireless local loop, as well as mobile communications, etc. The adaptive combiner and/or adaptive control gives excellent performance when jointly using the antenna polarization discrimination, antenna angle or pattern discrimination, space diversity, frequency diversity, and horizontal space diversity using antenna pattern or beam direction difference. The use of adaptive antennas is mainly based on implementing the excellent adaptive signal processing technologies, including the design of the excellent performance control algorithms.

#### **2.4.11 Software (defined) radio**

In accordance with the development of all digital function modules and the increase in DSP operational speed, software (defined) radio is going to be a very important technical approach when implementing IMT-2000 systems and other advanced wireless communication systems in order to perform high speed, real time/pseudo-real time adaptive control for system parameters and/or architecture.

Software radio is defined such that based on the same hardware environment to flexibly and conveniently realize the system upgrade, extension and/or multi-mode extension with adaptive operation by means of software control. For example, combined with the smart antenna, using A/D/A converters and high speed DSP to realize the effective adaptive control of every part of the system through a uniform software and hardware platform at the baseband, or IF band, or even at radio frequency band. This includes the adaptive electromagnetic compatibility analysis and dynamic control based on real time or pseudo-real time environment analysis, the control of adaptive changing of bit rate and/or modulation states by using asynchronous transfer mode technology, as well as the dynamic control of the multiband, multi-level cell structure and multi-mode operations. The main goal of the controls is to obtain the efficient and effective inter-operation characteristics and seamless connection for the multiband, multi-modulation channels and various data formats.

It is actually called “software radio”, only if the signal processing is at the radio-frequency band. Otherwise it is usually called “software defined radio” if the signal processing is at baseband or IF band; however, for simplification it is still called software radio, even if the processing is at baseband.

For advanced cellular mobile applications, especially for narrow-band time division duplex mode operation, the use of smart antenna combined with software (defined) radio can easily realize the hybrid multiple access of SDMA/CDMA/FDMA to increase the spectrum utilization efficiency and improve the sharing operation environment.

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