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A Shared Resource TDMA Approach to Increase the Rain Margin of 12/14-GHz Satellite Systems

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A method to increase the rain margin of a satellite system by as much as 10 dB is presented. The technique does not require site diversity, larger antennas, or greater satellite radiated power, all of which are quite inefficient because they represent additional system resources which are only infrequently called upon during rain attenuation events. Rather, the technique creates a small pool of time division multiple access (TDMA) time slots, shared among all earth terminals in the network, to be used only when needed by the sites experiencing rain attenuation above the power margin. Coding techniques are employed during rain events to extract additional margin from these pooled resources with little bandwidth penalty. The hardware complexity to enable TDMA operation with coding during rain events is assessed and found to be quite modest. Although the transponder data rate may be in the neighborhood of 600 Mbits/s, the decoder operates at a much lower speed by virtue of the low TDMA duty cycle associated with a given ground station.

I. INTRODUCTION

The current trend in communication satellites appears to be increasingly toward the use of the 12/14-GHz frequency bands and the use of digital modulation formats with time division multiple access (TDMA) techniques. The former provides freedom from existing 4/6-GHz terrestrial interference and also provides higher antenna gain and narrower beams for a given size aperture, while digital transmission in conjunction with TDMA provides for more efficient utilization of the available satellite system resources.

A major drawback associated with 12/14-GHz systems is the signal attenuation associated with rainfall.[1,2] In general, attenuation at these frequencies is an increasing function of rain rate, with the result that, over a large portion of the United States, significant power margin must be provided to prevent excessive outage due to rain fades. Standard techniques that might be employed to provide rain margin include (*i*) increasing the radiated power of the satellite and earth stations, (*ii*) improving the noise figure of the receivers, (*iii*) installing larger ground station antennas, and (*ii*) providing site diversity. Unfortunately, all these techniques are costly in that permanently dedicated system resources are used only infrequently, i.e., when it rains. Looking at this another way, the system has been tremendously overdesigned for the clear air conditions that might exist more than 99.9 percent of the time at any particular ground station location if, say, a 15- or 20-dB rain margin is required to achieve the desired rain outage.

A much more efficient technique to achieve the desired outage would be to reduce the rain margin to a lower (and more reasonable) value of, say, 5 to 10 dB, and provide a common pool of resources to be shared among all ground stations and allocated as needed to increase the rain margin only at those stations which might be experiencing a fade depth greater than the built-in margin. Clearly, such a shared approach cannot be applied to ground station facilities. However, the satellite resources can readily be shared among all users (demand-assigned TDMA is only one example of pooled resources). To increase the rain margin for a particular user for a short interval, we might, for example, consider providing onboard batteries to increase the radiated power of the transponder serving that user experiencing excess rain attenuation. Such an approach, however, is not very attractive because it requires dual-mode final power amplifiers and excess battery backup power, and also because the interference produced in adjacent transponders by this high power mode of operation might tend to become excessive.

In this paper, a different approach is taken to provide a pool of assignable resources used to increase the rain margin. For this scheme, the pooled resources consist of TDMA burst packet slots. Consider the downlink. In each TDMA frame, some small number of slots are reserved for use by any ground stations experiencing downlink rain attenuation. Then, for each slot occupied by a receiving ground station experiencing a fade, three or four slots would be assigned from the pool and would be used by encoding at the transmitting ground station using, for example, a rate $r = 1/3$ convolutional code. Thus, three channel symbols are created for each information symbol. These additional symbols are transmitted during the pooled time slots; there is no increase in the channel data rate. Such an approach might provide 8 to 10 dB additional fade margin with no increase in either satellite power or satellite or ground station antenna diameter. The overhead associated with the pooled reserve time slots would be about 3 percent for a system containing 100 ground terminals. Such an approach can also be used for up-link fades, but here it is more desirable to employ up-link power control, as is described later.

In Section II, the concepts of this approach are developed in greater detail, and a new interpretation of outage due to rain attenuation is developed. Section III contains a description of the modest digital hardware required at each ground station to implement this concept.

II. SHARED RESOURCE-CODING CONCEPT

The concept to be presented is equally applicable to area coverage systems,[3] fixed multiple spot beam systems,[4] and singly[5] or multiply[6,7] scannable spot beam systems. For simplicity, let us consider a single scanning spot beam system (or, more precisely, a system containing a single scanning uplink beam and a single scanning downlink beam). The satellite contains a single 500-MHz transponder. The service area is divided into N spot beam footprints, labeled F_1 through F_N, as shown in Fig. 1. Each footprint typically contains several ground stations.

