transmission errors, to serve as a form of registration.[12] When a user does not acknowledge within a zone during its assigned time slot (because the user has moved), the packet is retransmitted on a nationwide basis. The user terminal then will send an acknowledgment from its new location and the zonal location information in the control center will be updated. Subsequent packets, even for parts of the same message, thus are directed to the correct zone.

D. Forward Channel Transmission Protocol

Although subject to revision due to results derived from Mtel's field testing, Mtel currently envisions a protocol based on a forward/reverse cycle where the forward subcycle follows the format below:

Name	Bits	Function
PREAMBLE	128	Time margin and bit synchronization
SYNC	24	Word synchronization
$SYSTEM_1$	768	System packet no. 1
$SYSTEM_2$	768	System packet no. 2
$BATCH_1$	vbl	Packet batch no. 1
:	:	:
$BATCH_{64}$	vbl	Packet batch no. 64

Each packet batch follows the following format:

[12] Use of different registration schemes for certain applications, or even certain customers, may be more spectrally efficient.

Name	Bits	Function
SYNC	24	Word synchronization 1
SYNC	24	Word synchronization 2
$CALL_1$	768	Roll Call 1
:	:	
$CALL_i$	768	Roll Call i
$PACKET_1$	768	Packet no. 1
:	:	:
$PACKET_k$	768	Packet no. k

Each packet batch is intended for one of 64 groups of user terminals, which are classified by the 6 most significant bits in the terminal's address.[13] The number of packets in each batch is variable, and is dynamically assigned based upon real time loading considerations. Any particular terminal can ascertain when the batch assigned to its address will be provided by decoding the system packets at the beginning of each cycle (see Figure A4). These system packets contain a total information content of 1,008 bits, with the first 715 bits containing 65 11-bit offsets used by terminals to calculate the beginning and end of any particular batch. Remaining bits are used for universal time information and other system overhead.

Error checking is performed on each packet.[14] Mtel plans on interleaving 24

[13] By way of comparison, POCSAG uses 8 groups of pagers, ERMES uses 16 groups, and both use fixed batch durations. More groups allow shorter activity periods for longer battery life and larger address/feature range at the expense of more precise timing. Standard crystals with a stability of 10^5 can, however, handle the timing required in Mtel's proposed scheme. Variable batch length reduces the number of dummy codewords due to statistical fluctuations in traffic among groups, but requires programmable counters for timing purposes in the receivers.

[14] Mtel tentatively has determined that the use of BCH (31, 21) codes with an added parity bit will provide excellent performance in the presence of Gaussian noise and will strike a good balance between

codewords in BCH (31, 21), with an added parity bit, through the address and message information in a packet.[15] Data that are not properly acknowledged are retransmitted by the base station. Subtracting the bits used for error checking in each packet, NWN allows a total of 504 bits of data per 768 bit packet. Thus, Mtel's proposed system would involve a relatively small amount of overhead for a sophisticated error correction scheme.

The forward channel transmission scheme outlined above provides a great deal of flexibility for the system operator, while keeping user terminal costs as low as possible. The single most important factor, however, is total throughput. As previously noted, the throughput is substantial, with a multizone, 24,000 bps system supporting over 800,000 users, assuming a 13 percent busy hour call rate and 33 percent system overhead.

III. REVERSE CHANNEL TRANSMISSIONS IN MTEL'S MODEL NWN SYSTEM

NWN, as a two-way system, must allow user terminal units to originate extensive data transfers to the NWN base stations (see Figure A5). In Mtel's model system, reverse channel transmissions are picked up by a network of receivers

---

decoder complexity, the number of correctable bits, and added redundancy. Although burst errors due to impulse noise and transition through the Rayleigh fading valley are incorrectable by BCH (31, 21), Mtel proposes to alleviate these problems by bit interleaving.

[15] For comparison purposes, POCSAG has no bit interleaving, and ERMES protects only message bits with interleaving.

positioned to provide continuous coverage -- a network necessarily more densely arranged than the high power forward channel transmitter array. The reverse channel traffic is synchronized to the forward channel; *i.e.*, all time offsets are determined with reference to the cycle start of the forward channel. Two types of intervals are used on the reverse channel: (1) contention intervals when user terminals can initiate communications[16] and (2) deterministic intervals when user terminals responses are precisely scheduled. Specific, innovative protocols are designed for each type of interval.

A. Deterministic Interval Protocol

Most data traffic on the reverse channel occur through solicited responses, scheduled by NWN computers, with time slots assigned to user terminals over the forward channel (see Figure A6). Response time slots can be assigned as nationwide or zonal. Nationwide slots are used primarily to pass an initial packet to a user terminal that does not acknowledge a zonal packet or a user terminal located in the interference area between two zones. Since the location of most user terminals is known, zonal slots are assigned simultaneously to a number of user terminals in such a manner that no data collisions at any network receiver will occur. In other words, the same slot can be assigned to stations with mutually exclusive lists of adjacent receivers.

---

[16] A traditional polling concept will not be employed. Thus, no message will be sent on the forward channel unless a response is, in fact, to be solicited. The system will not canvas all user terminals asking if there is traffic to be transmitted.

This algorithm provides two important features to NWN:

- The network, transparently to the user, can automatically find a station which has moved from its last recorded position.
- Very high capacity is achieved on the reverse channel due to independent data reception on a number of network receivers, allowing Mtel to employ a simple modulation scheme (phase shift keying) with powerful error correction operating at only 9,600 bps (as compared to 18,000 to 24,000 bps on the forward channel).

