INTRODUCTION BY EDITOR

The article following, by John Puente, is the second in a two-part series on the early days of satellite communications. The previous article, by Joe Pelton, published here in the March 2010 column, focused more on policy issues related to satellite communications. It described the establishment of both Comsat and Intelsat, with a brief introduction to the technologies adopted for the Intelsat series of satellites. This article focuses on the technologies used in the early communication satellites. It is written by one of the key engineers participating at Comsat in these developments. It therefore provides insight into the development process, explaining how design issues arose and why specific technologies were chosen to address them. This insight has been a feature of all the columns devoted to significant communication systems and developments of the recent past. This article is noteworthy as well for its emphasis on the multinational nature of the engineering team selected to work at Comsat on the communication aspects of the Intelsat satellites. I found the article of particular interest personally since it vividly brought back the years in which my students and I, working and writing on new concepts in digital communications particularly applicable to satellite communications, relied so much on the published work of Mr. Puente and his fellow engineers at Comsat describing TDMA, SPADE, and related systems described and referenced here. As usual, we welcome your letters commenting on this article and others published in the History Column.

—Mischa Schwartz

THE EMERGENCE OF COMMERCIAL DIGITAL SATELLITE COMMUNICATIONS

JOHN G. PUENTE

TELECOM STATE OF THE ART CIRCA 1960

The state of the art for international communications was determined by the postal telephone and telegraph administrations (PTTs) of the world. The national monopolies of each country organized their networks and agreements in the Consultive Committee for International Radio (CCIR) and International Telegraph and Telephone Consultive Committee (CCITT) of the International Telecommunication Union (ITU) so that their traffic would interface seamlessly at major switching points in their respective countries. These switches were electro-mechanical. At the endpoints or last mile, four-wire voice circuits were terminated in two-wire connections at user handsets. The voice bandwidth was 4 kHz/channel. Any data that was transmitted or received was limited to this bandwidth and worked well because data rates were very low. The data speed varied, but we are talking about 50–120 b/s, which represented a very low percentage of voice traffic.

Voice traffic internationally was also carried by high-frequency (HF) radio, which depended on atmospheric conditions to complete a connection. In many cases you had to reserve time and wait up to six hours to get a connection. Prices per minute were very high, and the quality of the call was poor. This resulted in low international traffic between countries. The first voice undersea trans-Atlantic international cable (TAT-1) between Europe and the United States was initially designed to carry 36 channels at 4 kHz/voice channel. This was later increased to 48 channels by reducing channel bandwidth to 3 kHz/channel. The traffic increased rapidly even though the cost of a telephone call was on the order of \$10/min. The cable capacity was increased to 72 channels by using a Time Assigned Speech Interpolation (TASI) system. Quality remained good, but return echo was a serious user problem due to the four-wire to two-wire end-user handset in combination with long distances. By the time Intelsat I was launched in 1965, five transatlantic cables, TAT-1, TAT-2, TAT-3, TAT-4, and CANTAT-1, were in operation with 440 voice channels increased to 821 using TASI. Today most voice traffic across the Atlantic is carried by fiber optic undersea cable. Satellites remain competitive in broadcast and thin route applications. Video distribution remains strong for satellites, and in mobile applications such as maritime and military telecom requirements for voice, data, and video. In disaster situations (e.g. the earthquakes in Haiti and Chile) satellite trucks with generators and small Earth stations provide quick communications when terrestrial facilities are damaged or destroyed.

During this period technological change was happening very quickly. Satellites were being launched in low orbit for weather and military applications, and digital systems were being developed for access to mainframe computers over analog domestic wireline networks. Some transmission for voice was over pulse code modulation (PCM) 24-channel systems at 1.544 Mb/s in the United States at 64 kb/s per voice channel. The key to the revolution that changed information transfer was the transistor, leading to the microprocessor and the end of vacuum tube circuitry.

Arthur C. Clarke [1], the visionary who wrote in a 1945 publication that three synchronous satellites would cover the world, did not forecast the tremendous technological advances happening in so many areas, which eventually resulted in the formation of Comsat.