Figure 2 shows a typical TDMA switching sequence performed at the satellite to interconnect the various footprints. Within each frame are dedicated time slots used to establish a two-way signaling channel between a master ground station and each remote station in the network.[8] The signaling channels are used to enable TDMA synchronization, distribute system status information, handle new requests for service, assign time slots, etc. Except for the signaling slots, all other

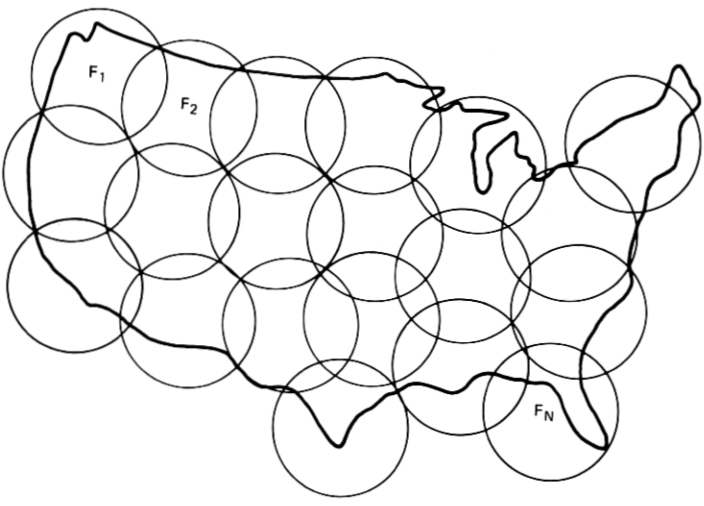

Fig. 1—A typical subdivision of the United States into N spot beam footprints labeled F_1 through F_N.

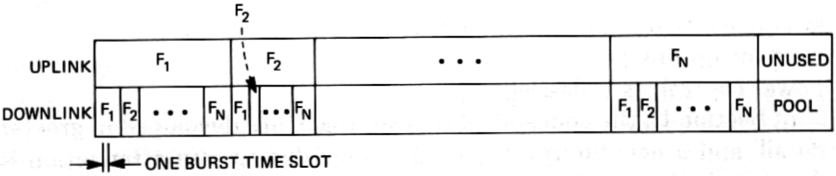

Fig. 2—Typical TDMA switching frame showing the interconnections between the N spot beam footprints and showing an unused pool of time slots.

slots can, if needed, be assigned upon demand. Also shown (at the end of the frame) is a pool of unused time slots. As will be described, these slots are to be made available to service ground stations experiencing downlink rain attenuation. For a multiple spot beam system with onboard switching,[6,7] a similar pool of unused time slots might be reserved for each transponder.

These slots can also be made available to any ground stations experiencing uplink rain attenuation. However, a more attractive means for combating uplink fades is via uplink power control. For this approach, the uplink power during rain events is adjusted such that a constant incident power is maintained at the satellite. When the rain attenuation exceeds the margin provided by the maximum ground station transmitter power, fading occurs on the uplink. Since uplink power is usually not at a premium, the maximum transmitter power can often be set to provide the desired outage. Thus, uplink power control represents a very attractive means for combating uplink loss of signal while maintaining a constant signal-to-interference ratio at the satellite (this latter concern arises with multibeam systems and also as far as coexistence with other satellite systems is concerned). A hybrid approach incorporating both shared satellite resources and uplink power control is also possible. It is the resource-limited downlink where rain attenuation presents a more serious problem.

When a downlink fade occurs, the carrier-to-noise ratio at the receiving terminal experiencing the fade is no longer sufficient to maintain the desired bit error rate. Thus, the capacity into that terminal is reduced. Suppose, for example, the rain attenuation is such that the signal level falls 8 dB below the value required to maintain a voice grade bit error rate (BER) equal to 10^{-3}. The channel error rate for Gaussian noise is then about 0.1; a lower bit error rate would result if both Gaussian noise and peak-limited interference set the error rate. The BER can still be maintained at 10^{-3} or lower if the bit interval is increased by a factor of 7 (i.e., 8 dB) via allocating seven times as much of the TDMA frame and by restructuring the receiver to accept the longer bit interval. Such an approach is unattractive, however, because not only does the longer bit interval involve a great deal of complexity at the receiver, but it also wastes valuable TDMA frame time through inefficient use of the available bandwidth.

