TO BIT SYNC OR NOT TO BIT SYNC? WHY THIS IS A QUESTION

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ABSTRACT

The original role of bit synchronizers ("bit syncs") was to form the interface between the video output of the FM demodulator and the programmable decommutator in a PCM/FM system. Modern receiver/detectors for PCM/FM, SOQPSK-TG, and ARTM CPM produce TTL-level data and clock outputs as a standard feature because bit and symbol timing are required for detection. This development has eliminated the original purpose for bit syncs. But because TTL-level data and clock remain common methods for moving data from one point to another on most test ranges, bit syncs are still required to serve this purpose. As IRIG 218 TMoIP networks become more common, the role of bit syncs in moving data will probably diminish further.

INTRODUCTION

The rapid introduction of new modulations and advanced receivers/demodulators since the early 2000's has changed some of the fundamental elements of telemetry ground station configurations. One of those changes is the role of stand-alone bit synchronizers ("bit syncs"). Young engineers sometimes encounter racks full of bit syncs and wonder what they are and if they should be using them. Too often the advice they are given is little more than a guess based on past use and its reputation as the "Swiss army knife" of telemetry systems [1].

This paper answers the following questions. Should bit syncs be used? If so, in what context? If bit syncs are not to be used, where did all those bit syncs in my telemetry center come from? Why were they purchased in the first place?

The answers to these and similar questions are found in history. Consequently, a brief re-telling of the history forms the next section. With the context of history in place, the section that follows provides answers to the "bit sync question."

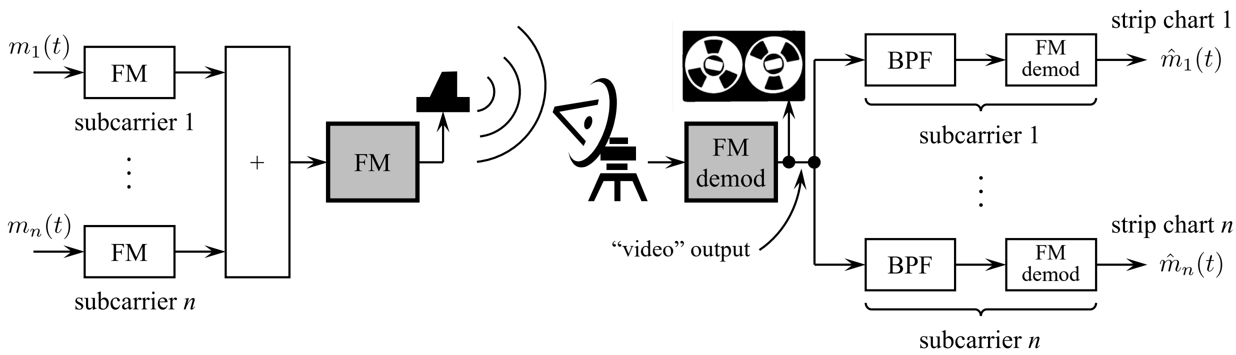

Figure 1: A simplified block diagram of an FM/FM system.

HISTORICAL BACKGROUND

Aeronautical mobile telemetry, as understood today, began in the 1940s as the need to attain air superiority in WW II drove the introduction of new aircraft that required testing. Of the many challenges facing telemetry engineers in the day, the two of interest to this article are multiplexing and the RF modulation used to transmit the multiplexed measurements to the ground. As Nichols and Rauch observed, "It is safe to say that nearly every conceivable type of multiplexing, modulation, etc. has been tried" [2]. By 1944, the use of subcarriers modulating an RF FM carrier emerged as the best solution. It must have been the case that FM's superior immunity to noise (when operating above threshold) and to amplitude variations caused by antenna pattern variations and RF propagation made it the choice for RF modulation.

The earliest telemeters did not perform multiplexing; instead each measurement directly modulated a different FM RF carrier. To reduce cost, size, weight, and power, it quickly became obvious that applying a multiplexed signal to *one* RF FM carrier was the way to go. Because the measurands were continuous-time signals, each measurement modulated a *subcarrier* usually using FM. The terminology that emerged was of the form

multiplexing/modulation.

If multiple multiplexing methods were used, the multiplexing part itself included a slash. In such cases, the acronym after the last slash defined the RF modulation.

