Communication Technology Trends

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6.0 SYSTEM BUILDING BLOCKS AND TOOLS: FUNDAMENTAL CONSTRAINTS AND LIKELY EVOLUTION.

6.1 Background

6.1.1 In this section, the advances in technology and some of the ramifications of those advances will be presented as they relate to the demand for wireless communications and the ability to fulfill those demands. Trend curves will be presented showing the history of these trends, and from them their future directions will be projected.

6.2 Digital Integrated Circuits

6.2.1 The fundamental technology thrust through the year 2010 will be, as it has been in the recent past, that of semiconductor technology. The impact that this has had on computer and communications needs and capabilities has created the demand for increased radio spectrum through the wireless demand for these services. The increase in semiconductor capability will permit the partial offset of the spectrum demand by improved information compression techniques as well as increasing the capability of communication channels. Communication system architecture and the associated spectrum management policies are also affected by semiconductor technology. In this section, we examine the impact of semiconductor technology on future public safety communications system requirements.

6.2.2 The improvements in semiconductor processing and materials have resulted in roughly an order of magnitude advance every five years. This trend is demonstrated in the histories of memory devices, microprocessors, and computer systems.

Figure 1 presents the chip density of Dynamic Random Access Memory (DRAM) in bits versus the year of original market introduction.[1] The clear trend, indicated here, shows that chip densities have increased by a factor of ten every four years. Although Figure 1 addresses only DRAM devices, similar trends with almost identical slopes are observed for other types of memory devices.

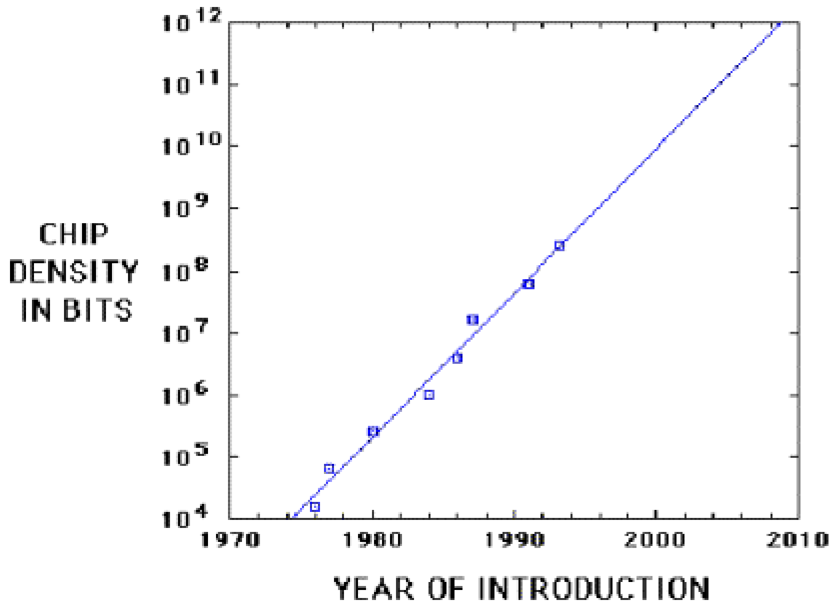

Figure 1 DRAM density trend over time

6.2.3 Rapid advancement is also observed in the progress of microprocessor technology over the last two decades. The increase in number of transistors per chip is displayed in Figure 2[3]. In this chart, each data point represents a new microprocessor plotted at its year of introduction, and it can be seen that the technology accomplishes an order of magnitude improvement about every 6 years.

6.2.4 The speed of microprocessors is also continuing to increase. The Semiconductor Industry Association predicts that on chip clocks will run at 1,100 MHz by the year 2010. [4] Their projection of the clock speed that will be resident on Microprocessors from the years 1995 through the year 2010 is shown in Figure 3.

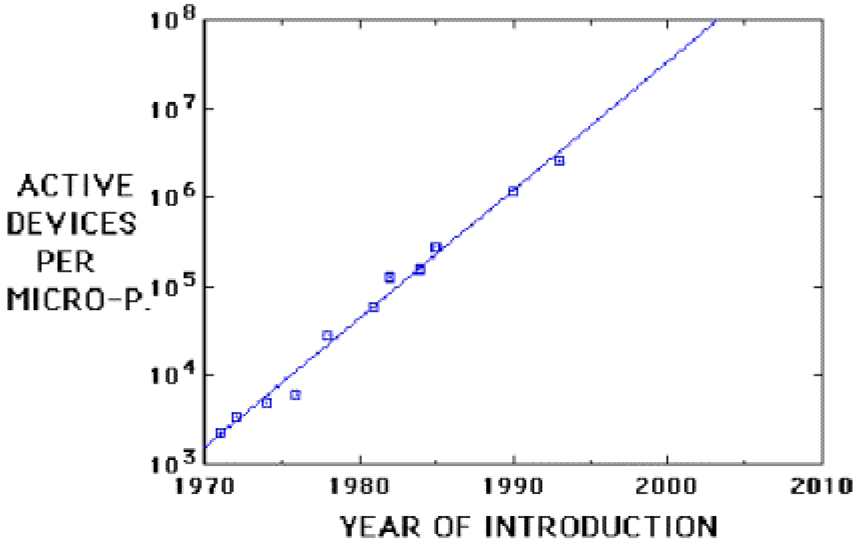

Figure 2 Microprocessor density trend over time.

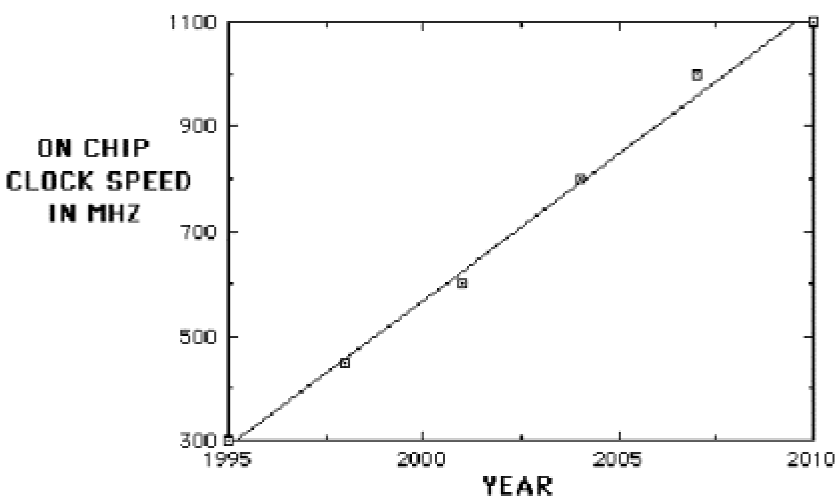

Figure 3 On chip clock speed projected to the year 2010

6.2.5 The result of these component level improvements has been that computer systems have advanced along similar trend lines. It has been observed that the performance of computer systems has advanced at approximately 35% per year.[5] Thus an order of magnitude improvement is seen every five years. In the case of computer systems, this is equivalent to a step of one platform tier. For example, the trend would predict that the current performance of a minicomputer will be available in a workstation platform after seven years, and in a portable laptop computer by the year

2010.

