DIGITAL AUDIO BROADCASTING

DAR CONCEPT

The introduction of digital audio radio (DAR), first in modified video, then specialized recording formats, and then in the widely accepted compact disc (CD) format, opened the concept of transmission of digital CD quality sound to remote receivers. Early experiments with transmission to fixed receivers proved the concept and the difficulty of the coming project for simplified transmission to mobile receivers. WGBH-TV, public television in Boston, conducted an after-hours transmission experiment, using the full 6 MHz video bandwidth for reception on specialized equipment and eventually incorporating video recorders for the digital audio.

DIGITAL COMMUNICATIONS BACKGROUND, USAGE AND TERMS

Over the past several decades the theory of digital data communications has advanced steadily. The physical limits have been explored and stated by Shannon et al. Advanced modulation and multiplexing techniques, such as PSK (phase shift keying) and OFDM (orthogonal frequency division multiplexing), have been devised to maximize the effective channel capacity and utility. However, even with advanced modulation the data rate necessary for transmitting high fidelity digital audio created an impractically large radio frequency (RF) bandwidth, as set by Shannon's Theorem (1). Digital audio data rate reduction of at least 5 to 1 was required for a practical data rate and RF bandwidth. Such inventions had to wait for other developments.

Large-scale integrated circuits (LSI) and application-specific integrated circuits (ASIC) enabled the production of large memory chips and digital signal processing (DSP) chips. These were combined with new data reduction software to achieve the real-time data rates, modulation, and inverse reception processes necessary for DAR. The circuitry necessary to receive the new digital radio signal, all at effectively real-time speed and within a practical and economical system, were now at hand. The task of devising, testing, and implementing a practical system began in the early 1980s.

Data communications, where the data path and media are well behaved, are most familiar in hard-wired and computer applications and have been developed to a high technical state of art. Expanding data transmission to the long free-space path and particularly to the mobile environment meets unique problems in the RF channel. Now, RF channel coding and error detection and correction methods, many thousands of times more powerful than in the computer environment, are used to aggressively apply data transmission to the mobile environment.

While the technical hardware necessary to transmit digital data in the mobile RF environment was developed, progress was also made on reducing the impossibly high data rate of readably available digital audio on CD. The field of psychoacoustics had early beginnings in studying and understanding the perception of sound by humans. Early achievements were made with the perception of "loudness" with early application to loudness meters and signal controls. Now psychoacoustics has advanced to the point that yields satisfactory digital audio at useful data rate reductions. This brief overview is expanded in detail below.

DEFINING DAR TECHNOLOGY

Digital audio broadcasting (DAB) is also called digital audio radio (DAR) and digital radio broadcasting (DRB). The general service will provide a data channel to the user to be used to carry digitally encoded audio and other related digital services.

Bit rate reduction is the process of reducing the audio data bit rate so as to fit within the constraints of the system. The reduction is not a compression as traditionally thought of in computer usage. Computer data compression is a "lossless" technique wherein the recovered data is a 100% faithful reproduction of the original data. Audio bit rate reduction is a *lossy* process where some data are removed and can never be replaced on recovery.

Following are some extended definitions of the major technical areas common to DAR or to some of the major proponents of DAR systems.

CEMA (Consumer Electronics Manufacturers Association), a division of EIA (Electronic Industries Association), is a standards organization.

COFDM (coded orthogonal frequency division multiplexing) is an RF multiplexing method, a specific case of OFDM (2–4). In COFDM the total data set is distributed over a wide bandwidth among many fixed, and individually relatively narrow, RF carriers in a time and frequency variable progression. OFDM has been known as a possible system for many years but practical systems could not be built with more than a very few carriers using discrete components. Recent developments in digital signal processing (DSP) and the use of fast Fourier transform (FFT) for both the generation and detection of the RF composite have made systems with hundreds or thousands of carriers possible. The individual carriers are spectrum-shaped by a geometric $\sin x/x$ function. The $\sin x/x$ function has a theoretically infinite but rapidly decaying bandwidth with two zero crossing values (zero carrier energy) for each sideband cycle. By carefully placing the center frequency of each carrier at the first zero crossing of its adjacent carrier, each is orthogonal with the other. This enables the individual carriers to be placed much closer to each other and still be detected and demodulated without interference. The group *multiplex* of carriers occupies the entire available bandwidth in a generally square-shaped frequency spectra with rapidly sloping sides and low residual sideband energy from the combined $\sin x/x$ sidebands. The bandwidth, frequency, maximum Doppler velocity, and so on, are all trade-off factors in an OFDM system. OFDM and COFDM techniques are used for several of the DAR proponent systems.

MPEG (Motion Pictures Expert Group) is an organization responsible for setting standards, particularly the audio bit rate reduction (coding) used in several of the proponent DAR systems. MPEG coding is available in several modes with MPEG-1 audio layer 2 being most often used for DAR.

This MPEG-1 audio layer 2 auto coding is identical with and was popularly known as *MUSICAM*, derived from the coding plan MASCAM (masking-pattern adapted sub-band coding and multiplexing) developed by IRT in the early days (1988) OF DAR (5,6).

PAC (perceptual audio coding) is a digital bit rate reduction system devised by Lucent Technologies—Bell Labs (formerly AT&T Laboratories). Like MUSICAM/MPEG, the PAC bit rate reduction coding goal is the effective reduction of audio data without perceptible audio artifacts.

QPSK (quadrature phase shift keying) is an RF modulation method, one of the many and often used specialized methods of generic phase shift keying (PSK) (3). Others include more or less states of phase keying or amplitude keying, such as QAM (quadrature amplitude modulation). Each RF transmission system may place special conditions on the modulation system used. For example, the COFDM modulation and multiplexing system cannot easily supply an absolute phase reference for standard QPSK demodulation. To counter this, one method used is a special class of QPSK with progressive 45° phase offset for each reference signal. The precise term for this modulation is $\pi/4$ D-QPSK.

SFN (single frequency network) is an implementation of a DAR system wherein a single frequency or band of frequencies is used for many adjacent contiguous and overlapping transmission areas (7,8). The system design must be able to tolerate or even actively use several transmitters signals, all time synchronized, transmitting extra signals or "active echos" into an area. The SFN usage is an outgrowth of the ability to operate smaller scale on-channel repeaters as discussed in the section on the EU-147 system. That system is the only one which has demonstrated either on-channel repeaters or the SFN. A system such as this, operating with several transmitters on the same frequency and with overlapping coverage zones, allows the continuing expansion of coverage by adding more SFN transmitter nodes. That system also provides enhanced service reliability within the coverage area by the simultaneous redundant reception of data from several different directions, each with their own uncorrelated fading or blockage probability. The resulting SFN gain is a theoretical and empirically proven parameter which defines the gain in service expressed as a decibel value related to the effective radiated power (ERP) of any one SFN node or within a system of multiple nodes. Timing the transmission of data from each node is critical, which places limitations on SFN operation and must be carefully planned to build such as system.

DAR SYSTEM TECHNICAL REQUIREMENTS AND POTENTIAL TRADE-OFFS

Nearly every technical parameter of a DAR system is subject to variation as other parameters are changed. DAR proponents are encountering this reality; when one parameter of a system is optimized it will at least affect, if not degrade, performance of the system in another area. Some of the earlier well-developed systems may have appeared to have their parameters frozen, ready for implementation as a standard. However, even the oldest, "most standard" system, may still find some modification with time. For example, the EU-147 system adopted a Mode IV operation, not as an extension beyond Mode III, but as a mode lying between II and III. Other systems which have been tested have discovered areas of poor performance and, in the process of attempting to improve one deficiency, have created or worsened others, again discovering the reality of such trade-offs.

Indeed, some compatible system modification must be accommodated in the future. By using a sufficiently flexible basic system design, to take advantage of new technical developments, additional other-than-audio data services for enhanced value added services will evolve.

Data Rates and the RF Transmission Channel

Working within the basic definition of DAR, the net data stream for the digitally encoded audio will be the main content for transmission and reception by the listener. Other data may be added to this and such additions serve to increase the gross amount of data carried by the RF channel. The starting data rate for audio coming from compact discs is approximately 1.4 million bits per second (Mb/s). The RF channel through which this data must be passed has its well-defined physical limits for data rate (bit/s/Hz) relative to the physical parameters of the channel (occupied bandwidth, power, background noise, channel disruptions, etc.) (see Shannon et al.).

Examining some RF channel parameters will give an example of the potential data rate to be transmitted. Based on the system parameters, the Shannon limit is the physical limit for the maximum channel capacity, and all practical rates lie below, sometimes well below, this limit.

The basic input digital audio data rate must be reduced approximately 5- to 10-fold to fit within a reasonable bandwidth and not violate the Shannon limit. This bit rate reduction is done by the perceptual audio coding used by all DAR systems. This coding uses a psycho-acoustic model to select and remove portions of the digitized audio which fall below the perception of human hearing. The unused data are removed and can never be replaced. If the perceptual coding process is successful the audio data rate will have been reduced to a usable value and there will be no audio artifacts detectable by any but the most critical listeners on the most sensitive audio test material. After rate reduction this net audio rate may be reduced to a usable rate of from 128 kbit/s to 256 kbit/s. The ultimate audio quality reproduced on reception, in the perfect unimpaired RF channel, is defined by this rate and the artifacts of the system of perceptual audio coding being used.

Added to the net audio data is all of the data error protection and channel overhead. Error protection data can significantly increase the gross data rate above the net audio rate, by 2 : 1 for example for rate one-half coding. Channel overhead can include timing and framing bits as well as communication protocol instructions. This may be carried on a relatively fast uncompressed part of the data stream repeated many times in sequence for enhanced reception probability. This fast information channel (FIC) adds a small percentage to the net data rate. If extra data, both program associated and ancillary, is added then this too adds to the gross channel data rate along with its own error protection data. For an effective audio data rate of 256 kb/s the gross channel data rate may be two to four times as large.

Data Protection: Error Detection and Correction

The coded audio must be protected from errors introduced in all phases of transmission. The errors must be detected, corrected, and if not corrected then at least the audio effects should be concealed to the point of being inaudible. After all that, at the point of failure (POF), the systems must mute the audio, ideally without artifacts. The systems tested in 1996 occasionally had slight audio artifacts and could be routinely identified by their behavior and artifacts at POF.