For example an "FM/FM" system meant each measurement modulated an FM subcarrier. The sum of the modulated subcarriers modulated an FM RF carrier. The FM/FM concept is illustrated in Figure 1. The ground station in the figure simply reversed the steps used at the transmitter: the received signal was applied to an RF FM demodulator; the demodulator "video" output[1] was demultiplexed using a bank of bandpass filters (BPF) centered at each of the subcarriers and FM demodulators operating at the subcarrier frequencies. In the figure, the subcarrier outputs drive strip charts as an illustration of how measurements were displayed when FM/FM was in common use.

[1]The use of adjective "video" here appears to be a modifier that indicates the bandwidth of the output is capable of supporting analog video (several MHz) as opposed to audio (up to 15$\sim$20 kHz) [3]. This speculation is consistent with the definition of "video frequency" in the Oxford English Dictionary [4].

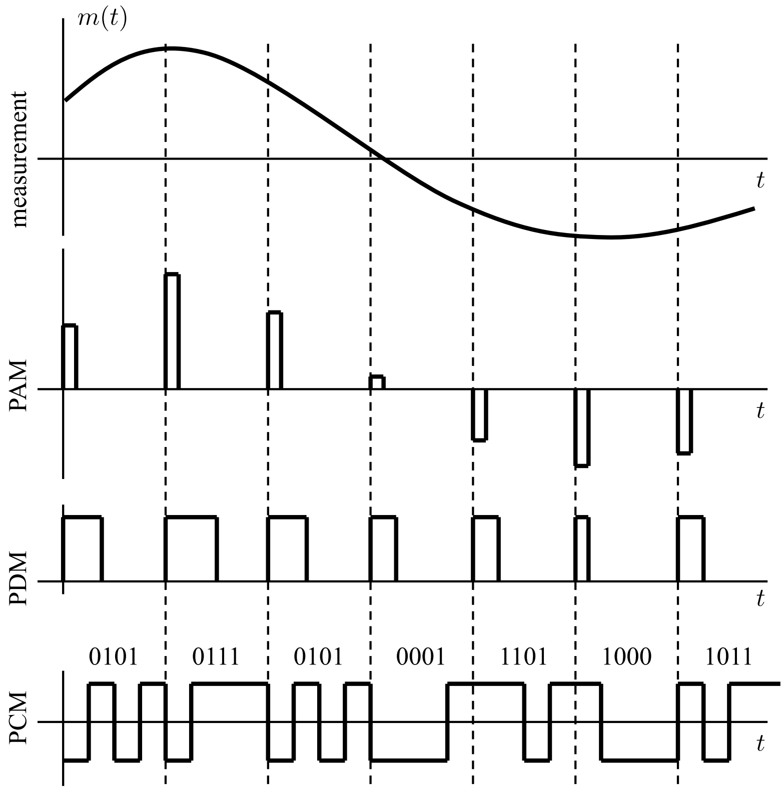

Figure 2: Pulse modulations used for time division multiplexing in aeronautical mobile telemetry.

It was common to record the “video” output of the RF FM demodulator on magnetic tape for post flight analysis as shown in the figure. Playback from magnetic tape worked as follows. The magnetic tape player replaced the RF FM demodulator in Figure 1: the output of the magnetic tape was applied to the bank of bandpass filters whose outputs were applied to the subcarrier FM demodulators whose outputs were displayed on strip charts.

The use of modulated subcarriers to perform multiplexing had a high cost in terms of size, weight, and power, both on the airborne side and on the ground. In the air, subcarrier oscillators had to be installed for each subcarrier modulator. On the ground, demultiplexing required racks of FM demodulators. As technology advanced, it become possible to *time-multiplex* pulses modulated by the measurements. The earliest pulse modulations used for time multiplexing were called pulse amplitude modulation (PAM) and pulse duration modulation[2] (PDM). In PAM, the amplitude of the pulse is proportional to the measurement amplitude. In PDM, the width of the pulse is proportional to the measurement amplitude. Examples of PAM and PDM are shown in Figure 2. The pulses resulting from the modulation were multiplexed in a round-robin fashion via a process called *commutation*. Telemetry systems that time-multiplexed using PAM were called PAM/FM systems. Systems that time-multiplexed using PDM were called PDM/FM systems.

The PAM/FM and PDM/FM concepts are illustrated in Figure 3. (In actual implementations, modulation and commutation occurred in the same hardware simultaneously [5]. Showing the two as separate in the figure is notional.) As before, the ground station reversed the sequence of

[2]By the time the authors were enrolled in university programs, PDM was called pulse width modulation (PWM).