6.3 RF Generation Devices

6.3.1 Batteries.

6.3.1.1 The batteries required to operate portable communications equipment are usually heavy, provide limited hours of operation, and can be expensive. A number of developments in battery technology are alleviating this situation. Some involve new technologies, such as nickel-metal-hydride and lithium-ion batteries. Another development is a zinc-air battery that draws oxygen from the atmosphere to extend its life. Power saving solutions that make more efficient use of battery power by communications equipment hold promise for extending battery life further; more power efficient amplifiers and more efficient sleep modes are examples of ways in which battery life may be increased.

Reference: Office of Technology Assessment, “Wireless Technologies and the National Information Infrastructure,” August 1995, page 16.

6.3.2 Oscillators.

6.3.2.1 Spectrum efficiency is improved if more communication channels can be placed within a given band of spectrum. In the past, the ability to decrease the channel size has been limited by both the transmission bandwidth and frequency stability concerns. Frequency stability in land mobile radio has also benefitted from improvements in semiconductors.

6.3.2.2 Figure 4 shows the trend of requirements on land mobile frequency stability. The trends for both base stations and mobiles track together until the mid-60's. Thereafter, the base station trend has continued toward tighter tolerances at a steeper slope than that of the mobile radio trend line. In both cases, the stability improvements were meet via two primary developments. These were the practical implementation of frequency synthesizers and the integration of temperature compensated oscillators.

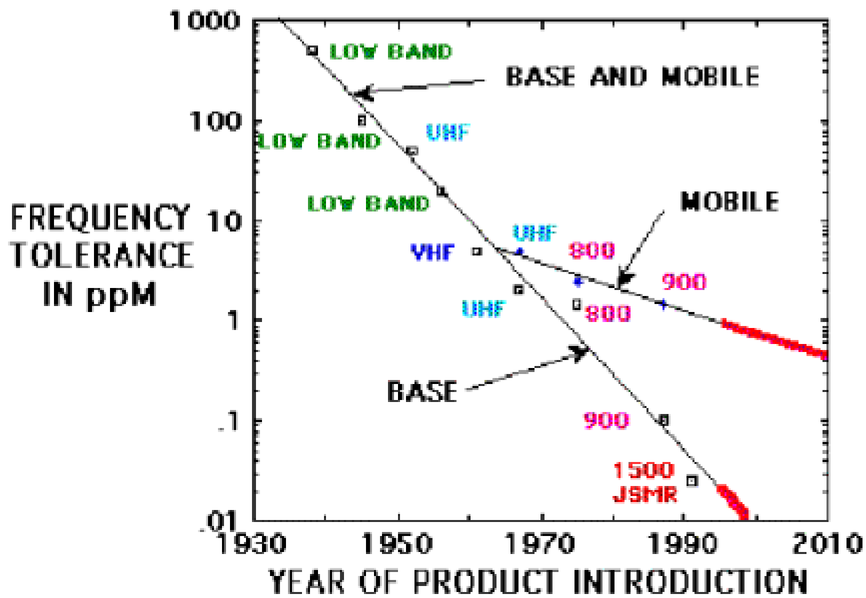

Figure 4 Trend of frequency stability over time.

6.3.2.3 Advances in semiconductors allowed the development of integrated temperature compensation circuits which could be packaged with the crystal. These compensation circuits dramatically reduce the variation in output frequency over the wide range of temperatures experienced, thus directly improving the frequency stability of the associated radio equipment.

6.3.2.4 The implementation of synthesized radio equipment was made practical by the integration of many complex functions into integrated circuits; among these are loop filters, phase detectors, and frequency dividers. The contribution of synthesizers to frequency stability was the standardization of the frequency source from which the signals were synthesized. This allowed effort to be focused on a small set of oscillator devices which drove the learning curve faster so the tolerance could be improved more rapidly.

6.3.2.5 Improvements in frequency stability can be used to enhance spectrum efficiency even when channel spacing is not reduced because the guard bands around the occupied bandwidth of each transmission can be reduced. The information content of the transmitted signal can be increased while maintaining acceptable adjacent channel splatter. This is important because reductions in guard bandwidth are limited by adjacent channel splatter considerations.

6.3.2.6 With the refarming report and order, the FCC has required that 6.25 kHz equivalent spectrum efficient technology be implemented for newly type accepted equipment after the year 2005.[6] The required frequency stability has also been improved to 0.1 ppM for the mobile units. However, system considerations, such as not assigning adjacent channels in the same geographic area can make it unnecessary to provide close in splatter protection. In crowded urban areas where cellular type of coverage is required (such as for different precincts in a city) this does not impact spectral efficiency and can reduce the cost of equipment. The refarming Report and Order is the subject of several petitions for reconsideration, and it is not clear what the result will be at this time.

6.3.3 Antennas

6.3.3.1 *Smart antennas*. Smart antennas is a term applied to a family of technologies that generally integrate active antenna elements with microprocessor technology. One of these technologies, planar arrays, spreads the power over a large number of radiating elements in a flat plane in order to achieve, typically, a narrow beamwidth. By changing the current distribution of the array, the shape of the beam can be changed electronically in real-time. This can be used to increase gain and narrow beamwidth as necessary. The same techniques can be used to place a pattern null in the direction of an interfering signal, whether a strong multipath reflection, unintentional interference, an intentional jammer. The ability of the array to be flat allows for an installation that mechanically conforms to the antenna support.

6.3.3.2 In a transmitting situation, such antennas must split the input power several times in order to feed it to the multiple radiating elements. This multiple power splitting results in inevitable power losses which, in turn, limit the achievable antenna gain. (Similar concerns obtain in the reciprocal receiving situation.)