The ability of a data coding system to be able to detect and correct errors is strongly dependent on the timing of data errors. Specifically, if the RF transmission system causes a relatively long disruption of the data, causing a long block of corrupted data, then the error detection and correction system cannot recover the lost data. For short block errors, affecting audio data only, the effect may be subtle or unobjectionable audio distortion. Longer block errors, affecting critical timing and data framing information, can cause a catastrophic system failure causing a long, several second loss of audio while the system reinitializes its operation. The potential for unrecoverable data errors is reduced by interleaving the data. On data reception and de-interleaving the individual bad bits are identified and corrected and then the data are decoded for audio reproduction. The currently used audio coding systems are tolerant of even a relatively error prone channel, supplying seemingly clear audio at data bit error rates (BER) approaching 10E−3, or one error in each 1000 bits of data.

Other data can be added to the various DAR systems. Typically, both program associated data (PAD) and separate data (ancillary), may be included for other uses. This total extra data rate can be 25 kbit/s or more for each audio channel. Like the net audio data, this too is coded to protect from errors. Since its use can be considered secondary to the audio, its transmission and reconstruction on reception can be significantly delayed and sent at relatively random times and rates, generally not exceeding several seconds in delay if associated with programming, and without even that time constraint for other ancillary data. Flexible time delay allows flexibility in the coding and transmission, such as bundling smaller data packets together for efficiency and allowing the use of coding with a minimum of required extra data. The flexibility also allows the audio data rate to be high when necessary for good audio performance and delay the ancillary data transmission until audio demands are low. However, unlike the audio material, coded by the perceptual coder and to which our hearing is relatively immune to minor defects, the reconstructed extra data may be much more sensitive to errors. For example, for text, photographs, or critical data, such as financial data, a one byte error may be easily noticed or critical to some users. The degree of PAD and ancillary data coding will most likely be equal to or more extensive than that required for audio data protection. Unlike the audio useful BER of 10E−3, a reasonable BER for critical data may be 10E−5 or better.

RF Bandwidth Needed for Data and Error Protection

The RF channel can carry a maximum data rate for the given parameters of a system. For a hypothetical 500 kHz RF channel, using QPSK modulation, delivering up to 2 bit/s/Hz data rate, we have a gross theoretical capacity of 1000 kbit/s/Hz. Operating at 256 kbit/s audio coding rate with 10% overhead and 25 kbit/s PAD and ancillary data with assumed double coding for protection (rate one-half coding) yields about 610 kbit/s gross data rate. While this fits within the hypothetical channel it requires considerable work to fit in a practical channel. As can be seen from this example the minimum possible channel data rate is sought to yield the narrowest RF channel width for each audio channel (for high spectrum efficiency) while the added data and protection requirements always act to increase the gross data rate. The point of diminishing return is quickly reached.

RF Channel Protection: Various Methods

The data can be directly protected from errors by several methods. The RF channel itself is the source of the most significant potential errors and it too can be directly approached to protect the data from transmission errors. This is accomplished by examining the RF characteristic of the channel and attempting to compensate for any weak point. A successful DAR system employs both data and channel coding. They are often thought of as being independent areas within a system but their action is highly interdependent and they are designed to operate synergistically with each other.

The RF channel causes impairments to reception, some of which are transient but can be monitored and compensated for, and some of which are fundamental to the channel and relatively fixed but can be avoided to a large degree by taking advantage of the physical properties of the channel. The mobile receiver with its dynamic movement within the physical (trigonometric) propagation paths of the channel are the major factors in generating difficult transmission conditions. Static (or long-term slowly variable) factors, such as background noise and allowed power, affect transmission to a lesser or at least consistent and more easily anticipated degree.

Multipath RF Channel RF Selective Fading

Multipath propagation is a term often used (incorrectly) to describe the observable artifacts of a propagation problem. Multipath means only the multiple and simultaneous propagation of the same radio signal from a transmitter to a receiver over several different physical paths. The multiple paths are generated either by reflections from objects or the purposeful introduction of duplicate signals, for example by gap fillers to fill under-served areas. When one or both ends of the path are in motion, or the parameters are changing with time, the multiple paths and the received composite signal becomes very dynamic in time. This dynamic feature creates significant challenges for radio reception and especially for digital systems.

When two paths carry the same RF signal at very nearly the same magnitude, and the paths are different in total length by a very small distance, up to a few signal wavelengths, the signals will combine at the receiver to create nearly twice the signal (when added in phase), or cancel to very nearly zero signal (when out of phase). Illustrating this, Fig. 1 shows the theoretical RF standing wave pattern in position, frequency, and signal delay for the stated conditions. This effect has very pronounced statistical parameters which can be used to avoid some of the multipath propagation problems. For example, two points in space nearby but separated by some finite distance will have little likelihood of both exhibiting a deep multipath fade on the same frequency at the same time. Also, the probability of unequal fading will increase as the separation between the two points increases. This is the basis of receiver antenna space diversity, to be discussed further, and illustrative of diversity in general.

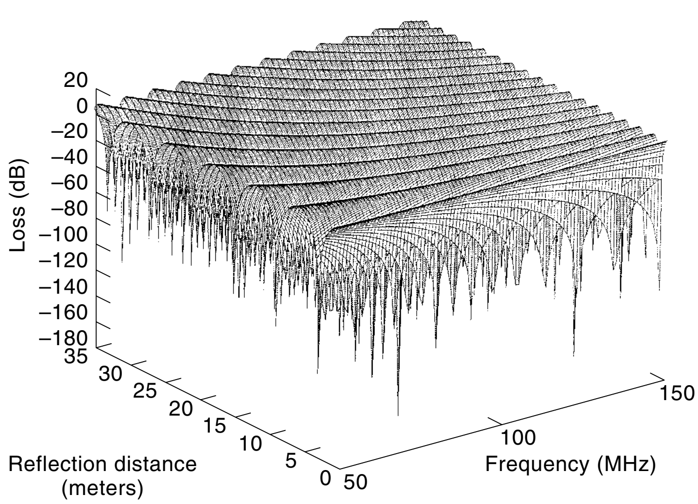


Figure 1. Calculated multipath standing wave. Loss calculated each 1/10 meter of reflection distance.

OTHER TECHNICAL SOLUTIONS

Equalization

As an expansion on the previous discussion, as a single antenna traverses a region of faded RF, the time spent in the faded region is inversely proportional to the velocity of transit and the physical width of the area. Some of the frequency-dependent fading within the occupied RF spectrum can be compensated for with active equalization. However, the faster the transition or deeper the fade, the more stress placed on an active equalizer. This approach has an upper bound in reception improvement because of the complex circuitry and extra training signals required for a fast equalizer response time. An obvious lower bound for usable equalization of the received signal is reached at the system noise level, below which no amount of equalization will recover an RF signal and data from the noise.

Interleaving

If the data being received has been interleaved as described previously, and on reception it is de-interleaved then, what would have been a rather large block of data errors is now spread into a longer group of individually small bit errors. If the total interleaving time and time of transit of a receiver antenna across a faded space all fall within the interleaver and data protection parameters then all errors will be detected and corrected or concealed. There is a definite upper limit to time interleaving due to the physical system circuitry required and the acceptable length of the audio time delay it would introduce. An audio delay of one or more seconds can be disruptive to the broadcast program, for example when tuning between programs. With the chosen interleaver maximum time limit there is a corresponding lower limit of the velocity (maximum limit to the time in the fade) of transit of a receiver through a disrupted area. Moving slow enough will eventually exceed the interleaver time limit. Stopping in RF faded areas, of sufficient fade depth and width, will eventually cause failure in any system protected only by this method.

DIVERSITY IMPLEMENTATION METHODS AND PROBLEMS

Frequency Diversity

Providing an alternative source of data to a receiver is the task of diversity. Sending additional data, replacement data, or spreading existing data so as to enhance the performance of error detection and correction algorithms are all met by various diversity systems. The EU-147 system, being a broadband multiplexed system, makes the clearest example of frequency diversity of any of the systems. The diversity aspect is not in transmitting separate replacement data but in spreading the data out in frequency so that a frequency-selective fade of finite bandwidth will not destroy enough data to disrupt the system. Other systems use multiple carriers within a narrower bandwidth and transmit redundant data within the total signal. The efficiency of frequency diversity is diminished in a comparatively narrow band system where frequencies more closely spaced do not behave independently in selective fading as do more widely spaced frequencies. Having a wide bandwidth of multiplexed users allows for individual carriers to add time and frequency interleaving by hopping over the entire bandwidth shared by all users. Early studies conducted on the EU-147 system proved a minimum total bandwidth of approximately 1.5 MHz for significant frequency diversity gain with their COFDM system.

Time Diversity and Interleaving

Interleaving of DAR data as described previously achieves diversity in a limited sense. True diversity allows for the transmission of redundant data and time diversity means that a sufficient time must pass for the channel parameters to be uncorrelated for the repeat transmissions to have an enhanced reliability of reception. The high priority repeated transmissions in some systems, carried on a fast information channel (FIC), is an example of this. The time interleaving used in DAR audio data is generally too short for effective time diversity, especially considering the potential of slow transit or short stops in faded regions. Furthermore, the interleaving does not transmit redundant delayed data, it merely spreads errors within a data sequence. The time required for true time diversity would be far too long to be practically implemented or used for the relatively real-time audio data of DAR but could significantly aid in the reception of nonrealtime ancillary data.

Space Diversity: Reception and Transmission

Space diversity can be considered the inverse analog of time diversity. For two or more receiver antennas separated in space by some finite distance, at a given velocity of transit, the time required for each antenna to individually pass through the same faded area is fixed. As velocity approaches zero the individual transit time still grows very long: as velocity increases the time grows short. However, if the spacing of the two antennas is sufficient the probability of both being in faded areas is small. The former slow transit case is a limiting factor in interleaving as discussed previously. The later fast case defines the limit of receiver space diversity, the speed with which a decision can be made on which signal to use and how to make the switch between two antennas and recover the data. At such high speeds, however, time interleaving is fully effective. Two or more antennas, possibly two separate receivers, data decoders, and data splicing algorithms could be needed, but perhaps simple RF decision switching at the antennas is all that is needed. Several present FM mobile radio systems, including some automobile FM radio receivers, use receiver diversity. A common problem with implementation of this potentially very valuable technique is the need for two or more antennas. A spacing of just under 1 wavelength has been shown to afford a 10 dB or better improvement with more spacing being slightly better within limits (9). As yet, no DAR systems are proposing receive antenna diversity.