Rather, when power measurements indicate that downlink attenuation exceeding the built-in power margin is imminent, let us use the signaling link to notify the master ground station, as well as all transmitting stations communicating with the fade site, that a fade is about to occur. Then, we borrow time slots from the reserve pool of Fig. 1 and use them as follows. Suppose that, before the fade, the fade site is using the time slot equivalent of V voice circuits. Let us borrow the equivalent of, say, 3V additional time slots from the pool, thereby providing the equivalent of 4V voice circuits into that ground station. At the originating ground station for each voice circuit, we employ a rate $r = 1/3$ convolutional code which produces three channel bits for each information bit. For both single and multiple spot beam systems, the switching sequence at the satellite is then modified via the signaling link such that each voice circuit packet is transmitted as four contiguous packets which contain the encoded channel bits (transmitted at the original full bandwidth data rate) plus an extended preamble containing 7 to 10 times the clear air number of bits required to enable carrier and clock recovery at a carrier-to-noise ratio as much as 8 to 10 dB below system margin (the bandwidth of the carrier and clock recovery circuits at the receiver are correspondingly reduced by a factor of 7 to 10). At the receiver, the entire extended burst for each voice circuit is serially detected by either a soft decision or hard decision detection device[9] and stored in a high-speed buffer. Since the duty cycle of burst arrivals is small, we read out of the buffer during the time interval between burst arrivals and process the detected channel bits by a relatively slow speed decoder to recover the original information bits.

Figure 3 shows the BER vs channel symbol-to-noise ratio (E_S/N_o) curves for (*i*) a constraint length $K = 8$, $r = 1/3$ code used in conjunction with hard-decision Viterbi decoding, and (*ii*) a $K = 4$, $r = 1/3$ code used with 3-bit soft decision decoding. Both curves assume that Gaussian noise is the only system impairment. We note that, without coding, $e_s/N_o = 7$ dB is required to provide a BER $= 10^{-3}$. Thus, the $K = 8$ code can maintain a BER $= 10^{-3}$ with 7.5 dB less power; the $K = 4$ code maintains a BER $= 10^{-3}$ with 9 dB less power. These margins generally increase if both Gaussian noise and peak-limited interference (e.g., cochannel and/or intersymbol interference) are present. Thus, by sharing a small number of TDMA slots among all users, it is possible to provide an additional 8 to 10 dB fade margin at no cost in terms of satellite power, satellite antenna gain, or earth station antenna diameter. We see from Fig. 3 that the additional fade margin provided by coding increases if the system BER threshold is reduced to a value less

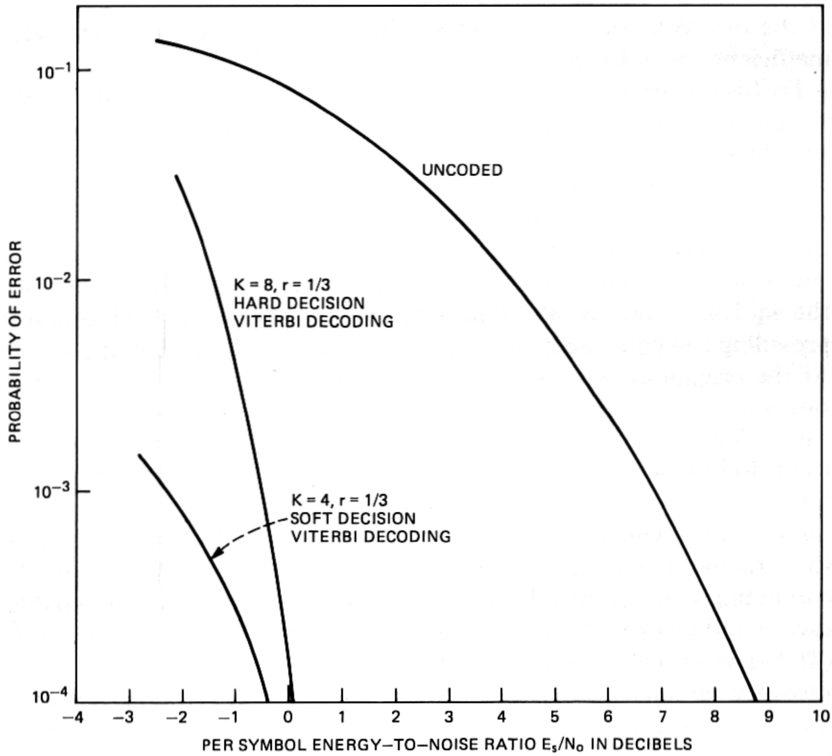

Fig. 3—BER performance for coded and uncoded transmission.

than 10^{-3}. Of course, other convolutional or block codes might be employed to achieve the same or similar results.