6.3.3.3 These techniques have been used for some time in military applications, but a re not widely used in commercial applications. This is likely to change with the attendant improvements in digital signal processing technology, which is necessary for economical implementation.

6.3.3.4 *Space diversity.* With land mobile radio communication, there is rarely a line-of-sight propagation path between the base and mobile station, and multiple signal paths exist. The signals from those paths combine both constructively and destructively at the receiver to produce multipath fading. For narrowband transmissions, the propagation delays associated with the various paths are extremely small compared to the inverse of the signal bandwidth. The channel can be considered as a Rayleigh fading channel with frequency flat fading. This fading results in both signal strength variation characterized by a Rayleigh distribution, and phase variation characterized by random FM noise.

6.3.3.5 Diversity is a commonly used technique for improving the quality of both digital and analog signals. When the new technique of single sideband is employed the use of multiple antennas becomes a virtual necessity, as when the vehicle is traveling at high speed, signal will become distorted due to phase shift. The most common form is space diversity, which is implemented using two appropriately spaced antennas. The advantages of this technique must be weighed against the disadvantages. There is some added cost for installation of the second antenna in a mobile vehicle, and a further cost for repairing or patching the hole when the vehicle is traded. Another concern is the difficulty in disguising the second antenna on unmarked or undercover vehicles.

6.3.3.6 For portable units, use of two antennas becomes even more of a problem, due to the limited space available. This concern for portables becomes even greater as agencies install infrastructures which provide portable coverage throughout the system and as portable units are used in vehicles in lieu of mobile units. There are at least two approaches to overcome this problem. One is the use of vehicle mounted adapter/chargers into which a portable unit can be inserted, which in turn connects to two space-diversity antennas on the vehicle. It should be noted that past use of such vehicular mounted devices has not been totally satisfactory due to the high incidence of wear and resultant equipment failure. Improved designs may overcome these former problems. Another method being researched is a one-piece diversity antenna system that uses two antenna elements, but performs the signal combining function in the antenna base and thus requires only one hole and one cable for mounting for either a mobile or a portable installation. In all instances, the difficulty of using two antennas is directly related to the frequency band used, with implementation becoming easier as the frequency increases.

6.3.3.7 Maximal ratio diversity combining is a third diversity technique which is used to combat fading. It is designed, as the name implies, to maximize the signal-to-noise ratio of the received signal. The performance of maximal ratio combining is theoretically the best of the three. In the past, the difficulties of practical implementation often rendered its performance relatively poor compared to the other two methods. However, with the advances in semiconductor technology, the implementations being made today reach the theoretical promise of this method.

6.4 Source Coding

6.4.1 Using today's systems, the additional traffic demands described above can only be met by increases in the available spectrum. However, the demands can, at least in part, be offset by utilizing semiconductor advances to make more efficient use of the limited spectrum resources. Information compression allows reduction in the amount of information which must be transmitted on the communications channel. Typically, this is done by removing redundant information, thereby reducing the overall information bandwidth. These improvements in voice coding technology must be couterbalanced with other factors. For example, it appears quite likely that public safety users (like other users of communications systems) will demand higher quality speech as that option becomes available. We note that some cellular equipment suppliers have moved from 8 kbps vocoders to 13 kbps vocoders in order to improve speech quality.

6.4.2 Voice

6.4.2.1 Digital speech encoding has received significant attention of late. This means of transmitting speech leads naturally to encryption which is one very important aspect in many public safety communications scenarios.

6.4.2.2 Figure 5 shows trends in digital voice compression technology. The top line represents the speech bit rate reduction experienced for high or "toll" quality speech as used over telephone networks. The lower line shows rates necessary for "communications" quality coders. These coders produce slightly degraded but demonstrably useful speech for public safety applications. Since the mid-1970s, the federal government has had a digital voice standard operating at 2.4 kbps. However, this standard, valuable though it is, provides limited speech quality and does not always operate well in noisy environments. It did provide an early technology for digital secure voice.

Reference: T.E. Tremain, "The government standard linear predictive coding algorithm: LPC-10," Speech Techno., vol 1, no. 2, pp. 40-49, Apr. 1982

6.4.2.3 In the past, these speech encoding systems have actually increased the occupied bandwidth due to relatively unsophisticated coding schemes, while noticeably degrading the audio quality. The 12 kb/s CVSD in Figure 5 is one example. More recently, advanced digital signal processors, made practical by improved IC technology, have contributed to the development of improved speech coding algorithms. For example, the 8.0 kbps VSELP shown in Figure 5 is used in Japan and US digital cellular and provides near toll quality audio with an information bandwidth comparable to analog speech.

6.4.2.4 Looking to the future, we can expect that increasingly powerful digital signal processing IC's will facilitate the introduction of more powerful and effective methods for reducing the amount of information that must be transmitted on the communication channel. Speech and image (facsimile) communications are two areas that should benefit greatly by these techniques. In 1995, the ITU started the process of producing a standard for a 4 kb/s speech coder for toll quality applications.[7] A closely related approach to improving spectrum efficiency is to use variable rate vocoders -- that is voice coding technology that outputs data at a variable rate reflecting the changes in speech patterns. Such vocoders are used today in some land mobile radio systems and related technologies have long been used in telecommunications. Such techniques can improve spectrum efficiency by roughly a factor of two. Variable rate vocoders also offer another potential advantage to public safety systems. They allow capacity and quality to be traded off. For example, a public safety communications system shared with highway maintenance might could, in a time of emergency, borrow capacity from the highway maintenance radio communications capabilities by reducing the bit rate used to encode their calls. Such a reduction would free up capacity for public safety communications, but would allow the highway maintenance staff to maintain communications connectivity - albeit at reduced quality.