Transmitter antenna diversity presents itself as another diversity alternative in some DAR systems. Previously, the use of on-channel repeaters, creating local active echos, and the SFN were described. Because of their displaced transmitter antennas they are examples of transmission diversity. When two or more RF signal sources intentionally radiate into the same area they create a standing wave pattern of alternatively reinforced and canceled (faded) RF signals, identical with naturally reflected multipath signals. With wide transmitter spacing, however, the frequency band width and physical size of each faded area are quite small. This built-in multipath can be easily handled by equalization or the frequency diversity of a wideband system. The wide transmitter spacing results in long signal delay times, up to several tens of microseconds, and also for the recovered data. This can create inter-symbol interference (ISI) which needs to be addressed by the data recovery and protection methods of the system. The EU-147 system is designed to satisfy this requirement with several modes of operation allowing data protection guard intervals as shown in Table 1. The maximum allowed time differential between arriving data and hence the maximum transmitter spacing is controlled by the length of the guard interval and the relative RF signal level from each transmitter. A more detailed discussion of this is presented

Table 1. Eureka 147 DAR System Design and Operation Parameters

	Transmission Mode		
Limiting/Planning Parameters	I	II	III
Guard interval duration	246 μs	62 μs	31 μs
Nominal maximum transmitter separation for SFN	96 km	24 km	12 km
Nominal frequency range (for mobile reception)	≤375 MHz	≤1.5 GHz	≤3 GHz
System Parameters			
Frame duration (T_F)	96 ms	24 ms	24 ms
Null symbol duration (T_{null})	1297 μs	324 μs	168 μs
Guard interval duration ($t\Delta$)	246 μs	62 μs	31 μs
Useful symbol duration (t_s)	1 ms	250 μs	125 μs
Total symbol duration (T_s)	1246 μs	312 μs	156 μs
No. of radiated carriers (N)	1536	384	192

later in the EU-147 discussion section and suggested items for further reading.

EXISTING BAND IMPLEMENTATION PROBLEMS

Implementing a DAR system in any relatively narrow or presently occupied band, including the existing FM or TV bands, creates several problems or at least built in restrictions. For example, the present Federal Communications Commission (FCC) FM channel allocation schedule allows for each station to operate within approximately a 200 kHz bandwidth. Any signal lying outside of that band must be significantly attenuated to avoid interference to other stations. This bandwidth restriction limits the options for frequency diversity and total channel capacity as described previously. Other stations in an area are required to be separated in space and frequency so as to not cause interference with one another. Adding a DAR signal outside of the normal FM bandwidth, even at reduced relative level, presents a very real interference potential to other users. Finally, the DAR sideband signals can interfere with the host center channel FM stations signal. Many typical FM receivers have an audio detection design which makes interference likely. The interference mechanisms were investigated and reported in the EIA-CEMA DAR testing program (10).

The FM band frequencies in and of themselves do not pose a problem but the present allocation specific restrictions do. It may be possible to totally reshuffle the FM band to allow for an in-band reserved or replacement channel (IBRC) or in-band adjacent channel (IBAC) system, possibly modified to enhance diversity capacity, to operate at FM frequencies. Transition to the new DAR system while maintaining some or most of the present analog service must be accommodated. Another potential frequency band is within the TV band as is proposed in some European countries. In the United States the channels recovered after migration to digital television might be recycled for DAB use.

BUSINESS OF BROADCASTING ISSUES

The existing FM band appears attractive, for various reasons, to those presently in the business of broadcasting. First, there is a large installed base of existing equipment which may possibly be used. The structure of radio broadcasting in the United States accentuates local coverage with each station serving its own competitive location. Each transmission facility is usually operated by an individual station and is maximized within FCC rules and sited to give the best competitive advantage. Multiple user shared sites and single owner multiple service sites are slowly becoming more popular, but even then the competitive individual station is still the norm. The FM band in general is very densely populated and any disruption or reallocation will be difficult. In the United States broadcasters appear to be very comfortable with the status quo, even with the potential loss of new DAR and data services.

By contrast other countries do not appear to have the broadcasting business characteristics listed. Many have limited private radio broadcast operation, relatively unsaturated radio bands, a strong central broadcasting authority, and the commonality that it encourages. Without the restrictive or competitive business issues inherent in broadcasting in the United States, others find it easier to study and consider a comparatively radical new broadcasting enterprise. DAR and its attendant changes appear well suited to emerging broadcasters and users to consolidate in a common system and explore a future of expanded options.

FUTURE POTENTIAL: AUDIO AND DATA

All DAR systems have capacity for significant data broadcasting, in addition to that used for audio broadcasting, and many people are actively engaged in defining potential new uses and related businesses. It is beyond the scope of this item to attempt to explain data casting, its present development, and potential. However, the basic DAR system parameters which promise the most data casting potential can be listed. Data casting uses will mesh quite closely with existing and new computer technology and applications. Therefore, maximum flexibility to grow with demands and changing technology is necessary. The ability for users to be able to tap into the widest possible data stream is mandatory. Data must be packaged for rapid delivery to many users with rapid identification of addressee and content. General data transmission will be scanned for relevance to individual users and discarded when not of interest. A small part of the general data will be retained for later review. This will create a local growing file of retained data for delayed “surfing.” Only a limited response channel will be needed to interact with the outside world. Specific targeted data, for example subscription data, must be protected from misdirection or interception. Capacity and flexibility are key to the future.

SPECIFIC DAR TECHNICAL DISCUSSIONS

From the preceding general discussion of DAR, several technical topics warrant discussion in detail. In the development of any technical system several of the parameters may be modified or changed to optimize the system to achieve certain goals, often at the expense of some of the other parameters. Technical parameters and nontechnical operational or service performance both enter into the possible trade-off action. Many of the items discussed subsequently are prime candidates for trade-off or are the secondary items affected by trade-offs.

Antennas

The antennas used for both transmission and reception of the DAR signals are dictated by the frequency in question and the transmission and reception positions. For example, systems using existing FM frequencies and facilities are constrained to use transmission antennas very much like those presently in use. Indeed, one of the major claims for using existing FM frequencies is to be able to use, at least in part, the existing transmission facilities.

That use probably will require (based on the EIA-CEMA testing and stated methods of implementation by in-band on channel (IBOC) proponents) the combining of two high-power transmitters, one each for the analog and DAR signals, into one common transmission line and antenna. The actual electrical characteristics of the antenna system, and particularly

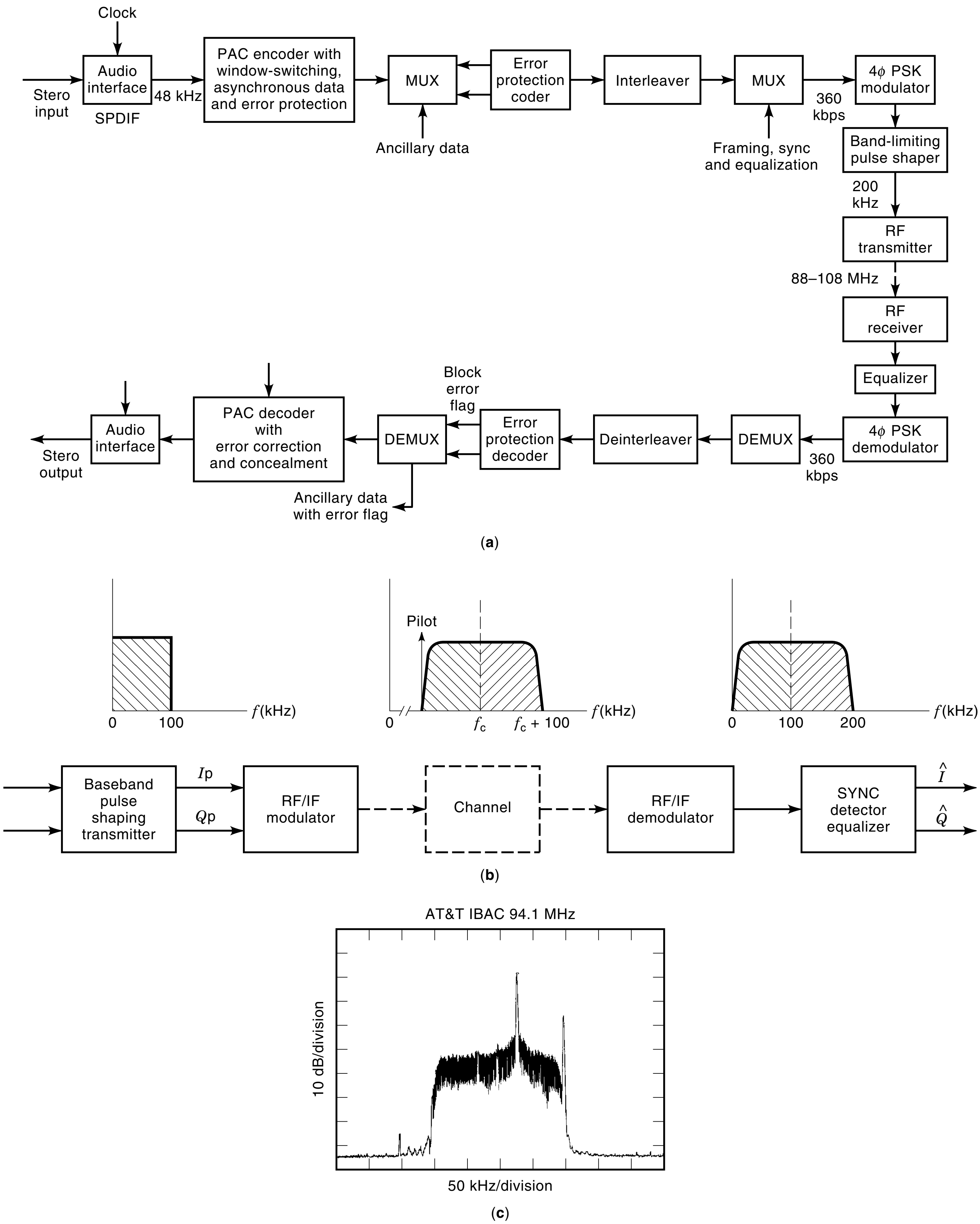


Figure 2. (a) AT&T IBAC block diagram. (b) Audio signal for system in part (a). (c) AT&T IBAC RF spectrum at 160 kbit/s for system in part (a). (d) AT&T preceptual audio coding, nonsimultaneous (time domain) noise-masking. (e) AT&T–Amati DAR IBOC RF spectrum.