TECHNOLOGY AND COMSAT

The formation of Comsat and Intelsat is described in the article written by Dr. Joseph N. Pelton [2].

From a technical point of view, the Intelsat consortium was a group of national PTTs who were concerned that satellite technology could disrupt their terrestrial national and international plans which they had worked so hard to achieve. As a representative of the U.S. government at an ITU, CCIR, and CCITT meeting in 1968 at Mar Del Plata, Argentina, Comsat was made aware of this concern when we tried to discuss and enter into questioning the role of satellites in future global networks. Comsat was in an awkward position since both AT&T and ITT were on the Board of Directors of Comsat and supplied voice circuits for Comsat to serve Europe. These relevant questions were entered into the procedural process of the CCITT for analysis and recommendations.

The long-distance terrestrial networks in the United States and Europe were primarily microwave relay sites with an average of 30 mi between towers. The multiplexing and modu-

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lation techniques were frequency-division multiplexing/frequency modulation (FDM/FM). Each carrier carried about 960 voice channels.

The PTTs viewed satellites as another "long" microwave link to their central office switches, so it was natural that the Intelsat I satellite carried FDM/FM carriers through their transponders. The 100-pound Intelsat I, or Early Bird, carried 240 voice channels per FDM/FM carrier vs. the TAT-1 trans-Atlantic cable of 48 channels. The voice channels were 4 kHz bandwidth. A problem for the geosynchronous satellite was its location at 22,300 mi in space. The voice signal delay of nearly one-third of a second enhanced the sensitivity of users to echo. Long-distance systems used echo suppression to control the echo that resulted from the four-wire to two-wire end link connection at the telephone handset. The received voice signal would leak back into the transmit side of the telephone hybrid, and users would hear echoes of their own voices. The echo became more annoying as the delay increased. Comsat Laboratories began to develop an echo canceller to alleviate this problem, which would cancel echo rather than suppress it. A one-hop satellite delay was acceptable to most users, but two or more hops created a delay that was objectionable to many users. Data transmission with forward error correction can provide 10^{-9} bit error rates or lower. Total data throughput was dependent on the power of the forward error correction (FEC) code, transmit power, and modulation used, as well as antenna size.

Multiple access is a process where more than one Earth station uses the same transponder in the satellite to communicate with other locations. For example, multiple FDM/FM carriers passing through a satellite traveling wave tube (TWT) transmit amplifier at full power create interference with each other due to the nonlinearity of the amplifier at high power. Thus, the operating point has to be backed off to a more linear TWT range, causing a drop in capacity in order to meet voice channel performance requirements. There was less concern about data transmission since it was a small portion of the total traffic (i.e., less than 10 percent of voice transmission predicted).

The number of Earth stations in Intelsat was growing, and multiple access requirements had to be addressed. Countries with low-capacity link requirements needed a direct link with other low-capacity countries *and* with the major countries in the world. Undersea cables were too expensive to reach low-capacity nations.

This was the period of time when return on investment (ROI) for PTTs was regulated. Generally, they were guaranteed a specific ROI on capital they invested; that is, the more capital invested over time, the more bottom line earnings. AT&T investments in equipment were depreciated over a long 40-year period, so new technology often was slow to enter the market. Satellites and new terrestrial network competition were on the horizon. Technology was pressing for new services, and entrepreneurs wanted to compete. MCI (Microwave Communications Inc., now a part of Verizon) was