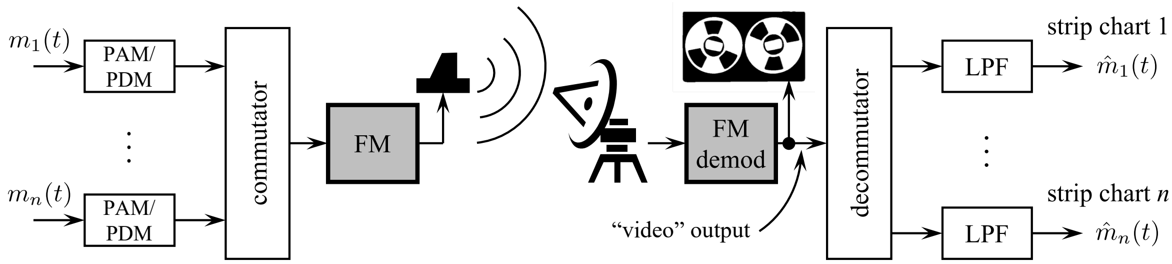

Figure 3: A simplified block diagram of an PAM/FM or PDM/FM system.

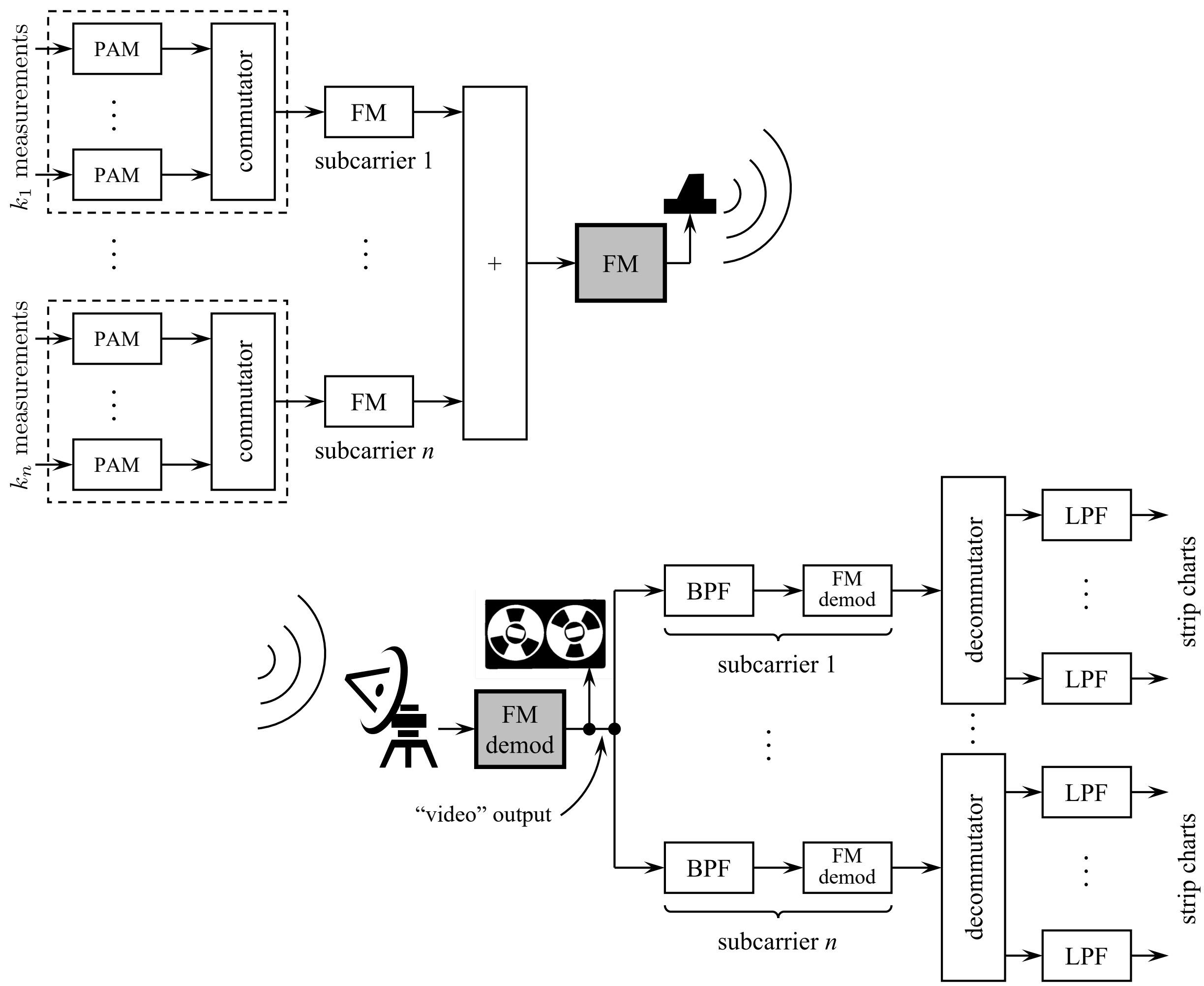

Figure 4: A simplified block diagram of an PAM/FM/FM system.