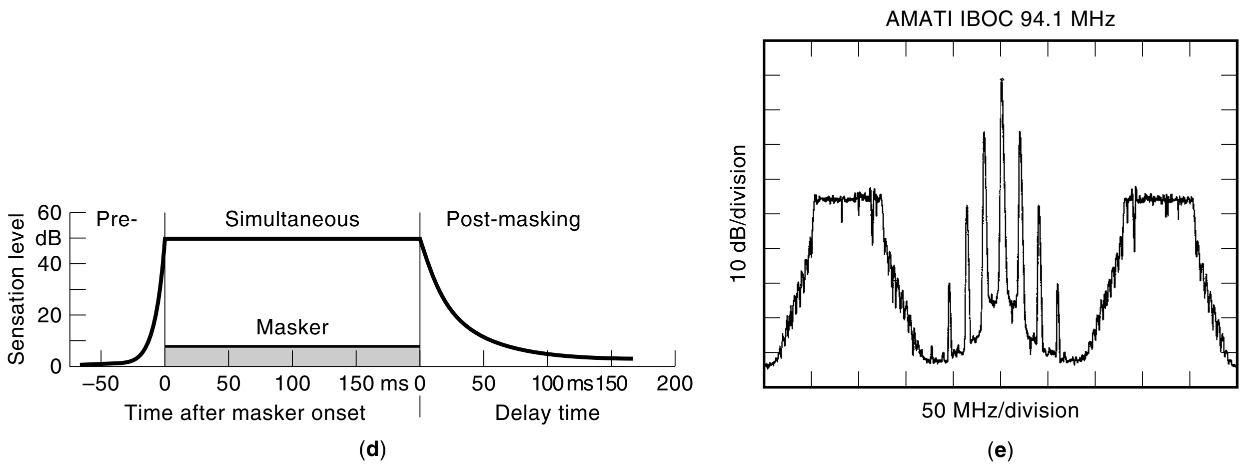


Figure 2. (*Continued*)

an antenna combining system, must be considered and accounted for. The bandwidthy and group delay limitations for each transmitter combiner in present multiuser FM antenna systems appear too restrictive to successfully carry the expanded bandwidth of FM IBOC systems.

Systems using other frequencies require antennas particularly to those frequencies. Higher frequencies indicate smaller antennas at generally less restrictive positions, or perhaps more creative positions, at both transmission and receiver sites. Likewise, a new system not constrained to existing transmission facilities can build innovative system designs such as the use of active repeaters and the single frequency network design.

AT&T: In-Band, Adjacent Channel and In-Band, Reserved Channel

AT&T (now AT&T Lucent Technologies) participated as an individual proponent with the AT&T IBAC–IBRC system and with a partner in the AT&T/AMATI IBOC system. The IBAC system is designed for operation within the FM band, directly on the FM channel center frequency as a DAR signal positioned between (adjacent to) FM station signals. The IBRC system is a replacement for existing analog FM transmissions. The AT&T/AMATI IBOC system has two side bands equally straddling the present FM analog frequency. Details of the operation of these systems can be found in Refs. 11 and 12.

The AT&T IBAC–IBRC systems, illustrated in the block diagram of Fig. 2(a), occupy the standard FM channel 200-kHz bandwidth generated by a single modulated carrier and reference tone, delivering a stereo DAR audio signal at 128–160 kbps as shown in Figs. 2(b) and 2(c). The system uses AT&T PAC (perceptual audio coding), multilevel error protection data coding, channel equalization, and four-phase QPSK modulation to deliver a robust CD quality audio program.

The AT&T PAC audio coding system uses the general psycho-acoustic principle of distortion masking where one signal can completely mask another signal depending on its relative level, frequency, and time. This is illustrated in Fig. 2(d). The system proponent contemplates future enhancements by short-term implementation changes and long-term improvements in audio coding, modem, and radio technology.

The AT&T/AMATI system is an IBOC dual or single side band system which also uses PAC audio coding and therefore is very similar to the IBAC system in many respects (12). The dual sidelobe digital system occupies a total RF bandwidth of approximately 140 kHz (12) and spanning approximately 400 kHz, as shown in Fig. 2(e). The AT&T/AMATI spectrum is generated by multicarrier modulation called discrete multitone (DMT), similar to COFDM, with dual pilot subcarriers, data subcarriers spaced at approximately 4-kHz intervals with a symbol duration of 250 μs and a cyclic prefix (guard interval) of 14.5 μs. These parameters do not afford the long delay protection from ISI associated with SFN systems using COFDM modulation but are sufficient to account for the reflections normally found in the environment. They also should be sufficient to allow for limited area on channel repeaters. The system is controlled by information contained in an auxiliary overhead channel (AOC) which directs the system receivers to the proper mode and data decoding.

Canadian Systems

Canada has been planning on using the EUREKA-147 system at L-Band in a terrestrial transmission mode with complementary satellite transmission in the future. The Canadian system development has led to some rather innovative and refined operation of the EU-147 system. For example the single frequency network system has been refined with the specific request to Eureka partners for a new operating mode. This mode trades some of the system parameters, such as guard interval, symbol length, number of carriers, and their frequency spacing to achieve greater immunity from signals arriving at long time delays, and the resulting intersymbol interference, from the separate SFN transmitters. This increased guard interval protection allows for easier implementation of various RF protection requirements including greater transmitter separation, relaxed ERP restrictions, and antenna pattern control. In late 1997 the Canadian broadcasters committed to the rapid introduction of DAB service with many programs in major cites. Coverage of 75% of the population early in the next century is a stated goal.

Data Compression Systems

The data representing the audio carried by the many DAR systems are reduced in magnitude by several different bit rate reduction systems. Typical PC digital data compression such as PKZip all reduce data file size by removal of redundant data. Those systems are all lossless in that the original data can be exactly reproduced on decompression. The maximum compression ratio is usually modest, about 2 to 1 for most data files unless they have unusually redundant and removable data.

The DAR bit rate reduction programs are not true data compression systems but instead are all lossy in that once they act on the data, the original data can never be precisely reproduced. The methods of DAR bit rate reduction all take advantage of the human psycho-acoustic response in the perception of sounds to actually remove and discard parts of the audio that cannot be detected by human hearing; at least not detected by many listeners in almost all cases. The task of designing an effective psycho-acoustical bit rate reduction system lies in finding an accurate and efficient model to remove the most redundant data possible without artifacts. Typical reduction programs achieve reduction ratios ranging from 5 : 1 to 10 : 1. Future developments will improve the action of these systems, within limits.

The two main bit rate reduction systems being used for DAR are MPEG Audio Layer-2 (MUSICAM), developed by the EUREKA partners, and PAC developed by AT&T Bell Laboratories, now AT&T Lucent Technologies.

Dolby

Usage of Dolby is not planned for DAR. Digital TV multichannel encoding (4.5 and 5.5 channel systems) are planned.

EIA–CEMA DAR Testing

All DAR proponents were invited to participate in the two phase test program described below.

Laboratory Testing. The proposed DAR systems were all assumed to be used in both a stationary and mobile environment. The potential receivers included those provided by the proponents. Testing for the IBOC systems impact on other users in the FM band required testing with contemporary receivers, including table models, mobile and personal portable. The velocity of mobile receivers was assumed to extend above 100 km/h and the velocity for portable receivers included very slow to stopped velocity. All mobile and portable uses were assumed to be possible over all areas, each with all possible types of terrain, urbanization, and so on. The laboratory simulation of these conditions is described in the two volumes reporting the laboratory testing and results (10).

Field Testing. The EIA–CEMA laboratory testing disclosed unique operating characteristics with several of the systems, prompting system modifications and re-testing in some cases. Field testing contemplated testing all systems that were laboratory tested at a challenging venue, eventually chosen in San Francisco. Several of the systems which had completed the laboratory testing were withdrawn from field testing for various reasons. See Table 2 for a list of the systems tested and the tests involved. The full EIA–CEMA field test results are contained in the "Report of the Field Test Task Group; Field Test Data Presentation" (23).

Table 2. DAR Systems Participating in EIA Laboratory and Field Tests

System	Band	Laboratory Tests	Field Tests
Eureka-147 (224 kbps)	L-band	X	X
Eureka-147 (192 kbps)	L-band	X	
VOA/JPL (satellite system)	S-band	X	X
AT&T/Lucent IBAC	VHF (FM-band)	X	X
AT&T/Lucent/Amati IBOC (double sideband)	VHF (FM-band)	X	
AT&T/Lucent/Amati IBOC (single sideband)	VHF (FM-band)	X	
USADR FM-1 IBOC	VHF (FM-band)	X	
USADR FM-2 IBOC	VHF (FM-band)	X	
USADR AM IBOC	MF (AM-band)	X	

Results and Recommendations of CEMA. After the completion and review of the laboratory and field test results, and subsequent input from proponents and interested parties, the EIA–CEMA Audio Systems Committee, DAR Subcommittee, issued a full technical evaluation of digital audio radio systems (24).

An overall evaluation of the systems under test was made relative to the six main DAR Performance Objectives set out in 1991 at the beginning of the CEMA test program. The Executive Summary of that report states that:

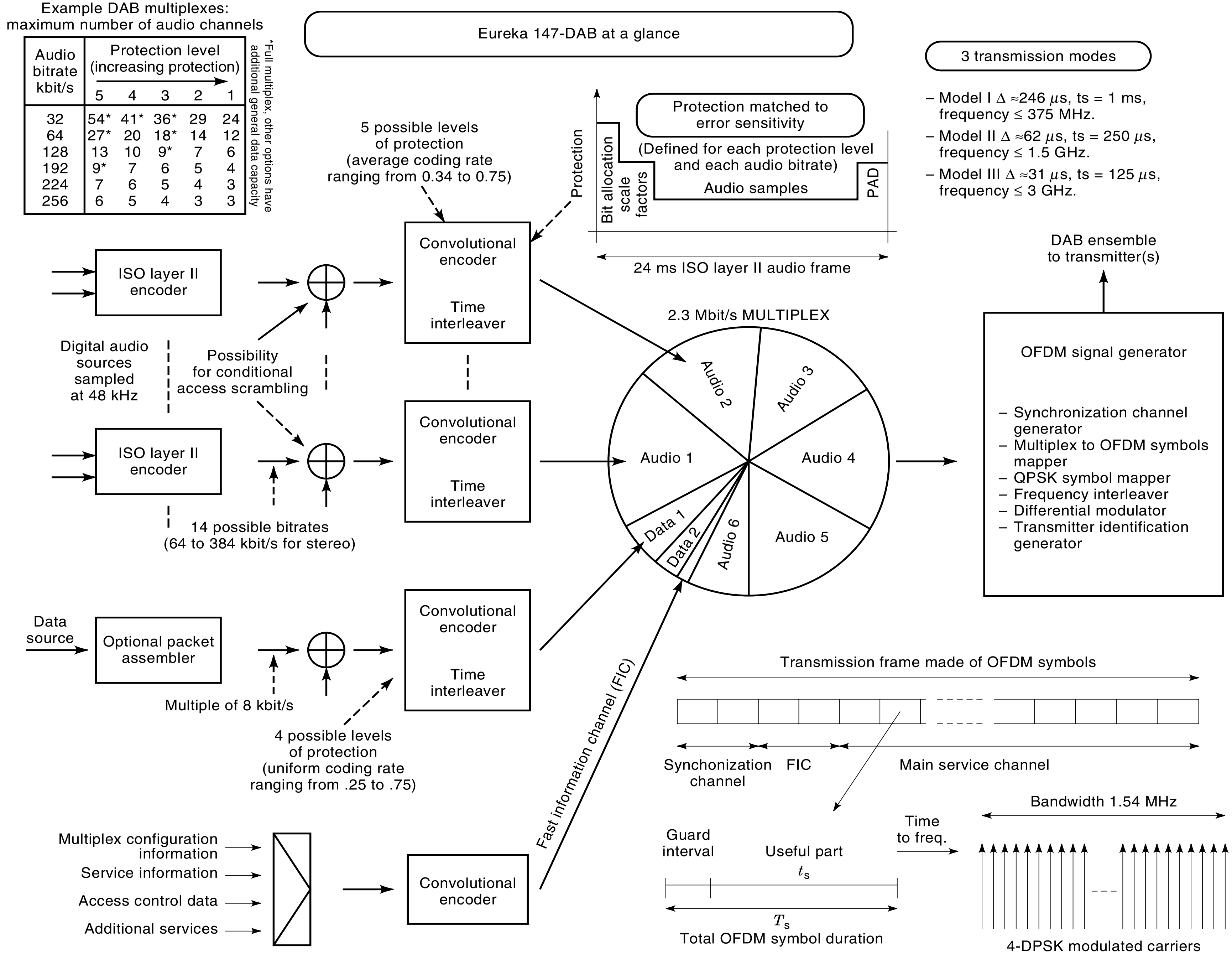
1. The IBOC systems are not feasible at this time due to deficient performance in the areas studied: audio quality, performance with channel impairments, RF compatibility and extent of coverage.
2. The IBAC system cannot be deployed due to interference with the current spectrum occupancy of the FM band.
3. The VOA/JPL (Voice of America/Jet Propulsion Laboratory) system a S-band frequencies is subject to continuous or repeated outages due to blockage.

Beyond those objectives some additional other findings from the test process were included relating to signal reacquisition, field testing results, and system present and future potential attributes.

Encryption

Data encryption plans are not presently known nor widely discussed. As a digital system, any and all of the data can be encrypted or otherwise restricted for use, for example by subscription users only. Data encryption for the relatively low data rate and not real-time ancillary services use could be very powerful, using long keyword encryption like the widely available PGP®, a "Freeware" product distributed by MIT, or other programs.

An adjunct to encryption, and potentially very valuable, is the possibility of addressability of DAR receivers. For example a class of receivers or a particular receiver can be addressed and enabled to receive particular information. A receiver within a defined distance of a traffic alert area can be enabled to receive messages and alternative routing information. From the user end of the system the receiver can be programmed



Example DAB multiplexes: maximum number of audio channels

Audio bitrate kbit/s	Protection level (increasing protection) → 5	4	3	2	1
32	54*	41*	36*	29	24
64	27*	20	18*	14	12
128	13	10	9*	7	6
192	9*	7	6	5	4
224	7	6	5	4	3
256	6	5	4	3	3

*Full multiplex, other options have additional general data capacity

Figure 3. EU-147 system overview.

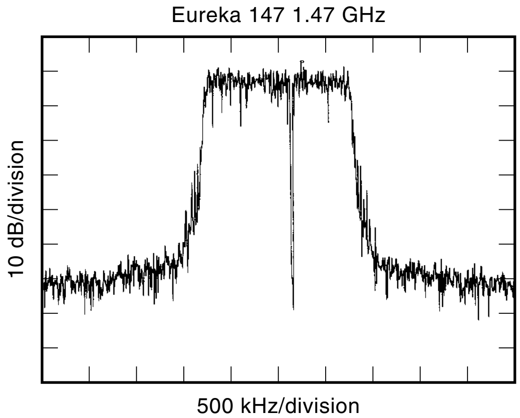


Figure 4. EU-147 RF spectrum lab measure.

from a standard or customized information pick list to accept and store information of interest to the user which is transmitted as part of a broad-based information channel. Information thus captured would be surfed at leisure by the user.

EUREKA-147

The Eureka consortium is a group of European companies conducting investigations and implementation of new technology. Project No. 147 is that group's DAR project. DAR has since become a registered trademark of the EU-147 consortium. Investigation and development began in the 1980s and proceeded to the point of practical demonstration in the late 1980s. The demonstration of the EU-147 DAB system and technical overview (15) at the April 1990 NAB (National Association of Broadcasters) spring exposition spurred interest and involvement in the United States and the rest of the heretofore uninvolved world. DAB has become a registered trademark of the Eureka partners.

The Eureka 147 system is the earliest and therefore the most fully developed DAR system. It is described in great detail in numerous documents (8,16,17). Within ITU the system is known as Digital System A, a potential standard system. A brief overview of the system, extracted from a variety of published descriptions, follows.

Figure 3 consists of several diagrams showing the conceptual EU-147 DAR system (18). Like all DAR systems the essential elements are easily seen; audio input, digital sampling and coding, data multiplexing, modulation and transmission, and the inverse processes for reception. Specialized items for the EU-147 system are shown in the area of multiplexing several audio programs and data services.

Like all DAR systems it is designed to provide high-quality sound to a variety of relatively simple fixed and mobile receivers. Features specific to this system are that it is designed to operate within any frequency band extending from approximately 30 MHz to 3000 MHz, with suitable physical and design tradeoff, and to even higher frequencies for fixed reception sites. It can use a variety or combination of terrestrial, satellite, and cable transmission media. The system uses a multiplex of data with enough capacity to accommodate several audio and data transmissions simultaneously. The multiplex is dynamically variable to allow for rapid change to any mix of programs and data rates, as well as to accommodate a range of source and chennel coding options.

The system is presently configured to operate using MPEG Audio Layer-2 coding, operating at various bit rates from 32 kbit/s to 192 kbit/s for each monophonic channel. Thus, it can carry a stereophonic signal in twice the data rate or two separate (bilingual) programs. In addition the coding can employ the joint stereo mode which uses the redundancy and interleaving of the two data channels to yield a lower total data rate for a stereo channel than for a monophonic channel pair.

Like all DAR systems, some extra data can be carried in addition to the audio program data. Each EU-147 program channel contains a program associated data (PAD) channel with a variable capacity with its minimum at approximately 670 bit/s. Information intimately associated with the program material would be carried in this channel with the same time delay as the program. The fast information channel (FIC) carries information critical to the operation of the system, such as multiplex configuration and timing. This critical data are not interleaved to avoid time delay and also are highly protected and repeated frequently to ensure reception.

A variety of audio related or ancillary (separate) services are possible, for example conditional subscription access to programming or travelers information data service. Ancillary data service can be conveyed as a separate data program, in any of several possible forms, including a continuous stream, segmented into 24 ms frames or packetized. The data service is arranged in multiple blocks of 8 kbit/s with larger needs using several blocks and lesser needs bundled into one or more blocks.

Unlike the other systems discussed, the EU-147 DAR system multiplex makes it capable of carrying many simultaneous channels of information and achieves its maximum spectrum efficiency in this way. The system main channel gross data rate is approximately 2.3 Mbit/s with an effective throughput, depending on coding rate, of from 0.6 Mbit/s to 1.7 Mbit/s. The coding rate is independent for each application and therefore an average throughput will fall within these limits. The signal is contained within a 1.5 MHz bandwidth multicarrier signal and therefore is capable of approximately 1 bit/Hz spectral efficiency.

The radio frequency modulation used is a specialized form of QPSK (quadrature phase shift keying) with COFDM (coded orthogonal frequency division multiplexing) to produce a multicarrier signal within the 1.5 MHz band occupied by each multiplex of programs. The system can operate in several transmission modes as shown on Table 1 with varying parameters. For example, the number of carriers changes from 1536 to 192 from the low to high transmission frequency extremes. The listed parameters are basic design parameters of the system and not capable of simple modification. However, the operating experience with the Canadian L-Band demonstration systems, particularly using single frequency networks (SFN) has led to the adoption of a new transmission mode. The multiple orthogonal carriers are generated (and detected) by an FFT (fast Fourier transform) process in signal processing circuits. Without this FFT processing, the practical implementation of OFDM with any significant number of carriers would be impossible. The ensemble of carriers has an RF spectrum which is approximately rectangular in shape with a Gaussian noise-like signal occupying the nominal 1.5 MHz bandwidth. The peak to average signal ratio is limited to approximately 8 dB by present signal processing. Like all DAR systems, this relatively high peak to average signal ratio is a challenge for

1 452–1 492 MHz	Allocation to Services	
Region 1	Region 2	Region 3
Fixed Mobile—except aeronautical mobile Broadcasting-satellite 722A 722AAA Broadcasting 722A 722AAA 722 723B	Fixed Mobile 723 Broadcasting-satellite 722A 722AAA Broadcasting 722A 722AAA	

ADD **722A** Use of band 1 492 MHz to 1 492 MHz by the broadcasting-satellite service and by the broadcasting service is limited to digital audio broadcasting and is subject to the provisions of resolution COM4/W.

ADD **7222AAA** Different category of service in the Federal Republic of Germany, Bangladesh, Botswana, Bulgaria, Burkina Faso, Colombia, Cuba, Denmark, Egypt, Ecuador, Spain, Greece, Hungary, Ireland, Italy, Jordan, Kenya, Malawi, Mozambique, Panama, Poland, Portugal, United Kingdom, Sri Lanka, Sweden, Swaziland, Czech, and Slovak Republic. Yemen, Yugoslavia, and Zimbabwe, the allocation of the band 1 452 MHz to 1 492 MHz to the broadcasting-satellite service and the broadcasting service is on a secondary basis until 1 April 2007.