When the fade has passed, the extra time slots are returned to the pool to be reassigned as needed to other ground stations in the network.

The primary virtue of this approach is that a relatively small number of equivalent voice circuits can be shared among a large number of users to provide additional rain margin when needed. The additional resources are not wasted by merely retransmitted uncoded data a number of times, but rather the entire transponder bandwidth is exploited to provide additional gain through redundancy coding. Other, lower-rate codes might be used to increase the fade margin still further.

The TDMA time slots reserved for rain fades can be allocated to nonfade sites during periods of high system demand. This possibility provides for an interesting interpretation of rain outage. During clear air conditions, each ground terminal in the network presents an instantaneous demand for some number of equivalent voice circuit packets; the capacity of the satellite is, however, fixed at C two-way voice circuits. Call blockage occurs whenever the total offered load exceeds C. A ground station which uses M one-way voice circuit and experiences a fade now demands additional one-way circuits to remain operational; the number of additional circuits required increases with the fade depth, and coding is employed in an attempt to minimize the additional demand. Provided that the additional circuits are available, outage will not occur. Thus, rain attenuation can be interpreted as placing additional demands upon the voice circuit resources of the satellite, and outage is interpreted in terms of demand exceeding capacity, i.e., blocked calls. Rain outage, then, is more likely to occur during the busy hour, and would be virtually nonexistent at other times of the day.

For practical reasons, it might be desirable to limit the excess demand for voice circuits due to rain attenuation to a factor of 4 or 5 above the clear air demand. Then outage occurs when the attenuation exceeds the additional rain margin provided by these extra circuits. Thus, when designing the network, the offered traffic must be contained to a level such that the desired rain outage and call blockage probability can be achieved by the satellite capacity C. Factors affecting this design would include the rain statistics at the various sites, the built-in rain margin, the number of ground stations, the clear air Erlang load of each ground station, and the statistical dependence of rain attenuation in excess of the built-in margin at the various ground stations.

Let us examine the TDMA overhead associated with reserving time slots for rain events. Suppose that S ground stations are in the network, and a total of N one-way voice circuits are available. We reserve R of these for rain events. Thus, on the average, each station uses $(N - R)/S$ one-way circuits. The value R is determined by noting that, for each circuit into a given ground station, we need three additional circuits to provide the additional rain margin of 10 dB. We will provide a reserve pool sufficient to accommodate M simultaneous fades. We then obtain the relationship

$$3M(N - R)/S = R \Rightarrow R = 3MN/(S + 3M).$$

Thus, the TDMA inefficiency η is given by:

$$\eta = \frac{3M}{S + 3M}.$$

Thus for 100 sites and allowing for two simultaneous fades, the inefficiency or cost is under 6 percent, assuming that all ground stations carry approximately equal traffic.

If the ground stations of a satellite network exhibit large traffic imbalances, then the rain outage objective for a few high traffic ground stations might be achieved by more conventional approaches such as larger antennas or site diversity, with pooled time slots reserved for the exclusive shared usage among a large number of somewhat lower traffic ground stations. In this manner, the shared resource approach can still be applied to efficiently provide the outage objective for most of the ground terminals, without requiring a large overhead penalty to protect a small number of high traffic users.

III. IMPLEMENTATION

The equipment needed to implement the pooled resource approach to combat rain fades consists for the most part of digital electronics which operate at a rate much less than the full transponder data rate of 600 Mbits/s. The bit rate reduction is achieved by virtue of the small duty cycle TDMA mode of operation. Consider the transmit function, shown in Fig. 4a. Data arriving at a ground station are formatted for transmission via satellite and the appropriate preamble is attached. Each burst is temporarily stored in a high-speed buffer. Then, infrequently throughout the TDMA frame, the buffer is quickly read out to the modulator at a data rate of 600 Mbits/s. The timing of these events is such that the bursts from the various ground stations arrive at the satellite on a nonoverlapping basis. The receive operation, shown in Fig. 4b, is analogous. The receiver carrier and clock recovery circuits operate continuously on the incoming full bandwidth packet stream, supplying recovered carrier and clock to the demodulator and bit detector. Via the signaling links, each receiver is informed of which bursts are intended for local reception. Allowing some guard time on each side, the correct bursts are rapidly read into a cache memory; between burst arrivals, the memory is slowly offloaded for subsequent slow-speed processing.