operations performed at the transmitter. The video output of the RF FM demodulator was applied to an analog decommutator. The analog decommutator produced parallel pulse sequences, one for each measurement. The pulses were used to reconstruct the continuous-time waveform. The reconstruction is shown by low-pass filters (LPF) in the figure.

Like FM/FM systems, the video output of the RF FM demodulator could be recorded to magnetic tape as shown in the figure. Playback was accomplished by applying the output of the magnetic tape player to the analog decommutator.

By combining commutated PAM or PDM with subcarriers, even more sophisticated multiplexing arrangements could be produced. An example is the PAM/FM/FM system shown in Figure 4. Here, groups of measurements were time multiplexed using commutated PAM. Each group of time-multiplexed measurements were applied to an FM subcarrier. The outputs of the FM subcarriers were combined and applied to an RF FM modulator. At the ground station, the steps were reversed. As before the video output of the RF FM demodulator could be recorded to magnetic tape as shown in the figure.

This example illustrates how the combination of time multiplexing and frequency multiplexing could be used to multiplex a large number of measurements on a single RF carrier. One advantage of this system was that it was possible to multiplex analog measurements (applied directly to one of the subcarrier FM modulators) along with time-multiplexed signals. Not all possible combinations were advised. Section 3.3 of IRIG 106-60 recommends against using PDM/FM/FM [6] stating "it is wasteful of bandwidth" because "it places three wide band modulation systems in cascade."

PAM produced noisy outputs at the ground station. This is because PAM itself is sensitive to amplitude noise generated by the electronics used to implement it. On the other hand, PAM modulators were low complexity and light weight: they required little more than switching circuits coupled to sample-and-hold circuits. Consequently, PAM modulators were inexpensive. This made PAM/FM a popular choice for missile telemetry where low complexity was a good match to the size, weight, and power constraints of a missile and the low expense was a good match to the disposable nature of telemeters used in missile tests. In contrast, PDM was much less noisy. This is because PDM depended on the time base; it was not sensitive to amplitude noise. The observed PDM/FM outputs were consistently "cleaner" than PAM/FM outputs [5]. But PDM was limited to low frequency measurements (10-20 samples/s) such as altitude and surface control positions. Other important measurements, such as vibrations, required more bandwidth and the only realistic option was FM/FM.

Pulse code modulation (PCM) changed all of this. In PCM, a measurement is sampled and the amplitude of the sample is quantized using a binary code. The bits comprising the binary code are sequenced serially. An example of a 4-bit PCM quantizer is illustrated in Figure 2. In the figure, the bits representing each sample are depicted by pulses using the NRZ-L format (see Chapter 2 and Appendix 2-A of [7]). PCM was the first "truly digital" option in aeronautical mobile telemetry and opened the door for advancements in digital electronics to be applied to telemetry systems. These advantages included reduced size, weight, and power of telemeters; increased flexibility in time division multiplexing; the "digital advantage" for RF transmission (reduced signal-to-noise ratio to achieve the same quality output as FM); and the natural ability to interface directly with digital computers.

One of the major selling points was (and still is) the flexibility for time division multiplexing. Time division multiplexing involves arranging the bits representing different samples in a particular

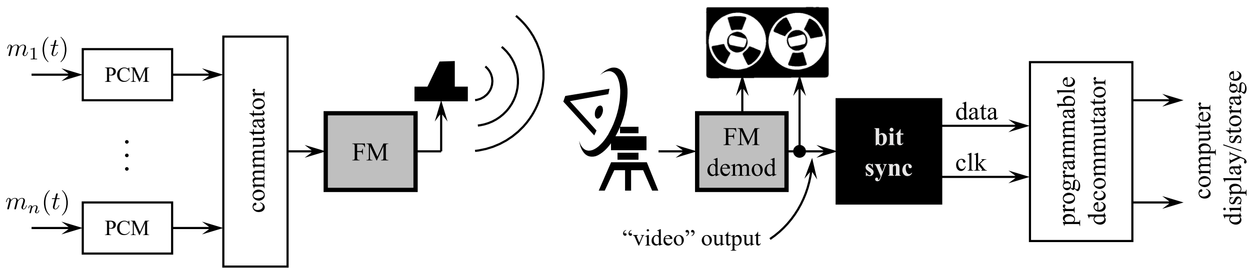

Figure 5: A simplified block diagram of a PCM/FM system.