Figure 1. *Comsat Laboratories.*

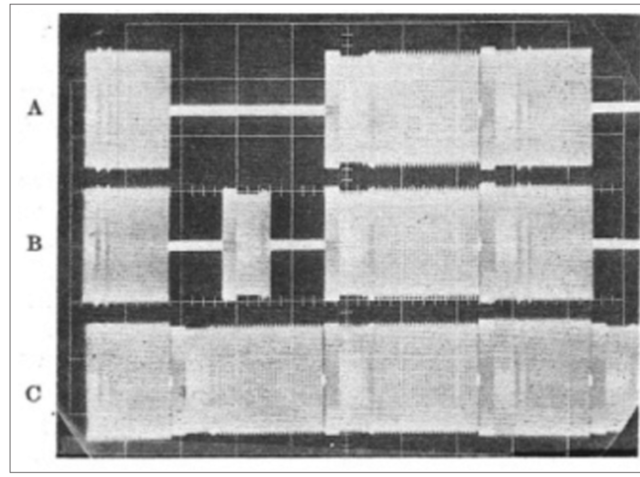

Figure 2. *a) Empty time slot; b) acquisition; c) lockup.*

a major instigator for change. Satellites had to find their niche — their major advantage was in broadcast mode. One geosynchronous satellite could cover close to one-third of the Earth. No terrestrial network can compete in that mode on a cost basis. Thus, the state of communications was changing rapidly, on both the technical and regulatory fronts.

COMSAT LABORATORIES

Comsat Laboratories (Fig. 1) opened in September 1969 under Wilbur Pritchard as director of research and development. It was a wonderful place to work as an engineer, and was wide open to improving spacecraft, antenna systems, baseband communication systems, propulsion, and much more.

The atmosphere was creative, and accomplishments were made across the board. New satellite applications such as television broadcasting, maritime, and private corporate networks were on the horizon. Comsat Labs was a place where all aspects of satellite communications were under scrutiny and improvement for commercial operations. The Intelsat program included engineers and staff from consortium countries who stayed on for two years or so and brought their own ideas. I was recruited to Comsat from IBM as a digital design engineer. At IBM I was developing a digital wireline modem at the "high speed" of 2400 b/s to access IBM mainframe computers. Access to the corporate mainframe computers over voice-based landlines without the need to have an independent mainframe at each major location was evolving. Being the only digital engineer at Comsat in its early days left me with time to look at the use of digital transmission for the developing network. I believe there were only 15 employees at Comsat at the time — November 1963.

This introduction leads us to the emergence of digital communication technologies such as time-division multiple access (TDMA), single channel per carrier (SCPC), and single channel per carrier multiple access demand assigned experiment (Spade), all of which became operational in the Global Intelsat system. In particular, the first operational network across the Atlantic was between large 30 m Earth stations in the United States, United Kingdom, France, Germany, and Italy with FDM/FM carriers over Intelsat I (Early Bird).

THE ADVENT OF TDMA

The first paper on TDMA of which I am aware is D. R. Campbell's [3], which was presented in June 1964 at the Symposium on Global Communications. This paper drew the attention of Comsat Labs as a possible alternative to FDM/FM transmission because of its several benefits:

- Using TDMA, multicarrier operation through a satellite transponder did not degrade capacity since each burst could use the full power of the transponder output power amplifier, a TWT. Only one carrier was present in the satellite transponder at any one instant in time.
- The ability to easily change capacity between Earth stations by changing the length of each station's burst of information (i.e., network management flexibility).
- The ability to transmit voice, data, or video in digital format in the same burst.

There were three papers published in *IEEE Transactions on Communication Technology* [4–6] describing the first TDMA experiment over an active satellite, Intelsat I (Early Bird). It was called Multiple Access TDMA Experiment (MATE). The results of the TDMA experiment on a satellite system designed for FDM/FM carriers led to a second higher-capacity TDMA system known as MAT-1 [7]. Later commercial operating TDMA systems were deployed worldwide and are in extensive use today. It is also of interest to note that the majority of cell (mobile) phones in use throughout the world today use the TDMA format. Dr. Tadahiro Sekimoto of NEC (Japan) was the manager of this project with John G. Puente (Comsat), O. Gene Gabbard (Comsat), and Winfried Schrempp (Germany) of Bolkow, Munich. The relevant details of the MATE experiment are in those papers. As with any new technology, many people were involved, and their contributions are listed in the references. In introducing TDMA into the Intelsat network we needed to test the existing Earth stations to ensure they would work with new digital systems. In one of these tests Gene Gabbard, who was at the Mills Village Earth station in Canada, noticed that when a digital burst was transmitted, he saw a burst at the receive side of the terminal, and began to investigate how that could happen. He measured the time of the received burst compared to the transmit burst, calculated a location on the waveguide, and asked a technician to open up the guide at that point. Inside the waveguide he found some nuts and bolts and removed them. This seems trivial, but the return burst was gone. The frequency translation from the transmit band (6 GHz) to the receive band (4 GHz) was being caused by arcing taking place in the waveguide when the transmit burst impinged on the nuts and bolts lodged in the waveguide. This is a small example of issues found at Earth stations designed