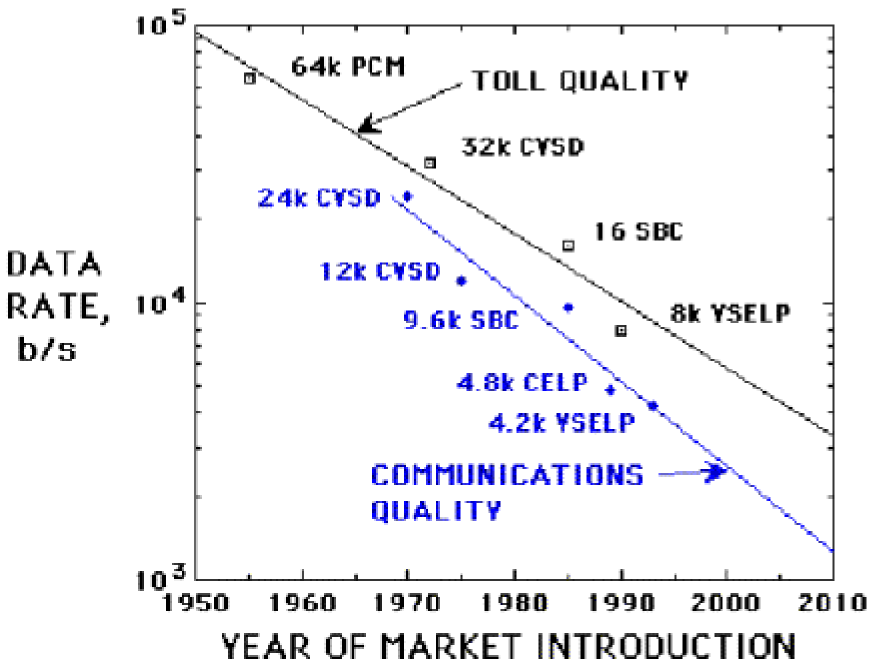

Figure 5 Trend of digital voice compression technology over time.

6.4.2.5 Of course, the mobile radio channel is subject to severe signal degradation due to shadowing and multipath fading. This degradation is more harmful to digital speech than analog, which tends to degrade gracefully in the presence of impairments. The recovery and regeneration of the source information from the compressed digital information is difficult due to the lack of redundancy. Thus, only with complex fading mitigation techniques such as error correction coding (which further increases the required bandwidth) and diversity can the compressed information be used effectively. Here again the digital signal processor IC will allow the implementation of the complex recovery techniques needed to realize usable communications in the mobile radio environment.

6.4.3 Image

6.4.3.1 *Facsimile.* Transmission of facsimile today is governed by two widely accepted international standards, ITU-T's Group 3 and 4. These standards specify both horizontal and vertical resolution, which governs the "information" content, in bits, for a typical 8.5 "x 11" page.[8] The Group 4 standard specifies a nominal resolution of 200 pixels per inch horizontally (300 and 400 pels per inch are also allowed) , and 100 lines per inch vertically (200, 300 and 400 lines per inch optional). Since the facsimile is a bitonal image, the nominal source content in bits, is:

8.5 in. x 200 pels/in. x 11 in. x 100 lines/in. x 1 bit/pel = 1.87 megabits (Mbits)

= 234 kilobytes (kbytes)

6.4.3.2 The ITU-T Group 3 and 4 standards also specify compression algorithms to reduce the number of bits, and hence the bandwidth, needed to represent a typical page. These compression algorithms are content dependent, i.e. the amount of compression is dependent on the source material. The ITU-T defines eight reference source pages to measure the effectiveness of the compression algorithms. The Group 4 compression scheme averages a compression ratio of roughly 10:1 over the eight reference source documents. Thus, one page of fax, transmitted at nominal resolution, can be represented in approximately 23 kbytes.

6.4.3.3 *Snapshot*. Unlike fax, snapshot images may contain full color or grayscale information, which greatly increases the amount of source data needed to represent an image. As stated earlier, the snapshot service may supply various resolutions and image sizes, according to the particular imaging application. As examples, two public safety applications which have received considerable interest may be represented by the snapshot application: wireless transmission of criminal fingerprint and mug shot descriptions.

6.4.3.4 The NCIC 2000 system will provide nationwide wireline and wireless access for criminal justice agencies to the FBI's considerable data repositories. Current data repositories contain information fields on such things as stolen vehicles, stolen articles, stolen guns, stolen license plates, wanted persons, stolen securities, stolen boats, missing persons, unidentified persons, foreign fugitives, and violent felons. In addition, the NCIC 2000 system will provide information regarding probation/parole status, fingerprint searches, mugshot information, generic image information, on-line ad hoc inquiries, and on-line manuals. Use of mobile data terminals, laptops and other wireless technologies by criminal justice agencies have spurred an interest and necessity in immediate, responsive information transfer. Mobile units will be capable of capturing a fingerprint image and transmitting it over wireless communications systems. Likewise, data retrieved from the national level will contain mugshot images which will require relay through the wireless medium to mobile units. As use of these capabilities increases, the demand on law enforcement spectrum allocations will increase.

6.4.3.5 The NCIC requirement is that a 24 kb (or 3 Kbyte) file be provided for fingerprint identification purposes. If a record is on file (based on a fingerprint or demographic identifier search), a copy of the mugshot (from chin to top of head) will also be returned to the requesting officer. These files will be 20 kb (2.5 kbytes). These file sizes have been purposely limited to a size that will create the least impact on the wireless channels. However, due to the current loading on these channels, it is anticipated that many systems will require expanded bandwidth and additional spectrum.

6.4.3.6 Other snapshot applications may be envisioned which require much higher resolutions, such as medical imaging. As an illustration of such an application, a 1024 x 800 pixel image will be assumed. For a full color image, three component colors must be coded per pixel, typically at 8 bits each for adequate color quantization. As a result, one 1024 by 800 pixel color snapshot image contains:

1024 pels x 800 pels x 8 bits/color x 3 colors = 19.66 Mbits

= 2.5 Mbytes

6.4.3.7 As with facsimile, a fairly well established standard compression algorithm exists. The JPEG (Joint Photographic Expert Group) standard, developed jointly by ISO/CCITT, has been developed to support a wide range of compression ratios for still color and grayscale images. The JPEG algorithm operates in two modes: a lossy and a lossless mode. The lossless mode provides modest amounts of compression with no degradation in image quality, while the lossy modes provide varying amounts of compression, which trades off directly for reconstructed image fidelity. It is generally accepted that the JPEG algorithm provides good quality image reconstruction at about 1 bit per pixel, or a 24:1 compression ratio, although this ratio is, like fax, source dependent. As a result of this compression technology, a snapshot image can be represented with good quality at about 820 kbits, or 102.5 kbytes. Of course, higher quality reconstruction may be obtained at the expense of added bits with the lossless mode, but this is a good estimate for high resolution and good image quality.

6.4.3.8 It should be noted that a specific timeline for the implementation of the NCIC 2000 technology requirements has not yet been finalized. However, these technology requirements need to be considered for the purposes of this report.