order. This ordering, still called "commutation," involves purely digital electronics and techniques. Not only are the electronics small, light weight, and low power, but the flexibility provides for an almost endless number of arrangements. On the ground, a programmable de-multiplexor (also called a decommutator) is capable of supporting essentially all PCM multiplexing arrangements. This reduces the size and cost of ground stations.

The standard for pulse code modulation in telemetry dates to 1959 with IRIG Recommendation 102-59 [8]. Chapter 5 of the 1960 version of IRIG 106 [6] describes PCM/FM. Despite the early date of its inclusion in the IRIG 106 standard, it took a while for PCM to catch on. For years frequency division multiplexing (e.g., FM/FM) and time division multiplexing (PDF/FM, PAM/FM, PCM/FM) coexisted. In fact, the technical program of the very first International Telemetering Conference (1965) included a session devoted to each technique. One example of simultaneous use was F-15 testing in the 1970s. It required the transmission of both digitized telemetry data in the form of PCM and continuous-time data for wideband signals such as vibrations [1, 9]. PCM was mapped to some FM subcarriers while the continuous-time signals were mapped to other FM subcarriers to form a composite PCM/FM/FM + FM/FM system [1]. A similar arrangement was used to test Sparrow missiles [10].

By the mid-1970s the benefits of PCM/FM compelled most programs to adopt it [11]. The current standard for PCM multiplexing is described in Chapter 4 (for transmission) and Chapter 10 (for digital recording) of IRIG 106 [7].

A block diagram of a PCM/FM system is shown in Figure 5. At the transmitter, each PCM block comprises an analog-to-digital converter (a sampler) together with an amplitude quantizer. The bits representing the samples are serialized to produce the output. The commutator can also be thought of as a digital multiplexor that outputs a high-bit-rate stream from the parallel input bit streams in a predefined way. At some point, the bits are represented by an NRZ-L pulse train that forms the input to the FM modulator.

At the receiver, the order is reversed. The received FM signal is applied to the FM demodulator that reproduces a noisy and lowpass filtered version of the NRZ-L pulse train at the transmitter. An example is illustrated in Figure 6. To constrain the power spectral density of the RF signal, a lowpass filter (called a pre-modulation filter in IRIG 119 [12]) is applied to the PCM NRZ-L signal. The result is a waveform that such as the one shown in Figure 6 (a). In Figure 6 (b), an example of the FM demodulator output is shown. When the demodulator is operating above threshold, the FM demodulator output at the ground station is a noisy version of the input to the FM modulator on the airborne transmitter. The FM demodulator output is not an NRZ-L signal, nor is there a clock signal. Because a programmable decommutator is a digital system that requires digital (data and

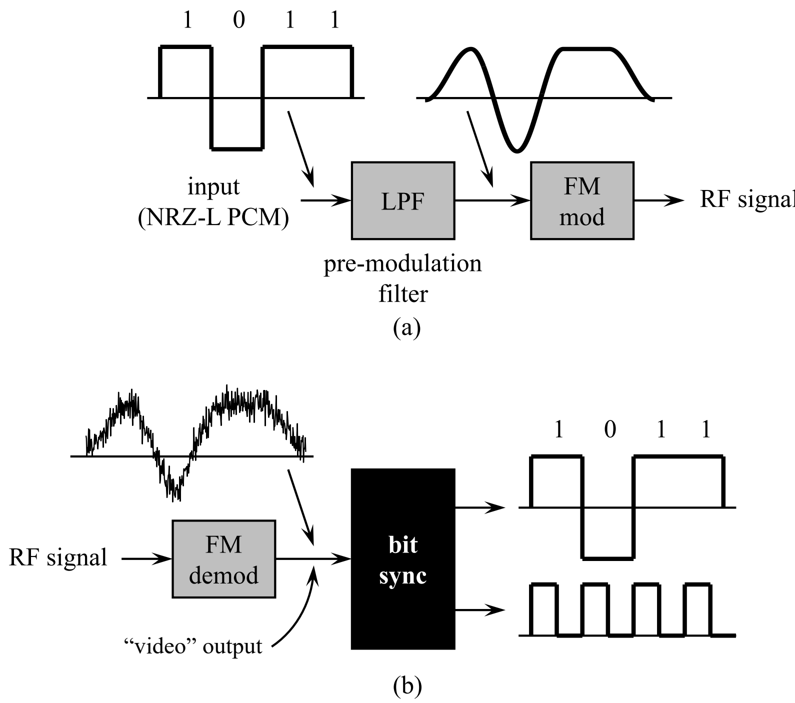

Figure 6: A detailed view of PCM/FM: (a) the generation of PCM/FM on the test article; (b) the detection of PCM/FM in the ground station showing the role the bit synchronizer (bit sync) played.