ADD **722B** Alternative allocation: In the United States of America, the band 1 452 MHz to 1 525 MHz is allocated to the fixed and mobile services on a primary basis. (See also No. 723.)

ADD **723B** Additional allocation: In Belarus, the Russian Federation, and Ukraine, the band 1 429 MHz to 1 535 Mhz is also allocated to the aeronautical mobile service on a primary basis exclusively for the purposes of aeronautical telemetry within the national territory. As of 1 April 2007, the use of the band 1 452 MHz to 1 492 MHz is subject to agreement between the administrations concerned.

2 300–2 450 MHz	Allocation to Services	
Region 1	Region 2	Region 3
Fixed Mobile Amateur Radio location 664 751A 752	Fixed Mobile Radio location Amateur 664 750B 751 752 751X	

ADD **750B** Additional allocation: In the United States of America and India, the band 2 310 MHz to 2 360 MHz is also allocated to the broadcasting-satellite service (sound) and complementary terrestrial sound broadcasting service on a primary basis. Such use is limited to digital audio broadcasting and is subject to the provisions of Resolution COM4/W.

ADD **751X** Space stations of the broadcasting-satellite service in the band 2 310 MHz 2 360 MHz operating in accordance with No. 750B that may affect the services to which this band is allocated in other countries shall be coordinated and notified in accordance with Resolution 33. Complementary terrestrial broadcasting stations shall be subject to bilateral coordination with neighboring countries prior to the bringing into use.

Figure 5. WARC '92 L-band satellite and terrestrial DAR allocation information.

nonlinear RF amplifiers and considerable power back-off from nonlinear operation, and possibly additional linearization circuitry and filtering, is necessary. Figure 4 shows the output spectrum measured in the EIA DAR laboratory testing.

In-Band

In-band generally means operation within an existing and presently usable or used radio band. Although this can mean any existing band the term is almost exclusively associated with the FM and AM bands in the United States. In-band is generally subdivided into segments like in-band on channel (IBOC) meaning within an existing band and centered on an existing (and co-used) channel. In this mode of operation the DAR signal can lie either directly on and within the existing RF channel of the "host" FM station or be placed symmetrically and very near by on either side of the existing channel. Another subdivision is in-band adjacent channel (IBAC),

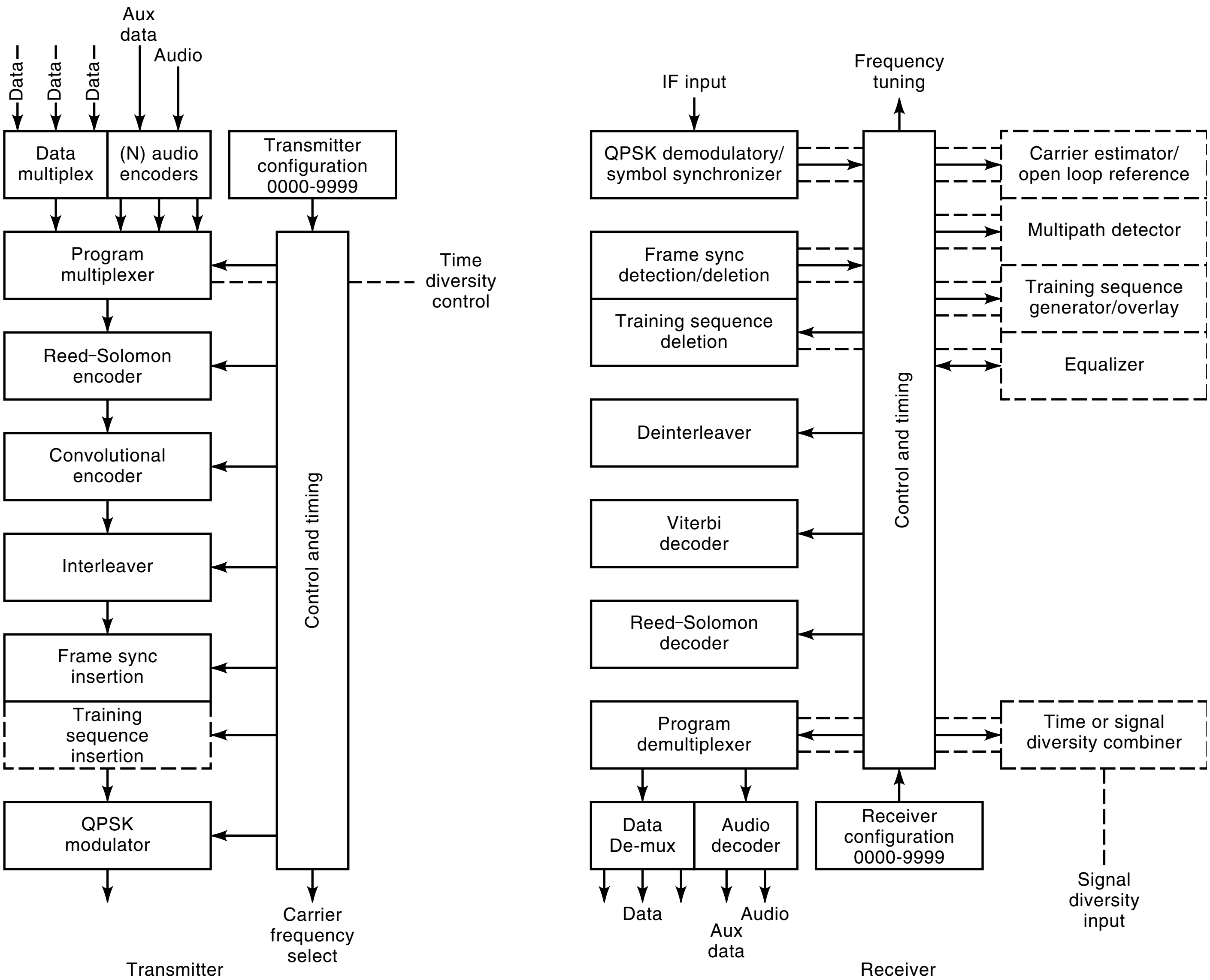


Figure 6. VOA–JPL satellite DAR block diagram.

meaning that the DAR RF spectrum is not centered on a presently used channel but rather positioned within an adjacent channel, such as two channels above or below the existing use, close but not too close as to cause interference. A last subdivision is a type if IBOC for future use called in-band replacement (reserved) channel (IBRC). This means that the DAR RF signal will be placed in the same frequency channel as a present analog FM operation, but at some time in the future after the analog carrier is no longer used.

Each of these implementations has its own problems and advantages. For example the IBRC system will operate with the most freedom, but will achieve this freedom only when analog service is abandoned and therefore protection to existing operations is not needed. IBAC will operate between existing operations with limited potential interference to the simultaneous operation of analog systems on adequately spaced frequencies, usually second or third adjacent channels. This may be considered a potential interim step to IBRC operation. However, in that interim time, the availability of sufficient spectrum between presently operating frequencies, and the freedom of interference to moderately distant co-channel and first adjacent analog stations on those same frequencies, is a problem. Clearly, in very large metropolitan and heavily populated areas the availability of channels for all potential IBAC DAR operations is in doubt. Finally, IBOC operation, as mentioned, places the DAR signal closest to the paired analog signal with the highest probability of interference to that frequency but reduced interference to other frequencies reasonably removed.

The complementary use of both the DAR and analog programs must also be considered. In some IBOC proposals, the totally independent programming of the two channels has been proposed. In other late proposals the analog program is proposed to become a fall-back transmission system for the DAR system audio program when it fails at the perimeter of coverage or in other difficult areas. This option is being described as requiring suitable time delay synchronization, decision making, and other transition smoothing operations. Only

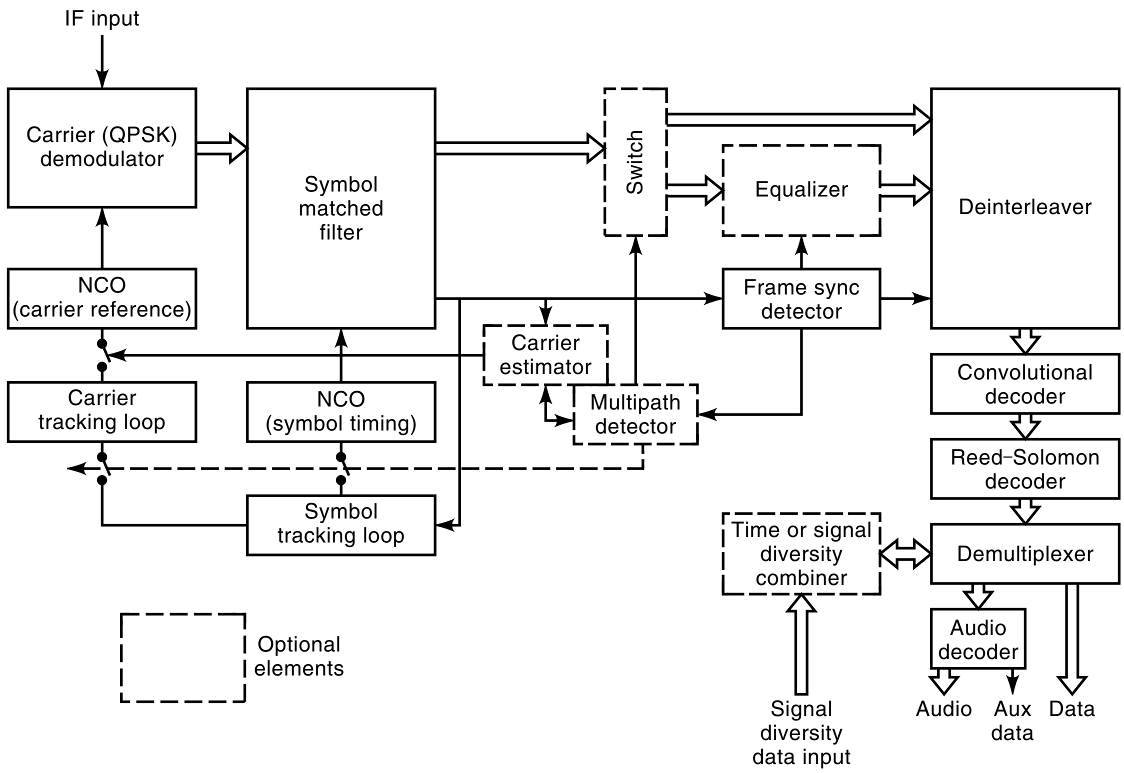


Figure 7. VOA–JPL receiver block diagram detail.

the audio portion is described as being supported and the DAR data are assumed lost.