6.4.4 Video

6.4.4.1 *Slow Video.* This is envisioned as a high resolution video service with very modest frame rates, approximately 1 per second. There are two audio/video compression standard suites which have seen widespread use: MPEG and H-Series. The ISO's MPEG-2 (Motion Picture Expert Group) standard is designed as a single direction protocol providing audio/video compression, using various spatial and temporal resolutions, targeted at CD-ROM applications, using a compressed rate of roughly 1.5 Mbps for 352 by 240 pixel frame at 30 frames per second with associated audio. The ITU-T's H-Series standard includes a two way protocol and is designed specifically for video communication services like teleconferencing, at a default resolution of 352 x 288 pixels per frame, and varying spatial resolutions from 1-30 fps. The H.261 standard is optimized for coded bit rates of 384 kbps. Both of these algorithms are designed to take advantage of temporal as well as spatial redundancies in the source material to achieve compression. For current planning purposes, it can be assumed that the current implemented art uses H.261 at roughly 384 kbps for the video and associated audio channel.

6.4.4.2 *Full Motion Video*. For the full motion video application, it can be assumed that the same spatial resolution as the slow video application obtains, but that the frame rate is increased to 30 frames per second. For this type of application, the current state of the art is represented by MPEG-2, which as stated above requires roughly 1.5 Mbps for 352 by 240 pixels by 30 frames per second audio/video.

6.4.5 Source Coding Advances 1996-2000

6.4.5.1 As digital processing capability improves, higher complexity compression algorithms will become viable, increasing the compression ratios possible for these services. Semiconductor technology trends show that microprocessor computing speed increases by roughly an order of magnitude every 10 years see Figure 3 and [9]. Special purpose DSP processors, which are more popular for the multiply-accumulate operations prevalent in compression, have demonstrated a similar trend. Thus, by the year 2010, compression schemes more than ten times as complex as those of today should be viable for public safety radio.

6.4.5.2 New directions in compression are already under development to take advantage of this increased processing capability. In the fax arena, a more general standard, called JBIG, has recently been formalized.[10] Although JBIG is not yet widely used, as time progresses, it is likely that the higher compression ratios associated with JBIG will become increasingly attractive to wireless applications. Computed over the same corpus of eight typical fax documents, JBIG provides roughly a 2:1 increase in compression relative to the currently popular Group 3 and Group 4 methods. As a result, our assumption of a 3:1 increase in source coding efficiency for fax by 2010 seems reasonable.

6.4.5.3 Haskell and Netravali[11] have quantified the compression efficiency versus complexity issue, by examining compression ratio in bits per Nyquist sample (pixel) in terms of relative complexity for video signals. Drawing from them, with the expected increase of roughly a factor of ten in complexity capability due to advances in microprocessor speed, improved compression ratios on the order of 5:1 should result in compressed data of 0.2 bits per pixel. While this level of compression is exciting, a more conservative estimate is used here: a 2:1 improvement over today's compression ratios, or roughly 0.25 bits/pel, should be achievable by the year 2010.

6.4.5.4 For slow video, MPEG-4 is in its early stages of development.[12] MPEG-4 should provide improved quality over H.263 with additional features, at a coded bit rate of 128 kbps. Importantly, MPEG-4 is the first video coding scheme to explicitly address wireless concerns; the requirements include constant bit rate and error resiliency. A 3:1 increase in slow video coding efficiency is indicated when we assume that MPEG-4 will be implemented by 2010.

6.4.5.5 The source content and compression capabilities of present day technology and expected gains in compression due to algorithmic advances and/or semiconductor technology gains are summarized in Appendix C of this report. These processing advances will allow more complicated, more efficient compression algorithms.

6.5 Modulation

6.5.1 Another method of improving improved spectrum efficiency is to increase the amount of information that the communication channel can support. A communication unit moving through an urban environment encounters severe multipath fading. As a result, there are serious limitations to the data rates that are achievable when compared to those in stationary point-to-point communications.

6.5.2 Figure 6 shows the modulation efficiency of some representative digital systems that have been marketed for land mobile communications.

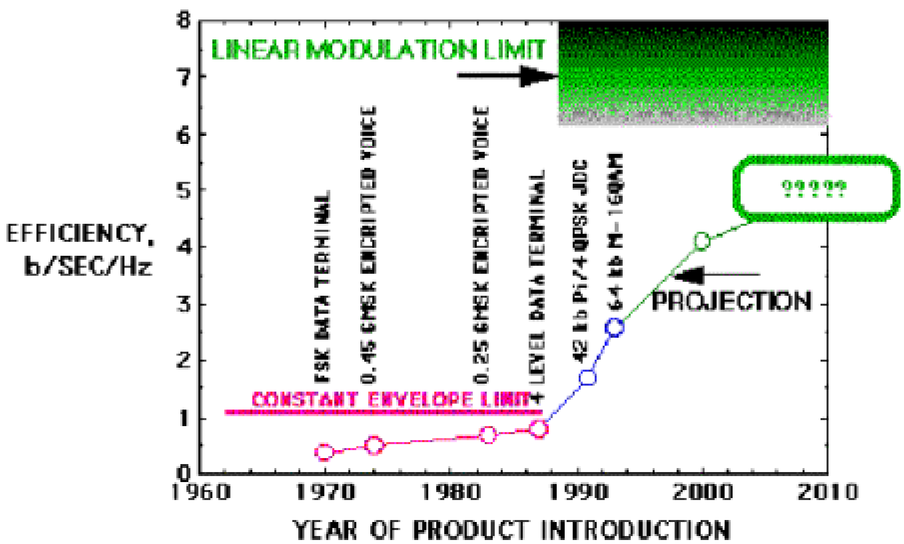

Figure 6 Modulation efficiency

6.5.3 Linear

6.5.3.1 Single sideband (SSB) modulation forms a basis for newer linear modulation techniques due to SSB's narrow-bandwidth properties; with standard SSB, the RF occupied bandwidth is identical to that of the information bandwidth. In addition to its spectrum efficient properties, SSB is a waveform preserving system, with the information waveform simply translated to an RF frequency, without the requirement for information source digitization and source coding. This makes SSB suitable for a wide range of information signals.

6.5.3.2 One common challenge of using SSB is its susceptibility to fading encountered in land mobile radio environments. Newly developed techniques are variations on traditional SSB that provide resistance to this fading. Many of these methods have been known for some time, but have only recently become economical to implement because of declining costs in digital signal processing technology.