The clear air burst packet structure is shown in Fig. 5. Each burst consists of six fields containing the following information:[10]

(1) Carrier and clock recovery preamble.
(2) Unique word signifying start of burst.
(3) Destination code.
(4) Source code.
(5) Identification of signaling or data burst.
(6) Text or signaling data.

Fields 1 to 5 collectively contain 67 bauds, and field 6 contains 400 bauds. Modulation is 4ϕ-CPSK.

The function of each field is elaborated upon in Ref. 10. For now, we describe the modification needed to assemble extended rain attenuation bursts. By using the $K = 8$, $r = 1/3$ code of the previous section, the system must be capable of operation at channel error rates as high as 0.1 to provide 7.5 dB of extra rain margin. The extended burst also is divided into six fields, each serving the same function as before.

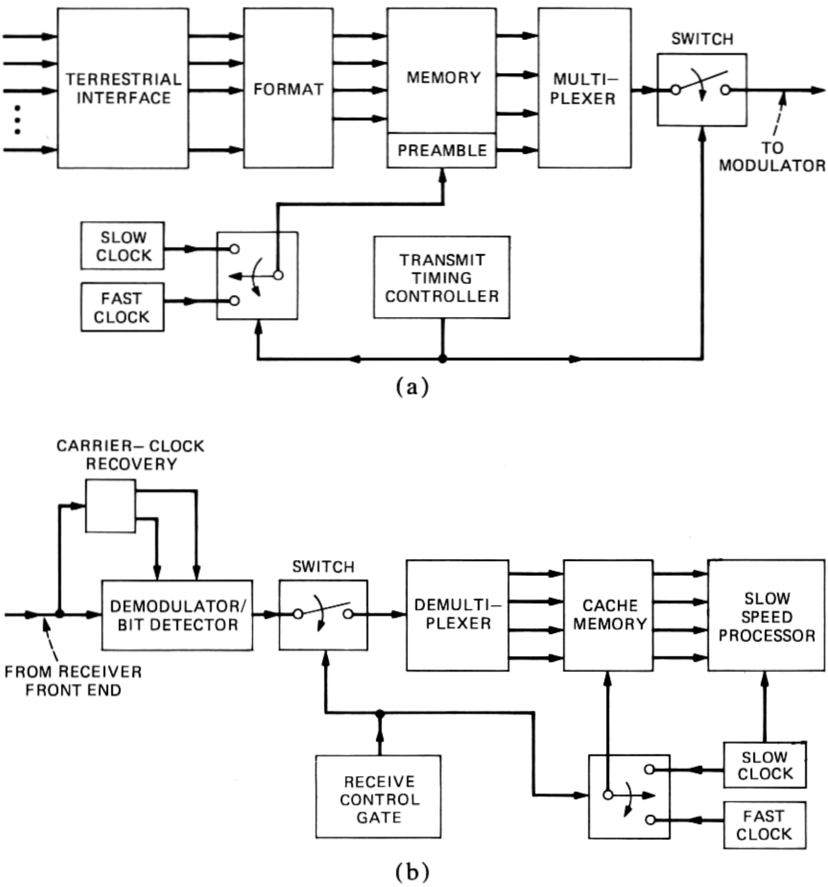

Fig. 4—Essentials of TDMA burst modem data processing. (a) Transmit function. (b) Receive function.

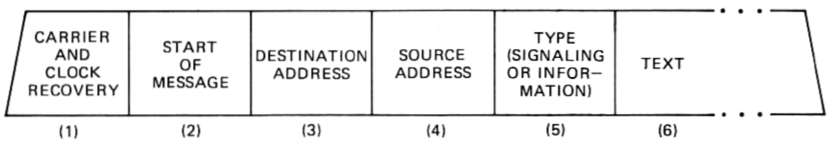

Fig. 5—TDMA burst structure.

However, field 1 must be extended by a factor of 6 to provide the same accuracy of carrier and clock recovery. This represents about 200 bauds. Also, the start-of-burst unique word must be extended to enable identification under degraded channel conditions. Discussion of this unique word extension and processing will be deferred until later. The data of fields 3 through 6 are transmitted in coded form. Encoding for the $K = 8$, $r = 1/3$ code appears in Fig. 6a, and that for the $K = 4$, $r = 1/3$ code appears in Fig. 6b. Data are read into the shift register one bit at a time; each time a shift occurs, three encoded bits are produced at the outputs of the modulo-2 adders. These encoded bits are augmented by the preamble and start-of-burst unique word, and the entire assembled burst is stored in a buffer awaiting transmission onto the channel. The length of the buffer is about 4000 bits, to be compared against about 1000 bits for clear air bursts.