L-Band

Technically, the L-band extends from 0.350 GHz to 1.550 GHz. The portion of the L-band generally being described for DAR operation extends from 1.452 GHz to 1.492 GHz. The use of L-band as a terrestrial and complementary satellite DAR frequency was adopted at the World Administrative Radio Conference (WARC) in 1992. Figure 5 provides detailed information on that allocation and the various unilateral national options adopted at the conference.

The L-band is presently used for other services in many areas of the world. In the United States the L-band is used for aerospace testing, control, and telemetry. This use is strongly protected by the US aerospace and defense industries as a valuable and irreplaceable use. Confusion existed over the initial US broadcasters support for L-band, then for the turnabout discouragement of L-band in favor of IBOC and other frequencies at the time of WARC '92. This led to the strengthened US position to preserve L-band for aerospace use and discourage the use of L-band for DAR use. By a footnote in the agreement, S-band was reserved as an option in the United States. However, S-band is also used for aerospace telemetry in the United States and in Canada so that conflict in the border areas of both L-band and S-band exists.

Out-of-Band

Out-of-band is a convenient label for all systems no otherwise classified as in-band, or more specifically, not within the FM band.

S-Band

Technically, the S-Band lies between 1.550 GHz and 5.200 GHz. That portion proposed for use by the United States as a result of WARC '92 extended from 2.310 GHz to 2.360 GHz. Like the L-band, the S-band of frequencies has other uses which must be shared and protected. Recent FCC notices of Proposed Rule Making have proposed to add additional uses and displace some of the initial S-band frequencies that have been used by DARS (Digital Audio Radio Satellite). The FCC has reallocated 2.305 GHz to 2.320 GHz and 2.345 GHz to 2.360 GHz to Wireless Communications Service (WCS), leaving 2.321 GHz to 2.344 GHz for DAR. The EIA-CEMA DAR satellite testing used a NASA Tracking and Data Relay Satellite (TDRS) satellite at 2.05 GHz, close to the proposed operational DAR satellite frequency.

Satellite Radio

The Voice of America and Jet Propulsion Laboratory (VOA-JPL) have proposed a satellite system which was submitted to the EIA-CEMA DAR testing program. The US satellite proposal is in S-band as described previously and other countries will opt for different frequencies in the same general bands, L-band and S-band.

The satellite system consists of space transmitter and ground segments as shown in Fig. 6. The space up-link segment is not shown as a separate item as it is assumed to be a transparent conduit for the DAR signal from the ground station to the satellite broadcast platform. The receiver functional block diagram in Fig. 7 illustrates the system of signal reception and audio detection. As described in VOA-JPL fact sheets (19,20) the system allows for a flexible modular re-

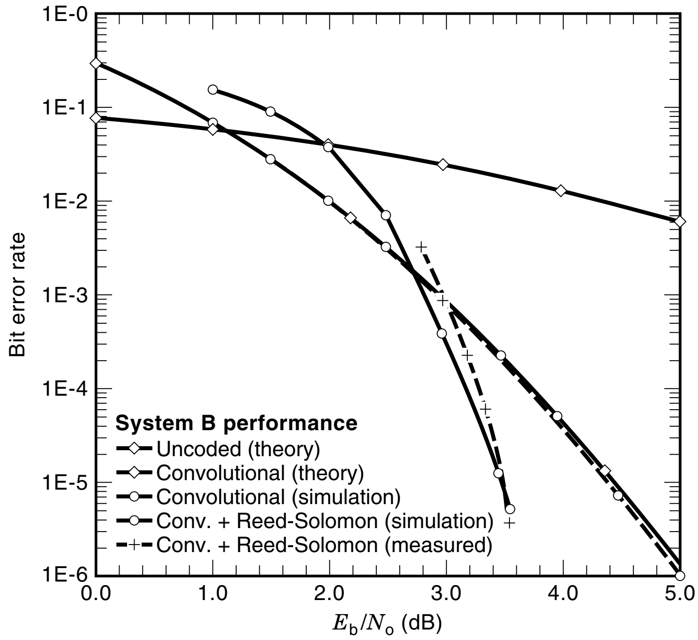


Figure 8. VOA–JPL Rx performance vs. coding graph.

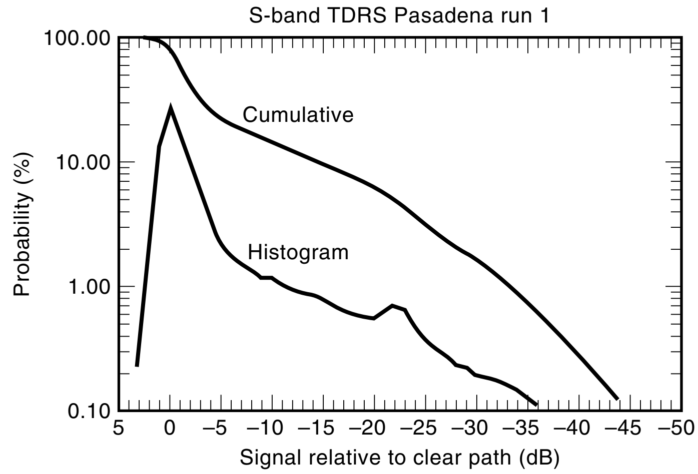


Figure 10. VOA–JPL signal blocking statistics.

ceiver system. Capabilities can be added on, such as those needed for mobile reception over and above the standard receiver used for fixed reception. The design is promoted as using standard and well-proven signal processing techniques for which low cost integrated circuits already exist. The system is presented as a design and test, targeted as a low-cost alternative to the world-wide broadcasting of VOA. Actual development is left up to those who choose to utilize the system.

Several system problems unique to the satellite systems are contemplated by and propose to be accommodated in the VOA-JPL system. The frequent blockage of the satellite signal by overhead or nearby obstructions was quite evident in field testing and is addressed in one way by long-term time diversity using delayed data retransmission. Further reception diversity can be accomplished by diversity receive antennas. Transmission diversity is supported by signals emanating from two physically separated satellites transmitting on different frequencies. Finally, on channel terrestrial boosters may be used.

Any audio bit rate reduction method may be used with the audio encoded data rates being applied to the data multiplexer in multiples of 16 kbit/s. Several audio data and ancillary data streams will be multiplexed together with the total rate limited only by satellite and bandwidth resources. The channel data rate is anticipated to be in the range of 1 Mbit/s to 10 Mbit/s. Both convolutional and Reed Solomon encoding are applied to the data, they are interleaved in time, frame synchronized using a PN code word with each frame with a channel equalizer training sequence inserted if needed, and then the entire data stream is QPSK modulated at an IF frequency for satellite transmission.

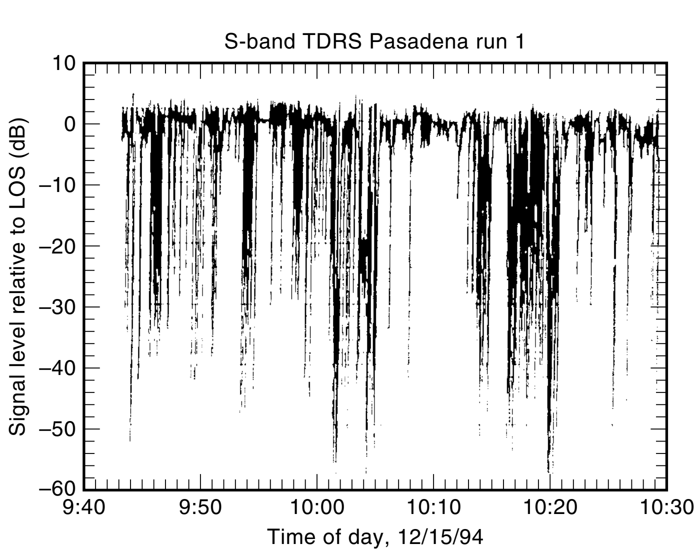


Figure 9. VOA–JPL RF signal blockage along a path.

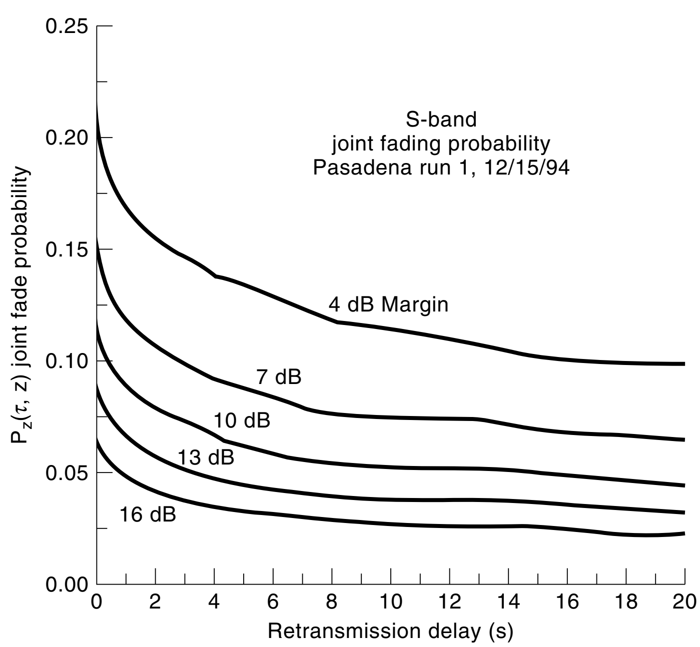


Figure 11. VOA–JPL time diversity statistics.

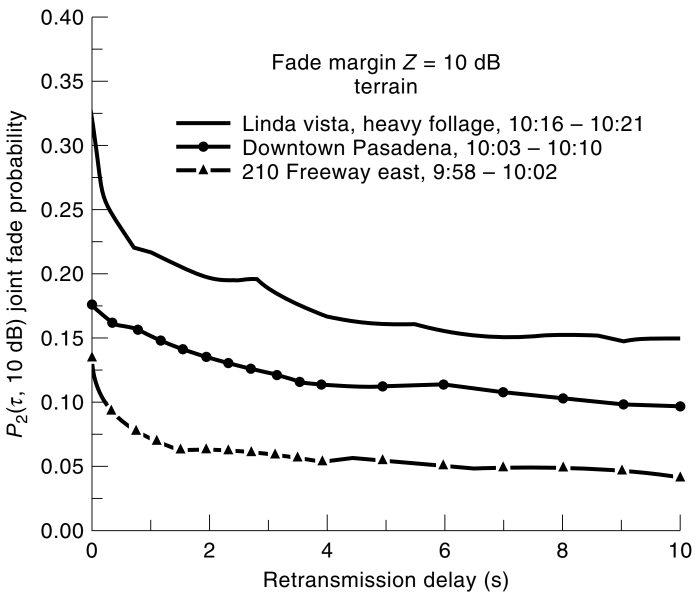


Figure 12. VOA–JPL time diversity tests.