6.5.3.3 Among the techniques used by current manufacturers of linear modulation technologies is Transparent Tone In Band (TTIB), which applies corrections to the received signal as necessary to produce known pilot tone characteristics, and thus correct the accompanying information signal. Fast Forward Signal Regeneration (FFSR) is also used for improving the performance of TTIB. A new TTIB linear modulation product now undergoing FCC type acceptance can send 14.4 kbps in a single 5 kHz channel, for a spectrum efficiency of 2.88 bits/sec/Hz. Tone Above Band (TAB) performs similarly, but with the pilot tone placed above the information signal instead of at its center.

6.5.3.4 A newly developed SSB technology is Real Zero Single Sideband (RZ SSB), which obtains information from zero crossings of the received signal, making detected signal quality independent of input RF signal amplitude. Equal-gain combining of RF signals can be used to improve performance by using pilot assisted cophasing circuits. RZ SSB equipment in prototype form can send and receive 19.2 kbps in a single 5 kHz channel, for a spectrum efficiency of 3.84 bits/sec/Hz.

6.5.4 Nonlinear

6.5.4.1 Constant envelope systems have approached 1.28 bit/sec/Hz, considered to be the limit for those systems. However, this advancement has been achieved largely through the use of more complex multi-level, partial response, and channel coding techniques, made possible by the improved performance of digital signal processing hardware.

6.6 Multiple Access Techniques

6.6.1 FDMA, TDMA, CDMA, and TDD are different channel access methods. Each has specific strengths and weaknesses. Because of these differences they are each best suited for various applications. FDMA is employed in narrowest-bandwidth, multi-licensed channel operation. TDMA is employed in exclusive license use, moderate bandwidth applications. CDMA is employed for widest-bandwidth in both single system applications such as cellular as well as distributed uncoordinated applications such as the Industrial, Medical, and Scientific band (ISM). TDD is employed to achieve full duplex operation in a single radio channel.

6.6.2 FDMA is the acronym for Frequency Division Multiple Access. In FDMA different conversations are separated onto different frequencies.

Advantages: Maximizes licensable channels, simplest talkaround, simplest configurations, maximizes range

Disadvantages: Limits maximum bit rate, duplexer required for full duplex, more stations for multi-channel sites, increases guardbands required.

6.6.3 TDMA is the acronym for Time Division Multiple Access. In TDMA different conversations are separated into different time slots.

Advantages: Bandwidth on demand, minimizes stations for multi-channels, additional channel(s) for single licensee.

Disadvantages: Range limited, exclusivity needed, talkaround complex, doesn’t increase licensable channels.

6.6.4 CDMA is the acronym for Code Division Multiple Access.[13] In CDMA all conversations are separated by code space.

Advantages: Possible increased capacity and reuse.

Disadvantages: Significant bandwidth required, power control complexity.

6.6.5 TDD is the acronym for Time Division Duplexing Multiple Access. In TDD, a single radio channel is shared in time to achieve full duplex operation.

Advantages: Full duplex without duplexer, maximizes licenseable channels.

Disadvantages: Range limited, sensitive to timing.

6.7 Error correction coding

6.7.1 In radio systems the primary goal is to reliably deliver communications. In digital communications systems this equates to maximizing the ability to successfully receive digitally coded messages. In radio systems this is influenced by a variety of factors such as modulation sensitivity, receiver sensitivity, antenna gain, antenna height, transmitter power, etc. These measures may be impractical or prohibited by rules restricting effective radiated power.

6.7.2 Another method of improving signal reception that is specific to digital communications is to employ error control. A simplistic method to improve reliability is to send messages more than once. This has the serious disadvantage of increasing transmission time by the number of times the message is repeated. More efficient methods uses error control techniques that add bits to the data stream in a precise fashion. The extra bits, however, are placed in a precise mathematically-prescribed pattern at the transmitter such that complementary circuitry in the receiver can tell when an error has occurred, and determine what the correct bit value should be.

6.7.3 Two types of error control techniques are Forward Error Correction (FEC), which provides the ability to receive a correct message even in the presence of transmission errors, and error detection which provides the ability to detect the presence of errors within a transmission. Error detection is often employed in concert with Automatic Repeat reQuest (ARQ), which uses a return channel to request retransmission of corrupted data. FEC is more commonly used in voice communications or one-way data communications, while error detection and ARQ are more commonly used in two-way data communications.

6.7.4 Adding extra bits (redundancy) to the transmitted data stream may at first seem unusual, as increasing transmission rates tends to REDUCE modulation sensitivity. However, as long as the improved success reliability more than compensates for the reduced modulation sensitivity a net gain in communications reliability can result.

6.7.5 Often, the added error correction information may amount to 50% or higher of the raw data rate, and significantly reduce the throughput. On the other hand, error detection typically requires only a modest increase in transmission overhead.

6.7.6 As described in the earlier section on specific services used in public safety land mobile radio systems, different methods of error control are traditionally applied to different services. Further, errors that escape the error control process vary in their effect based upon the nature of the communications. Voice or video decoders in the receiver can sometimes interpolate what a few missing bits should have been, while error induced text or numeric translation might have serious consequences. However as voice and video coders advance, each transmitted bit generally becomes more important, increasing the importance of error control techniques.

6.7.7 In addition to inadequate signal strength or excessive interference, the timing of the received bit energy also affects the bit error rate. In hilly and mountainous areas, and in urban settings, reflections cause multiple signal echoes to arrive at the receiver some time after the signal is received directly from the transmitter. If the directly-received signal is weak due to shadowing, the reflections can be stronger than the direct signal. The reflected propagation path lengths are longer than the direct path, and are often many in number. Such multipath effects are commonly recognized as "ghosting" in broadcast television. Much as ghosting can impair picture quality, multipath distortion can impair the ability of the receiver to determine if a received bit has the value of 0 or 1. Adaptive equalization, while not categorized as a form of error correction, can be used within constraints to alleviate the multipath problem, by determining what the multipath profile of the received signal is, and then adjust the timing of the received signal in the receiver such that the received signal is processed with the inverse of the multipath delay profile, canceling out the multipath effects.

Reference: Roger Freeman, "Telecommunications Transmission Handbook," New York, John Wiley & Sons, Inc., 1991, p. 772-778.