At the receiver, carrier and clock recovery, demodulation, and bit-

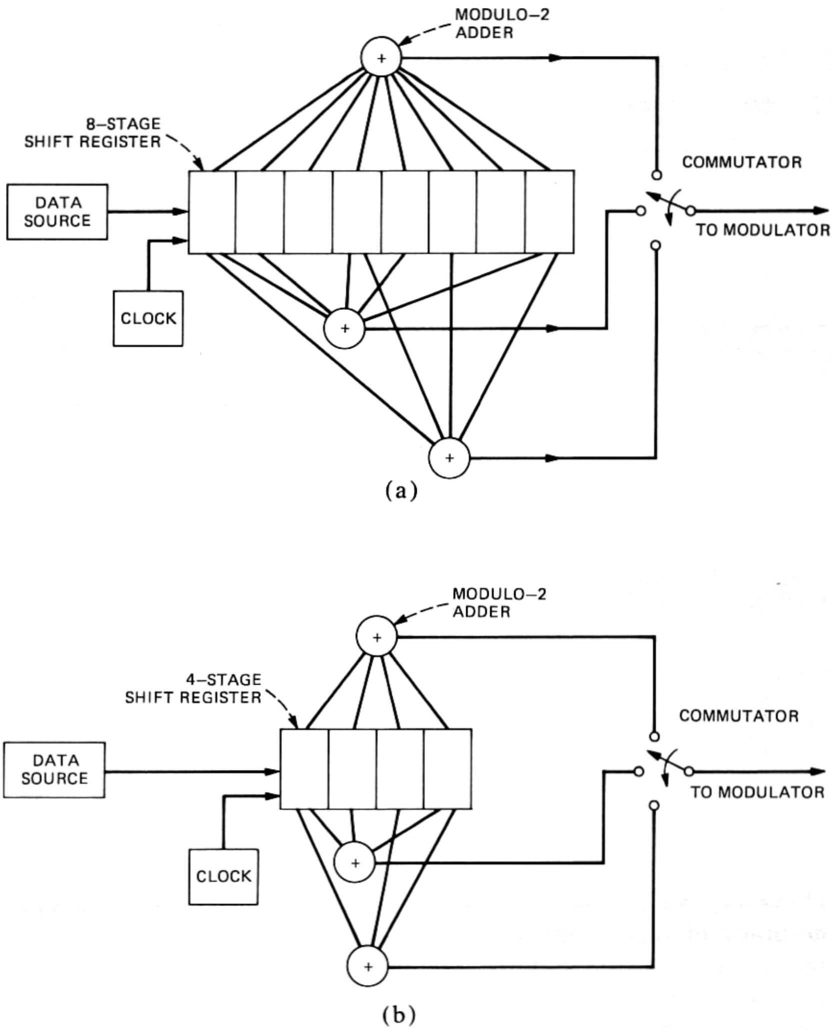

Fig. 6.—Convolutional encoders. (a) $K = 8$, $r = 1/3$ encoder. (b) $K = 4$, $r = 1/3$ encoder.

by-bit detection (either hard-quantized or soft-quantized) are performed as shown in Fig. 4b. Upon command of the timing circuitry (see Ref. 10 for details), a window is opened to seize only intended bursts. Fields 2 through 6 of the burst are demultiplexed into perhaps eight parallel rails for storage in a cache memory. The size of this memory is about 4000 bits for hard decisions and about 12,000 bits for 3-bit soft decisions. Between burst arrivals, a relatively slow-speed unique word processor, shown in Fig. 7, locates the beginning of intelligible data; only the sign bit of soft decision 3-bit words is used for this function. The processor consists of a digital correlator followed by a comparator which compares the number of coincidences between the contents of the correlator and the known unique word bit pattern against some preset threshold. The length of the unique word and the threshold (required number of coincidences) are such that reliable detection is possible on a degraded channel. For example, suppose the channel error rate is 0.1, there are 50 bits in the unique word, and we require 30 or more coincidences. Then the probability of missing the start-of-burst unique word is about 4×10^{-9}.