Figure 3. *50 Mb/s MAT-1 terminal.*

for FDM/FM transmission, and that when new systems are introduced, you can get surprises that are not predictable. In FDM/FM you could not see the problem since the signals transmitted are continuous. This discovery and removal of the foreign matter from the waveguide improved performance of the Mill Village Earth station for both analog and digital transmission by almost 2 dB.

The MATE system demonstrated TDMA burst and synchronization, carrier recovery, bit timing recovery, and unique word detection for independently arriving bursts, as shown in Fig. 2.

These bursts could stay in their time slot with nanosecond accuracy at a satellite 22,300 mi away. After this experiment, the key technologies were tested and analyzed, which proved that TDMA was a viable multiple access system. This led to a 50 Mb/s MAT-1 [7] terminal design accepted by the Intelsat consortium (Fig. 3).

TDMA for large-capacity links had one major limitation: Earth stations had to be able to transmit high-power 50 Mb/s bursts. The equipment was expensive for low-capacity requirements, and countries that only needed a few voice channels to several other countries found TDMA too expensive. A $3–5 million Earth station (Fig. 4) did not make much economic sense for low-capacity links.

These requirements led to the need for lower-cost stations and baseband equipment that was relatively cheap. SCPC was an answer.

The MATE project team has met every five years to celebrate the world's first TDMA experiment. After leaving Comsat, Dr. Sekimoto returned to NEC and became the chairman and president of NEC Corporation in Japan, a worldwide supplier of computer and communications equipment. Mr. Schrempp went back to Bolkow GmbH (now a part of Benz) and had an outstanding career in Germany. Puente and Gabbard left Comsat with others to start Digital Communications Corporation (DCC), which, after two changes in ownership, is now Hughes Communications, Inc., an independent company listed on the NASDAQ. Our last, 40th anniversary meeting, 14 September, 2006, was in Tokyo. Sadly, Dr. Sekimoto has passed away since the last MATE meeting.

Figure 4. *Typical 30 m Intelsat Earth station.*

THE DEVELOPMENT OF SCPC

The first internal memo written on SCPC [8] was a brief description of the capacity that was possible using PCM (64 kb/s) or delta modulation with orthogonal coding through an Intelsat I transponder. A follow-on paper on SCPC [9] was later published at an AIAA meeting.

Comsat was not alone in looking for a solution. NEC and Hughes developed a system called STAR [10]. This was a demand assignment system using SCPC FM carriers. Channel assignment was centrally controlled. Earth stations could not self-assign their capacity, which meant assignment was in control of a single country location. This was not a popular idea among the consortium as no country wanted a single entity to assign its traffic. By using FM per carrier, the data rate for non-voice traffic was limited to 4 kHz bandwidth, whereas digital systems could use the full 64 kb/s information rate. Analog FM carriers passing through a nonlinear TWT amplifier cause intelligible crosstalk between the individual carriers. Listening to other conversations during your long-distance call is worrisome (e.g., can they hear my call?). To meet CCITT specifications on intelligible crosstalk, the TWT must operate in its more linear range. This results in reduced output capacity in voice channels. End users are much more sensitive to intelligible crosstalk than the noise caused by bit errors in digital systems. These problems were resolved by the Spade system.

SINGLE CHANNEL PER CARRIER MULTIPLE ACCESS DEMAND ASSIGNED EXPERIMENT

At Comsat Labs the experimental demand assigned SCPC system was called Spade. A. M. Werth [11] was program manager. Each channel was a phase shift key (PSK)-modulated digital voice bitstream (Fig. 5). Since it was digital, data transmission per channel was also permissible. Voice statistics were used to turn off the carrier during voice silence, approximately 40 percent of the time during a conversation.