At typical satellite elevation angles above 20° the transmission path, when not blocked, is characteristic of a Rican AWGN (additive white Gaussian noise) channel. The measured VOA-JPL receiver performance is shown in Fig. 8 illustrating threshold audio performance, at a BER of 10E-3, of approximately 3.0 dB Eb/No. This performance is approximately 8 dB to 10 dB better than the best terrestrial system which must accommodate Rayleigh fading multipath propagation.

The satellite blocking probability was measured by the proponent and is presented in Figs. 9 and 10. The effective use of time diversity by retransmission at delayed times is shown in Figs. 11 and 12. Figure 13 is the satellite link budget for the system tested by EIA-CEMA.

United States

In the late 1980s and early 1990s, the potential of DAR was made known to the world by the demonstration of the EU-147 system at several venues. The annual spring NAB conference demonstrations accelerated this process in the United States. The US broadcast industry, as represented by the NAB, adopted varied positions of EU-147 and DAB in general in the early and following years. In late 1991 the Electronic Industries Association (US) Consumer Electronics Group, now Consumer Electronics Manufacturers Association (CEMA), began an investigation and plan for testing all potential DAR systems. The process was open to all potential DAR systems, complete with both audio encoding and RF transmission components. More than a dozen early system proponent ideas were reviewed with five proponents submitting eight initial or later modified systems for eventual testing. See Tables 2 and 3 for a list and description of the systems tested.

USA Digital (FM-1)

USADigital Radio is a consortium of broadcasters and others who began an investigation into DAR in the early 1990s. The original members, CBS, Gannett, Westinghouse, Stanford Research Institute, Corporate Computer Systems, Hammett & Edison, Inc., and so on announced the DAR development project "ACORN DAB" in early 1991 (21). The timetable presented then was: prototype development, April, 1991: mobile demonstrations, 1991/1992; experimental DAB systems, 1992/1993: system implementation, 1994/1995. The original system design employed multiple digital carriers spanning approximately 400 kHz, twice the FM channel normal bandwidth, at a level of approximately 35 dB below the peak of the FM carrier (22,23). Subsequent research and testing revealed problems with the operation of digital carriers directly under the FM signal and the approach was modified to a dual side band (side saddles) on either side of and immediately adjacent to the FM carrier (24,25). This FM analog and DAR sideband approach occupies slightly more than 400 kHz RF bandwidth. The original system continued through EIA-CEMA DAR laboratory testing but was renamed FM-2 and the newest system become known as FM-1. A simplified block diagram is included as Fig. 14.

The FM-1 (new) system technical development was assumed by a new company, Westinghouse Wireless Solutions Co., which joined the USADigital project in 1996. A June 1996 study by the Deskin Research Group (24) confirmed the problems which had been defined and illustrated in the 1995 EIA-CEMA DAR Laboratory test report. The USADigital paper from 1997 (25) presented the Westinghouse Wireless analysis of those problems and some possible solutions.

Table 3. DAR Systems—Main Characteristics

DAR System	Frequency Band	System Class	Audio Coding	Audio Bit Rate (2 Channels)
Eureka 147 #1	1452–1492 MHz	NB	MPEG layer 2	224 kbit/s
Eureka 147 #2	1452–1492 MHz	NB	MPEG layer 2	192 kbit/s
AT&T/Lucent	88–108 MHz	IBAC	PAC	160 kbit/s
AT&T/Lucent/Amati #1	88–108 MHz	IBOC/LSB	PAC	128 kbit/s
AT&T/Lucent/Amati #2	88–108 MHz	IBOC/DSB	PAC	160 kbit/s
VOA/JPL	2310–2360 MHz	DBS	PAC	160 kbit/s
USADR-FM1	88–108 MHz	IBOC	MPEG layer 2	256 kbit/s (max.)[a]
USADR-FM2	88–108 MHz	IBOC	MPEG layer 2	256 kbit/s (max.)[a]
USADR-AM	0.54–1.7 MHz	IBOC	MPEG layer 2	96 kbit/s

Legend: NB, new band; DBS, direct broadcast satellite; IBAC, in band/adjacent channel; USADR, USADigital Radio; IBOC, in band/on channel; MPEG, moving picture expert group; LSB, lower side band; PAC, perceptual audio coder; DSB, double side band; VOA/JPL, Voice of America/Jet Propulsion Laboratory.

[a] For USADR-FM1 and 2, variable bit rates were used. The instantaneous rate ranged from 128 kbit/s to 256 kbit/s.

Link budget for line-of-sight digital audio broadcasting reception at S-band (2.05 GHz)			
Audio bit rate (stereo)	256.00	160.00	kbps
Satellite transmitter power	7.00	7.00	watts
Satellite transmitter power	8.45	8.45	dBW
Frequency	2.09	2.09	GHz
Satellite antenna diameter	5.00	5.00	m
Satellite antenna gain	38.19	38.19	dBi
Satellite antenna beamwidth	2.01	2.01	deg
EIRP	46.64	46.64	dBW
Satellite elevation angle	30.00	30.00	deg
Slant range	38807	38807	km
Free space loss	−190.58	−190.58	dB
Atmospheric losses	0.25	0.25	dB
Signal at antenna	−144.19	−144.19	dBW
Receive antenna gain	8.00	8.00	dBi
Receive antenna pointing loss	3.00	3.00	dB
Received signal	−139.19	−139.19	dBW
Antenna temperature	150	150	K
Receiver noise figure	1.50	1.50	dB
Receive system noise temperature	274	274	K
Receive system G/T (on antenna axis)	−16.37	−16.37	dB/K
C/No	65.04	65.04	dBHz
Bit rate	54.08	52.04	dB
E_b/N_o available	10.95	13.00	dB
Theoretical E_b/N_o, BER = 10E-6	3.50	3.50	dB
Receiver implementation loss	1.00	1.00	dB
Interference degradation	0.50	0.50	dB
Receiver E_b/N_o requirement	5.00	5.00	dB
Link margin, beam center	5.95	8.00	dB
Link margin, beam edge	2.95	5.00	dB

Figure 13. S-band satellite link budget.

The USADigital FM-1 system tested by EIA-CEMA used dual sidebands, similar to the AT&T/AMATI system, of approximately 100 kHz each for a usable bandwidth of 200 kHz spanning an RF bandwidth of approximately 440 kHz as shown on Fig. 15. In the latest (9/97) reported implementation of this system the information in the upper and lower sidebands is redundant. USADigital is still designing and testing FM-1 with later versions than were tested by EIA-CEMA.

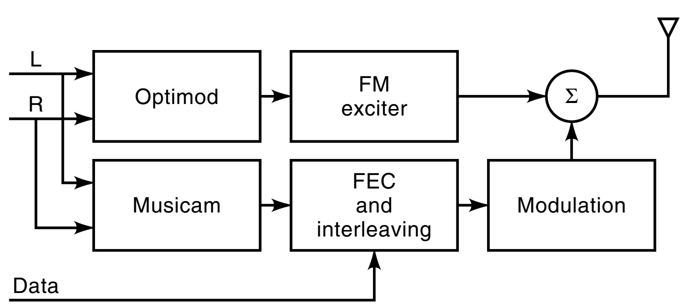


Figure 14. USADR block.

World-Wide Compatibility

The 1992 World Administrative Radio Conference (WARC) assigned a world-wide DAR allocation at L-band. Several of

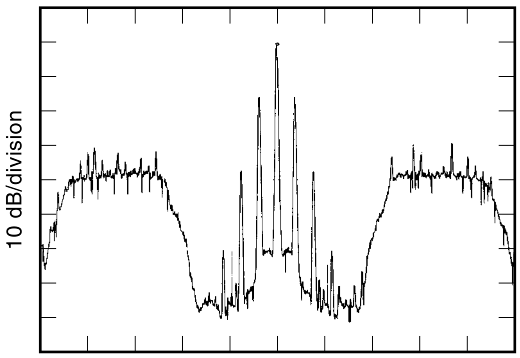


Figure 15. USADR spectrum.

the participating countries opted to use other additional or substitute frequencies. The administrations opting for frequencies other than L-band can move back to L-band unilaterally and resolve any conflicts raised by existing or proposed other frequency usage.

Achieving world-wide compatibility is possible with more than one frequency in use but would require smart receivers, common or adjustable system parameters, and wide band or multiband tunable RF preselectors and antennas to match. Use of one carrier frequency band simplifies this task.

CONCLUSION

The development of DAR has progressed substantially to the time of this reference article. Begun in Europe with the Eureka Project 147, development was picked up in other countries, significantly in the United States. Pressure from US broadcasting industry representatives spurred the search for a more directly compatible system to utilize the existing broadcast bands. This approach entailed burdens, such as a shared occupied band, and the technical restrictions that came with it, limited bandwidth and interference potential.

The EU-147 system is now on the air and service is growing in Europe, Canada, and soon many other countries. Receiver design and functionality along with other ancillary data services are now in active refinement and introduction to the consumer. The United States commitment to an in-band solution is evident in the ongoing effort to present a functional system in the face of the inherent technical limitations.

The past several years of development and testing have seen a general acknowledgment by various proponents of the advances by others, eventually to the extent of the incorporation of such advances and even alliances between former rival proponents. Such an alliance was most recently seen in late 1997 between USADigital Radio and AT&T to jointly develop a system. Future developments will surely see the continued rapid introduction of EU-147 DAR, although significantly tempered from what it would have been had a world-wide standard system been the product to be introduced. The U.S. efforts to field an in-band system will eventually end with a system that may be a stand alone system, a hybrid new system, or perhaps, after a brief stand alone period, a shift to or an amalgam with EU-147 technology. Whatever the outcome, the next 10 to 20 years will be a period of change for audio and growing digital data broadcasting in the world.

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DIGITAL AUDIO RADIO (DAR). See DIGITAL AUDIO BROADCASTING.