clock) inputs, the output of the FM demodulator is not a suitable input.

The purpose of the bit sync is to bridge the gap between the FM demodulator output and the decommutator input. The bit sync accomplishes this by creating an an NRZ-L signal and its corresponding clock from the FM demodulator output. It may appear that the bit sync does little more than "square up" the noisy lowpass filtered signal. But this is not correct. For readers familiar with introductory digital communications, the bit sync is a detector for binary PAM[3] [13]. It treats its input (the FM demodulator output) as a noisy and distorted version of a binary PAM signal: it applies a matched filter, performs timing synchronization (usually with a timing PLL), and produces *bit decisions*. This is why data sheets for bit syncs usually included bit error probability curves comparing the bit error probability of the bit sync output to "theory" (the mathematical expression for the probability of bit error for binary PAM in the additive white Gaussian noise environment).

The bit decisions are mapped onto a waveform pulse and a clock is synthesized from the timing synchronizer. An example of the bit synchronizer output using NRZ-L is shown in Figure 6 (b). In theory any waveform pulse may be used. The two most common in aeronautical mobile telemetry are the NRZ-L and bi-phase pulses.

Recording PCM/FM to magnetic tape presented some challenges. Because magnetic tapes do not have a DC response, the video output of the RF FM demodulator was not always recorded directly to magnetic tape. The work-arounds to this problem included the following.

[3]"PAM" in the sense used here refers to the case where only two amplitudes, say $-A$ and $+A$, for the pulses are possible. Hence the name "*binary* PAM." Binary PAM is the baseband version of BPSK. This is different from "PAM" in PAM/FM or PAM/FM/FM systems where the amplitude can attain any value in an infinite continuum of values.

1. The final IF stage in the receiver was heterodyned to the center of the magnetic tape pass band and recorded to magnetic tape [14, 15]. This signal was labeled "tape out" on many RF FM demodulators [1, 10, 16]. The useable bandwidth of the magnetic tape tended to be the limiting factor.
2. The "bi-phase" (also called "Manchester") pulse was used in place of the NRZ-L pulse. Because the bi-phase pulse has a zero DC component, the video output could be recorded directly to magnetic tape [17]. But because the bi-phase pulse has twice the bandwidth of the NRZ-L pulse, this solution also suffered from bandwidth limitations [15, 17].
3. The statistics of randomized (later encrypted) data tends to a sequence of independent and equally probable bits. When a bit sequence with these statistics are mapped to the NRZ-L pulse, the DC component is zero. This allowed direct recording of the video output [15].

The two lines connecting the RF FM demodulator in Figure 1 represent the practice of recording either a heterodyned IF signal or the video output of the RF FM demodulator.

The systems shown in Figures 1, 3, 4, and 5 have many similarities. This is not by accident. Given the long life times of most programs, test ranges through the 1960s and into the 1990s needed to maintain the capability to accommodate a variety of different multiplexing techniques. As one example, the Eastern Range documented in 1967 its capability to support PCM/FM, FM/FM, PAM/FM/FM, PDM/FM/FM, PCM/PM/PM,[4] PCM/FM/PM,[4] and SS/FM[4] [19]. For this reason, range architectures that exploited the common features of the multiplexing/modulation possibilities were the most cost effective. The naming convention reflects this point of view.

The advanced range telemetry program (ARTM) [20] was launched in 1997 in response to federal auctions of telemetry spectrum to commercial uses [21]. One of the primary goals was to adopt more bandwidth efficient modulations. At this time, most (but not quite all) telemetry systems were based on multiplexed PCM. Consequently, the search was restricted to *digital modulations*. This distinction was profound because there is a fundamental difference between analog modulation and digital modulation. For analog modulation (primarily AM, FM, and PM), the process of recovering the modulating signal from the carrier is properly called *demodulation*: the (noisy version of) the amplitude, instantaneous frequency, or instantaneous phase is produced from the received signal for AM, FM, and PM, respectively. For digital modulation the process is to decide if a "1" or a "0" was sent (in the case of binary modulation). This process is properly called *detection*. Demodulation and detection are different. Often, detection does not require demodulation in the sense it is used here.