6.8 Constraints on using various bands

6.8.1 Propagation issues (including air-to-ground).

6.8.1.1 Radio waves are blocked and reflected by mountains and buildings. These impairments greatly affect the working of mobile radio communications systems. The mobile radio channel presents one of the most difficult engineering challenges seen in communications engineering. Providing reliable service to mobiles and portables throughout an agency's service area is extremely hard.

6.8.2 Multiband/Software radios

6.8.2.1 A software programmable radio is a radio in which the applications are configured under software control and in which the application, in whole or in part, is implemented by software resident in the radio. A software radio requires that he information is presented in a digital format for processing.

6.8.2.2 The software radio is seen by proponents as having several advantages. A number of applications can be hosted on the same hardware platform, which reduces the total amount of equipment required. The radio can be upgraded without changing the hardware for increased effectiveness and cost savings. New multimode/multiband capabilities can be achieved efficiently through dynamic allocation of radio assets in a multimode installation, including bridging among different air interfaces, which can facilitate interoperability in fixed and mobile applications.

6.8.2.3 Functional integration is used in the software radio to reduce the number of radio types into a single general-purpose programmable waveform processor. It is possible for multiple military, law enforcement, and commercial air interface standards to be implemented in a single radio, despite different physical layers (modulation, frequency bands, forward error correction), link layers (link acquisition protocols, link maintenance, frame/slot processing), network layers (network protocols, media access protocols, network time maintenance), upper layers (source coding), timebases and bandwidths.

6.8.2.4 The software radio can be compared with the personal computer (PC), with the PC's operating system functioning similarly to the software radio run time system, which runs applications under a high order language. The radio operating system is a set of utilities and interfaces that control the flow of information within the radio, and can be computed with the basic input output system (BIOS) of the PC. Unlike the personal computer, the software radio requires real-time processing to process a continuous signal, and requires low-latency processing for real-time acquisition responses.

6.8.2.5 The military is placing an increasing emphasis on digital radio technology because of its potential for lower cost, reconfigurability for multimode/interoperable communications. A current military project developing a software radio is the Speakeasy multiband multimode radio program. Hazeltine is the prime contractor, with TRW, Rockwell, Motorola, Martin Marietta, and Texas Instruments as major subcontractors. The goal of the program is to develop an open system architecture for radio service and demonstrate interoperability of multiple and simultaneous waveforms across a frequency range of 2-2,000 MHz.

6.8.2.6 Aspects of the program include study of a 2-2,000 MHz front end, implementation of a 2-2000 MHz (contiguous) RF subsystem, assessment of alternate processor technologies, multi-chip module integration, and wideband HF, VHF, and UHF antennas. Emphasized in the Speakeasy program is open bus standards to foster competition, third-party participation, evolutionary technology insertion, and reduced life-cycle costs. Also being studied is an open application programmer's interface, which eases design and integration, eases software maintenance, and encourages new applications and third-party participation.

6.8.2.7 There are many challenges to producing a practical and economical software programmable radio. Antenna systems must operate across a wide frequency range; a single multiband antenna systems is preferable to many antennas for different frequency bands. These antenna systems may be augmented with "smart" antenna technology to increase range and node density. Other enabling technologies under study include multiband power amplifiers, tunable preselectors, interference cancellers, low-noise synthesizers, wideband low noise amplifiers, wideband linear mixers, high- throughput digital signal processors, and smaller chip packaging.

6.8.2.8 Software radios are now much more expensive that hardware- based radios, with the market being confined to military, big business, and government applications. Over time, the cost of software radio enabling technologies will decrease as does the cost of digital signal processing chips, analog/digital and digital/analog converters, and memory and interconnection hardware. It has been projected that, within a few hardware generations, software radios will sufficiently leverage the economics of advancements in microelectronics, and provide seamless communications at a vest-pocket and palmtop level of affordability and miniaturization.

6.8.2.9 To summarize, as radio protocols and air interfaces become more complex, software-based technology solutions will play an increasing role. Software radios can be effective for facilitating interpretability by providing for multiple wireless standards at a single cell site, and for accommodating roaming mobiles crossing system boundaries.

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6.9 Backbone System Elements

6.9.1 Most public safety mobile communications systems need a reliable backbone to carry signals to and from the base station sites to the control points. Historically, many of these links have been provided over microwave connections operated by the public safety agency. Leased lines obtained from the local telephone companies have also been used.

6.9.2 We expect the future supply of backbone system elements to look much like the past but with two major exceptions. First, the lowest microwave frequencies (2 GHz) are no longer available for such backbone systems. Rather, such systems will have to be established at higher frequencies where rainfall attenuation may pose a greater problem. Such propagation problems may restrict the length of microwave hops and raise the cost of new systems.

6.9.3 We also expect fixed microwave systems to continue to improve and additional digital capabilities are built into the radios. Modern microwave radios already allow for integration of their systems into current technology operations and management systems (OMS). We expect such trends to continue. Similarly, we expect that microwave radios will evolve to support the latest signal formats (e.g. ATM).

6.9.4 The second exception is the supply of facilities by the local carriers. Historically, only one firm, the local telephone company, provided telecommunications services for hire. However, changes in law and technology have led to the entry of new competitors in many markets and the probability of extensive further entry. We expect that most urban areas will have several firms offering ground-based fiber connectivity. Firms offering such services are now known as competitive local exchange carriers (CLECs). Such firms include MFS, Teleport, local cable companies, and even AT&T and MCI. Many of these fiber systems will use a ring architecture, allowing service to continue even if the fiber is cut at one point. Such backup capabilities give modern fiber rings substantially higher reliability than traditional copper wire telephone services. It is reasonable to expect that fiber rings will provide connectivity to many public safety communications centers and to many of the major antenna sites. Modern (1996 state-of-the-art) fiber system provide the most capacity of any widely used communications technology. Operational fiber systems carry gigabits per second of capacity on a single fiber. The theoretical capacity is far higher. Considering all these factors it is reasonable to conclude that these commercial fiber systems could provide valuable backbone alternatives for many public safety communication needs. However, the use of any ground-based carrier for public safety systems in earthquake-prone areas may be undesirable. In contrast, in areas affected by hurricanes, such as the southeastern coastal areas, an in-ground fiber network could be preferred.