Having identified the start-of-burst sequence, the remainder of the cache memory is slowly read to the Viterbi decoder. The principles of Viterbi decoding are well known,[11] and the required operations will be only briefly described here. For simplicity, we consider the $K = 3$, $r = ½$ code shown in Fig. 8a. The decoder is segmented into $2^{K-1} = 4$ states, corresponding to the four possible contents of the initial two states of the shift register. Upon entry of a new data bit into the encoder, permissible state transitions, and the corresponding channel

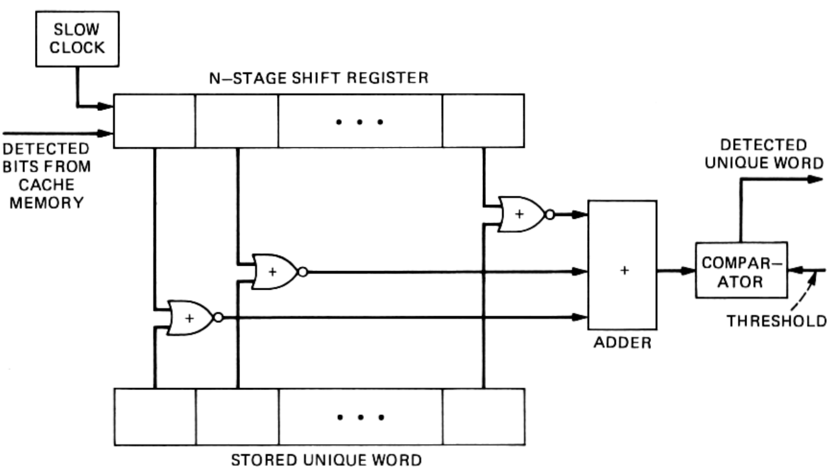

Fig. 7—Standard correlator to detect occurrence of a unique word. Detection occurs whenever the contents of the shift register agree with the unique word above a value set by the threshold.

bits generated, are as shown in Fig. 8b. Decoding is in accordance with Fig. 8c. The decoder must correlate the two received words with the channel bits generated for each possible transition, add the appropriate correlation to a metric representing the likelihood of each initial state, and choose which of two merging paths for each state is most likely. The metric of the surviving path for each state is retained and becomes the initial metric for subsequent calculations. Also stored are the surviving paths into each state, to a depth of four or five constraint lengths (about 40 bits for a $K = 8$ code). Thus, to implement hard-decision Viterbi decoding for the $K = 8$, $r = 1/3$ code, an add-compare-store module to operate on the one-bit received words and a 40-bit memory must be provided for each state. For soft-decision decoding, the add function consists of adding three 3-bit words (appropriately weighted by ±1) to the old metric (perhaps a 5-bit word); the compar-

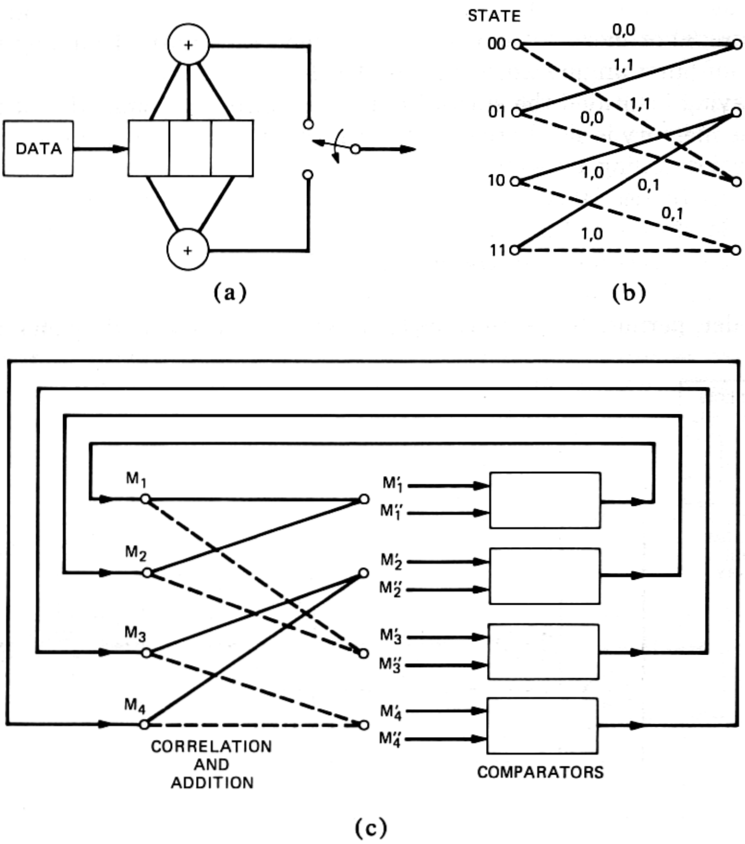

Fig. 8—Viterbi decoding for $K = 3$, $r = 1/2$ convolutional code. (a) $K = 3$, $r = 1/2$ encoder. (b) State transition diagram and generated channel symbols. (c) Decoder path metric update.

ison is between two 5-bit words, and the storage is a 5-bit word. For the $K = 8$ code, 128 such add-select-store modules, each operating upon 1-bit data, must be provided; for the $K = 4$ code, this number is reduced to 8 modules, but arithmetic operations must be performed upon multibit words. Thus, Viterbi decoding can be accomplished with about one to three cards of digital electronics.