The ARTM program produced two new modulations that are now described in IRIG 106: SOQPSK-TG and ARTM CPM [7]. Because these modulations were conceived as strictly digital modulations, the market place has only ever produced *detectors* (not *demodulators*) for them. Because detection uses symbol-synchronized samples of detection filter outputs to make bit decisions, bit decisions and timing synchronization are embedded directly in the detection process. For this reason, the clock signal is produced along with the bit decisions in the detector.

An interesting byproduct of the search for bandwidth efficient digital modulations was the reinterpretation of PCM/FM as the special case of a digital modulation known as continuous phase modulation (CPM) [22]. Readers unfamiliar with CPM may consult [23–26]. The result of this

[4] PM is the acronym for phase modulation. PM is closely related to FM in that both are constant amplitude and carry the modulating signal in the instantaneous phase of carrier. The SS in SS/FM is single side band AM. SS/FM was used to support testing of the NASA's Saturn rocket program [18].

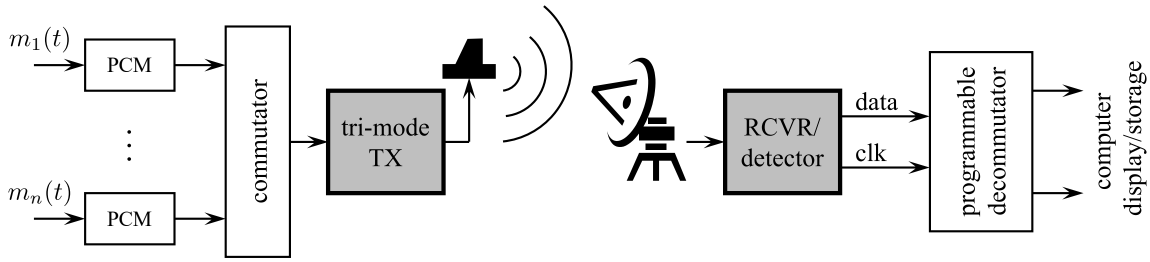

Figure 7: The current state of the art in PCM-based multiplexing and digital modulation.

interpretation was a new detection technique that improved the detection efficiency of PCM/FM by 2 to 3 dB relative to the legacy approach involving an FM demodulator and a bit sync [22].

The current state of the art for multiplexing and modulation/detection is illustrated in Figure 7. Most telemetry transmitters are capable of producing PCM/FM, SOQPSK-TG, or ARTM CPM (hence, the term "tri-mode"). The ground station is equipped with a (tri-mode) detector instead of an FM demodulator. The detector output comprises data and clock signals for the reasons described above. Because the modern detectors are not demodulators, **no bit sync is required**. The modern detector outputs everything the programmable decommutator needs.

The following points summarize the history:

1. Advances in technology allowed telemetry systems to transition from frequency division multiplexing (e.g., FM/FM), to time division multiplexing (e.g., PAM/FM, PDM/FM, PAM/FM/FM) to fully digital time division multiplexing in the form of PCM/FM.
2. The transition was rarely linear and orderly. The introduction of new techniques overlapped previous techniques. The overlap forced most ranges to support multiple multiplexing standards.
3. The most economical way to support multiple multiplexing standards was to leverage the commonalities between them. For this reason, the multiplexing standards were conceptualized as "multiplex/FM" to focus on the common features of each approach. The common features are highlighted by the gray blocks in Figures 1, 3, 4, and 5. Ground stations supported multiple multiplexing standards by the equipment connected to the output of the FM demodulator. *The combination of the bit sync and the programmable (digital) decommutator in Figure 5 replaced the bank of bandpass filters and FM demodulators in FM/FM systems shown in Figure 1, the analog decommutator and bank of lowpass filters in PAM/FM and PDM/FM systems shown in Figure 3, and the filter banks, FM demodulators, and analog decommutators (and their filter banks) in PAM/FM/FM systems shown in Figure 4.*
4. By the conclusion of the ARTM program, more bandwidth efficient digital modulations were adopted in IRIG 106. Along the way, PCM/FM was reinterpreted as a digital CPM. Because the detectors for these three derived timing synchronization as part of the detection process, the bit decisions and their corresponding clock are produced by the detectors. This eliminated the need for stand-alone bit syncs attached to the receiver/detector.