6.9.5 Fiber is another option for high-density ground-based systems. The long distance carriers abandoned microwave for fiber not only because fiber had greater capacity and a lower error rate but because it was a less costly technology. In most fiber systems the largest cost is for the installation of the fiber itself. If municipalities have access to utility rights-of-way or utility poles, this cost can be markedly lowered. Self provision of fiber systems by public safety agencies will remain a valuable alternative in the years to come.

6.10 Performance Modeling and Verification

6.10.1 As wireless communications systems evolve, the complexity in determining compatibility among different types of such systems increases. Geography, frequency, modulation method, antenna type, and other such factors impact compatibility.

6.10.2 Spectrum managers, system designers and system maintainers have a common interest in utilizing the most accurate and repeatable modeling and simulation capabilities to determine likely wireless communications system performance. With increasing market competition in wireless communications systems, in terms of both technical approaches offered and the number of entities involved, a standardized approach and methodology is desirable for the modeling and simulation of wireless communications system performance. Such an approach should be technology neutral, and consider a variety of technical practices at all frequency bands of interest.

6.10.3 In addition, subsequent to wireless communications system implementation, validity or acceptance testing is often an issue subject to much debate and uncertainty. Furthermore, long after a system is in place and optimized, future interference dispute resolution demands application of a unified quantitative methodology for assessing system performance and interference.

6.10.4 The Telecommunications Industries Association (TIA) Land Mobile Radio Section TR-8 WG-8.8 Technology Compatibility Committee is working under a charter and mission statement to address the following technical challenges:

Accommodating narrowband/bandwidth-efficient technologies likely to be deployed as a result of the Commissions “Spectrum Refarming” efforts;

Assessing and quantifying the impact to existing analog and digital technologies from new narrowband/bandwidth- efficient digital and analog technologies;

Assessing and quantifying the impact to new narrowband/bandwidth efficient digital and analog technologies from existing analog and digital technologies; and

Addressing migration and spectrum management issues involved in the transition to narrowband/bandwidth-efficient digital and analog technologies. This includes developing solutions to the spectrum management and frequency coordination issues resulting from channel splitting from 25 kHz to 12.5 kHz, and from 25 kHz or 12.5 kHz to 7.5, 6.25 kHz or 5 kHz channel spacing, as well as increases in capacity of existing channels to provide equivalent narrowband spectrum efficiency.

6.10.5 To accomplish these objectives, the WG-8.8 Committee is working with the Institute of Electrical and Electronic Engineers (IEEE) Vehicular Technology Society’s (VTS) Propagation Committee. The IEEE Propagation Committee’s contribution to this technology compatibility effort is in the area of supporting development and adoption of standard two-dimensional (2D) and three-dimensional (3D) electromagnetic wave propagation models, a diffraction model, and standards pertaining to the selection of terrain and land use data bases. The propagation related effort shall be generalizable to the electromagnetic wave propagation modeling and simulation of both current and future land mobile wireless systems.

6.10.6 WG-8.8 has noted a TIA commitment to the spectrum refarming effort, a request from APCO Automated Frequency Coordination, Inc. for post refarming technical support, and a request for expansion of the Committee s work by the Land Mobile Communications Council (LMCC). The WG-8.8 effort has focused on the following:

Establishment of standardized methodology for modeling and simulating narrowband/bandwidth efficient systems operating in a post “Refarming” environment;

Establishment of a standardized methodology for empirically confirming the performance of narrowband/bandwidth efficient systems operating in a post “Refarming” environment; and

Aggregating the modeling, simulation and empirical performance verification standards into a unified “Spectrum Management Tool Kit” that may be employed by frequency coordinators, system engineers and system operators.

6.10.7 The Committee’s draft document, entitled “On the Standardization of a Methodology for the Modeling, Simulation and Empirical Verification of Wireless Communications System Performance in Noise and Interference Limited Systems Operating On Frequencies Between 30 And 1500 MHz,” is near completion, and is intended to ultimately serve as a standard to define the compatibility criteria of the various different modulation types using terms consistent with overall TIA and IEEE land mobile efforts.

6.10.8 The expressed purpose of the document is to define and advance a scientifically sound standardized methodology for addressing technology compatibility. This document provides a formal structure and quantitative technical parameters from which automated design and spectrum management tools can be developed based on proposed configurations that may temporarily exist during a migration process or for longer term solutions for systems that have different technologies.

6.10.9 The document puts forth a standardized definition and methodology for a process for determining when various wireless communication configurations are compatible. The document contains performance recommendations for public safety and non-public safety type systems that should be used in the modeling and simulation of these systems. The document also attempts to satisfy the requirement for a standardized empirical measurement methodology that may be useful for routine proof-of-performance and acceptance testing and in dispute resolution of interference cases that are likely to emerge in the future.

6.10.10 To provide this utility requires that various performance criteria be defined for the different modulations and their specific implementations by specific manufacturers. Furthermore, sufficient reference information is to be provided so that software applications can be developed and employed to determine if the desired system performance can be realized.

6.10.11 Wireless system performance will be modeled and simulated with the effects of single or multiple potential distortion sources taken into account. These sources include:

Co-channel users

Adjacent channel users

Internal noise sources

External noise sources

Equipment non-linearities

Transmission path geometry

Delay spread and differential signal phase

6.10.12 Predictions of system performance will be based on the desired RF carrier versus the combined effects of single or multiple performance-degrading sources. Performance will be based on a faded environment to more accurately simulate actual usage and will consider both signal magnitude and phase attributes.

6.10.13 It is anticipated that the document will serve as the standard reference for developers and suppliers of wireless communications system design, modeling, simulation and spectrum management software and automated tools.

6.10.14 It is envisioned by WG-8.8 that future wireless systems that employ the WG-8.8 standard in the design, modeling, simulation, and implementation processes will benefit from consistent performance as designed. Furthermore, the Committee expects that spectrum management based upon the same precepts and standard will not only be "consistent" with the designs submitted, but will be more accurate and more flexible accommodating each unique set of conditions rather than relying upon generalized tables and "rules-of- thumb."

6.10.15 Since the migration from the analog world of today to the digital future will be gradual, it is anticipated that there will be additions to the collective knowledge base. Therefore, on a regular basis, initially on an annual basis, the WG-8.8 document will be revised based upon the receipt of relevant additions and/or corrections. Updates will also be issued that reflect refinements as requested by the body of systems designers, and spectrum managers who will ultimately be the users of this standard.

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[1]

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[8]“Information” as used here refers to the uncompressed bit content, not the source entropy, as in a strict theoretical sense.

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