For the TDMA mode envisioned here, each burst will start with the encoder initially in the all-zeros state, and $K - 1$ zero bits will be stuffed into the encoder after the final data bit; the overhead is small (21 channel bits out of about 4000 for the $K = 8$ code), and ambiguity is prevented at the decoder.

The operating speed of the Viterbi decoder is readily estimated by dividing the satellite transponder data rate by the number of ground terminals; this is an estimate of the average bit rate to a given user. Thus, for a 600-Mbit/s transponder and for 100 users, the required decoding speed is on the order of 6 Mbits/s. TTL decoders which can operate at rates up to 10 Mbits/s are readily available. High rates are also possible with TTL; alternatively, ECL decoders at speeds up to 50 Mbits/s are possible. Another option for increasing the data rate, if necessary, might be to parallel several low-speed decoders.

To maintain frame synchronization during rain attenuation conditions, a second, extended frame marker is inserted into each frame marker burst. Recalling that the initial, short frame marker was provided only to enable rapid acquisition during clear-air conditions, we can readily use the second, extended frame marker to maintain synchronization after initial acquisition. The function of the second frame marker is analogous to the extended start-of-burst word described earlier, namely, to permit identification via a slow-speed, correlation threshold as depicted in Fig. 7. Since the entire frame marker burst is stored in cache memory, we can slowly read from this memory into the correlator to find the frame marker. Then, by counting the number of elapsed bits until the frame marker is encountered, we can maintain frame synchronization.

IV. CONCLUSION

A shared-resource TDMA approach to increase the downlink rain margin of a 12/14-GHz digital satellite system by as much as 10 dB was described. The motivation for such an approach is the observation that dedicated resources (higher transmitter power, larger antennas, etc.) are a costly means for increasing rain margin since, during the overwhelming clear-air fraction of time, the system would be tremendously overdesigned. By contrast, we can view the TDMA resources of the satellite as representing a common pool of resources which can be dynamically assigned as needed to increase the rain margin at only those sites where they are instantaneously needed. By assigning additional TDMA packets to sites experiencing excessive rainfall and using coding to efficiently utilize the additional bandwidth (time slots) so made available, we can increase the fade margin by as much as 10 dB with no increase in downlink radiated power or satellite or terrestrial antenna size.

Additional margin on the uplink is achieved by uplink power control. This is attractive since it allows constant incident power at the satellite from all users, thereby avoiding severe interference from nonfade users. Also, terrestrial power is not nearly as precious as space platform power.

The overhead associated with reserving TDMA bursts for fade conditions was shown to vary with the number of ground stations served. If we wish to reserve sufficient resources to provide 10 dB extra fade margin simultaneously at two sites, then the overhead is about 1.2 percent for a network containing 500 sites and about 6 percent for a network containing 100 sites. It is not, however, necessary to reserve these slots; rather, during peak demand periods, all resources can be assigned if needed, but the additional fade margin is lost. During nonpeak hours, excess capacity is available and fade margin can be provided.

The additional hardware needed to implement this approach is mostly digital electronics and consists of a convolutional encoder at each ground station and a decoder at those ground stations expected to require additional rain margin. The decoder operates at data rates much lower than the transponder bit rate, since desired bursts arrive at a low duty cycle and are buffered; between bursts, the decoder can slowly read from the buffer and process the data. The decoding speed might be as high as 20 Mbits/s for a 20-ground-station network, or as low as 1 Mbits/s for a 600-ground-station network. Such decoders are readily available using TTL logic; if higher rates are required, two or more decoders can be operated in parallel, or a faster decoder using ECL can be used.

In addition, a quite modest amount of digital hardware is needed to maintain frame synchronization, identify start of burst indicators, and provide recovered clock and carrier. The cost of the additional electronics is by far smaller than the cost associated with either antennas exhibiting 10 dB more gain or satellites with 10-dB more radiated power.

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