THE BIT SYNC QUESTION

From the discussion in the previous section, it is easy to conclude that bit syncs are now obsolete. This is not quite true. What is true is the use of bit syncs is not as prevalent as it once was. Some examples of current bit sync use include the following:

1. An FM demodulator is used as the first detection stage for PCM/FM. This is not recommended for IRIG-106-compliant PCM/FM because there are better detection strategies [22]. For non-IRIG-106-compliant PCM/FM (usually because the FM deviation is greater than 0.35 times the bit rate), the FM demodulator is the only practical option available at most ranges.
2. To reproduce the clock from data in the case where only the data is available at the source but a data sink requires both data and clock. An important example is the case where a data-only source needs to be connected to a decryptor. At least one test range has a patch panel that outputs only the data signal of its data/clock input pairs. Why the patch panel was designed this way is lost to memory. Curiously, the authors have received reports of a practice where only the data output of a receiver/detector equipped with *both* data and clock is connected to a bit sync to generate the clock signal. The reason for ignoring the clock output from the receiver/detector in favor of one *reproduced* by an external bit sync is not clear.
3. To distribute multiple copies of data and clock from a single source to multiple sinks. A distribution amplifier could also be used. But because bit syncs are readily available, they are often used for this purpose.
4. To change the waveform, say from bi-phase to NRZ-L. This functionality is used in the case where a source produces data and clock with one waveform, but the sink requires a different waveform.
5. To change the phase of the clock relative to the data, say from bit transitions on the rising edge of the clock to the falling edge of the clock.
6. To convert the data signal level from TTL data and clock to RS-422.
7. Because bit syncs have built-in randomizers and derandomizers, bit syncs are used to randomize an un-randomized data source or derandomize a randomized data source.

All but one of the applications in the previous list deal with moving telemetry data on the ground. Ground transport involves the movement of telemetry data from one device to another in the telemetry ground station as well as transport to the telemetry data processor for processing and display. Frequently encountered problems include data inversion and improper phasing of the clock to the data. Most of the time, these problems can be traced to improper settings on one or more of the bit syncs in the transport chain. In these situations, the bit syncs are functioning exactly as they were designed; the problem is improper selection of the bit sync options—the number of options can bewilder a young telemetry engineer new to the task.

The ongoing migration *from* TTL level data and clock *to* IP-based networks will have a profound impact on the use of bit syncs for the movement of data on the ground. Following the rest of the network world, test ranges use IP-based networks to move data for both inter-range and intra-range applications. The IP-based standard for moving telemetry data over an IP network is IRIG 218 Telemetry Over Internet Protocol (or TMoIP) [27]. Standardization is extremely important because TMoIP hardware from different manufacturers must interoperate.

An example of a TMoIP network is the connection between the RF receiver/detector in a ground station and the front-end telemetry data processor (TDP) for processing and display of the telemetry data. As of this writing, the most common output formats from a receiver/detector are TTL-level data and clock and RS-422. The receiver/detector output format must be converted to a format more suitable for network transport. After conversion to the TMoIP format, the data are transported from the telemetry ground station to the TDP using the TMoIP network. At the front-end TDP, the TMoIP data must be converted back to TTL data and clock or RS-422.

If the TMoIP distribution of data is extended to the telemetry receiver/detector and to the front-end TDP, this would result in only packet-based data being distributed. No longer would data and clock be present anywhere along the path from the RF telemetry signal to control room display. This move to only packet-based telemetry data is occurring today. An increasing number of receiver/detector manufacturers include an ethernet output option that confroms to the TMoIP standard. When the transition to TMoIP is complete, there would seem to be little rationale for continued use of bit syncs.

CONCLUSIONS

Bit synchronizers ("bit syncs") have become the "Swiss army knife" for moving telemetry data on the ground. Their original purpose was to convert the video output of the FM demodulator in PCM/FM systems to a signal useable by a programmable decommutator (also called a digital demultiplexor). The prevalence of TTL-level data and clock in moving telemetry data from one point to another in ground stations and telemetry display centers made the bit sync an important tool. Modern receivers/detectors produce TTL-level data and clock or RS-422 as standard outputs. This development has removed the original role for bit syncs. As network-based solutions (TM over IP [27]) for moving data around become more common at test ranges, the remaining role of bit syncs (data movement) will probably diminish. To borrow a famous line from *Monty Python and the Holy Grail* [28], bit syncs are "not dead yet."

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