A key feature of this technology was the ability of each Earth station to access satellite capacity by self-assigning channels without central control. The control and terrestrial interface of the network was developed by George D. Dill [12, 13] and N. Shimisaki using minicomputers. The fact that Spade was an SCPC carrier system led to smaller low-cost Earth stations for "thin" routes between all Earth stations.

Earth station antenna size is dictated by spacing between satellites in the geostationary orbit to avoid Earth station interference to adjacent satellites. Testing for SCPC operation was necessary to confirm analytical results. The optimum performance for multicarrier opera-

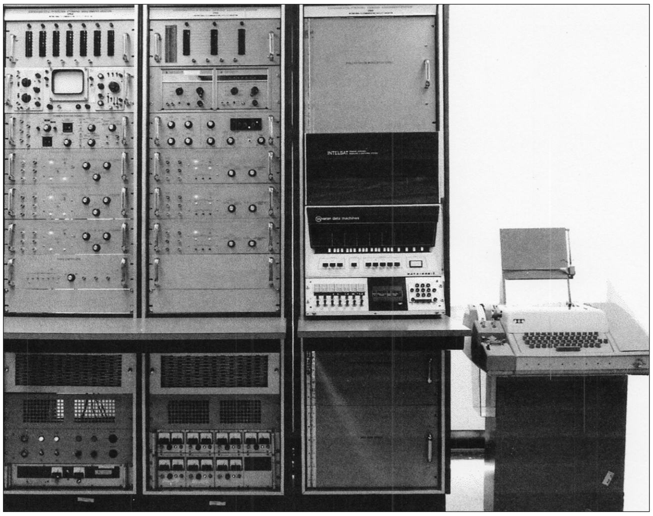

Figure 5. *SPADE — A PCM FDMA demand assignment system.*

tion resulted when the TWT input signals were backed off 4 dB from peak operating power. In order to reduce antenna size, the up and down links had to go to higher-frequency Ku band transponders at 14 GHz up and 12 GHz down. This reduced transmit and receive beamwidth for the same size antenna and allowed smaller inexpensive dishes. Original Earth station costs were $3–5 million each and were 30 m in diameter, as noted earlier. Domestic networks using small Ku band antennas can cost $500–$10,000, depending on the application. The applications have grown dramatically for private digital networks in energy, transportation, and off-shore drilling, to mention a few, because of the lower costs.

SUMMARY

The emergence of commercial digital satellite communications was a result of many factors. This article mentions some of the key ones:

- Comsat and Intelsat
- Technology in geosynchronous spacecraft design, antenna systems, digital systems, propulsion, and solid state electronics
- Computer access from remote locations

This was a remarkable period of change in domestic and international cooperation for global networks to transmit and receive voice, data, and video information. The world became a little smaller and, hopefully, a better place for all of us.

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BIOGRAPHY

JOHN G. PUENTE (johnbev@aol.com) became director of technology at Comsat Laboratories. He managed the RF Laboratory, the Communications Laboratory, and the Spacecraft Laboratory before leaving in 1972. After leaving Comsat he joined American Satellite as vice president, engineering. In 1977 he joined Digital Communications Corporation (DCC) as chairman and president. DCC was eventually acquired by Hughes Aircraft and is today Hughes Communications, Inc., an independent company now on the NASDAQ exchange. He was a founder and chairman of SouthernNet, which built and operated a fiber optic network from Washington, DC to New Orleans, Louisiana. SouthernNet became Telecom USA and was acquired by MCI in 1990. He next joined Orion Network Systems as chairman and CEO. Orion launched geosynchronous commercial satellites over the Atlantic and Pacific Oceans and was later acquired by Loral. He is currently chairman of the Board of Capitol College, an engineering school in Laurel, Maryland, and is a Board member of Micros Systems, MCRS, NASDAQ.