Again, the complexity of scheduling will grow with an increase in traffic, and Mtel will continue to improve the scheduling algorithm and the processing speed of the network computers to meet demand.

B. Contention Interval Protocol

The network will accommodate traffic initiated by the user terminals. This traffic will consist of brief messages of fixed duration, including:

- Message priority.
- Request for a number of time slots on the reverse channel for a data transfer.

The contention interval is subdivided into slots, and is demand oriented. The contention protocol likely will either be a pure "slotted Aloha," providing a Poisson distribution of number of attempts to successful attempts, or an optimized derivative

using a tree or stack structure. Distribution of addresses to customers across the country will be accomplished in a manner designed to minimize collisions.

* * * *

By combining a number of innovative advances in communications technology, NWN has the ability to satisfy a substantial demand for digital two-way communications in a modest allocation. In Mtel's model NWN system, the forward and reverse channels each have been optimized to provide fast, reliable communications for low cost terminal units. Largely, the efficiencies achieved by Mtel are the result of three interrelated factors: precise system synchronization, nationwide operation, and extensive network computing power. Without precise synchronization, throughput would deteriorate as users compete to transmit, terminal battery life would decline as users monitor and decode all transmissions, and reliability would be harmed by lost acknowledgments. Without nationwide operation, certainty of locating terminals would be lost, with commensurate effects on Mtel's ability to zone for added capacity, and system synchronization would become haphazard. These two factors, when employed in a system that utilizes a high degree of computing power, produce a synergy in operation and allow Mtel's model NWN system to achieve a commercially feasible, singularly high throughput two-way transmission service.

FIGURE A1

NWN Block Diagram

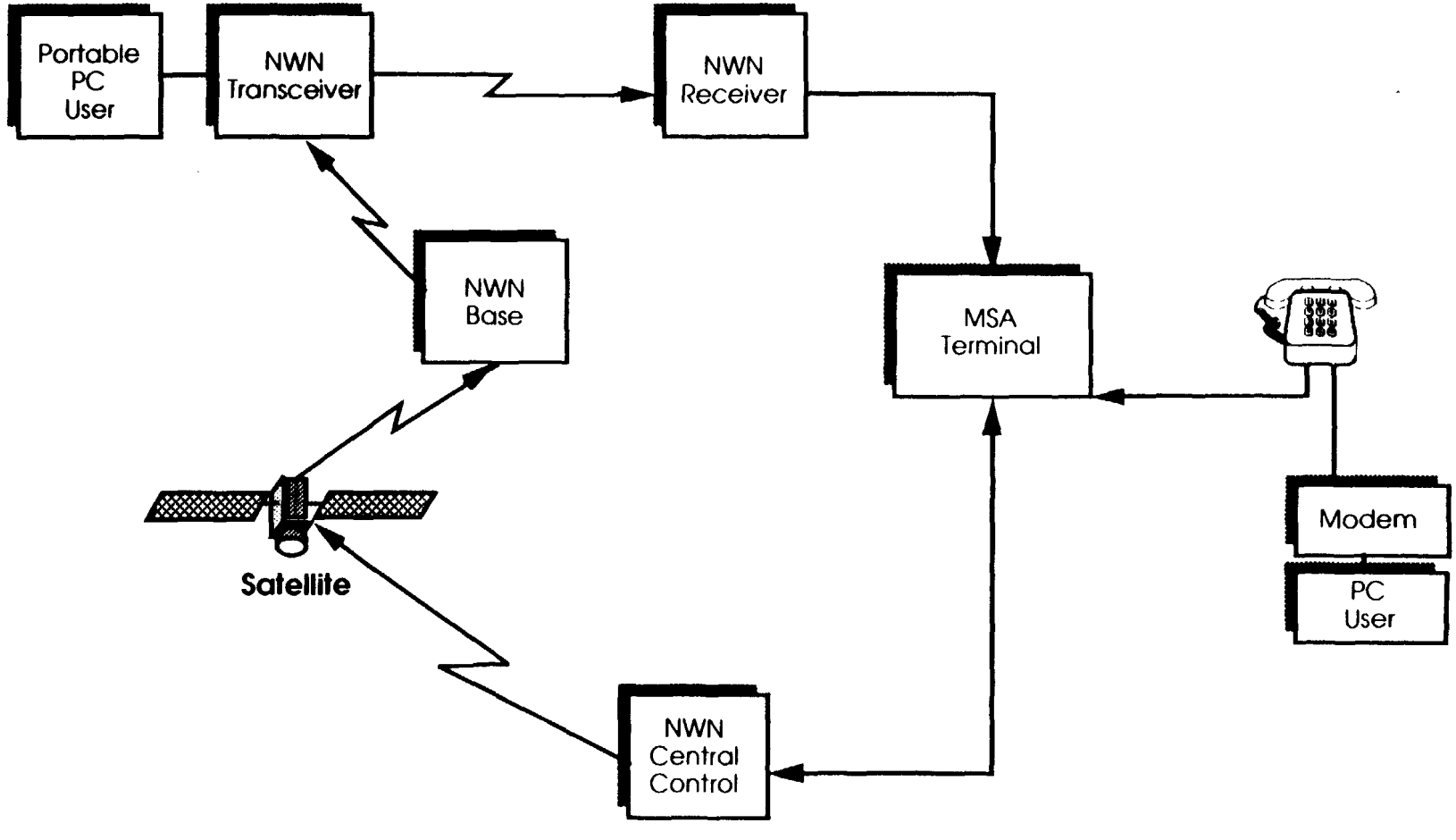

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FIGURE A2

Outbound

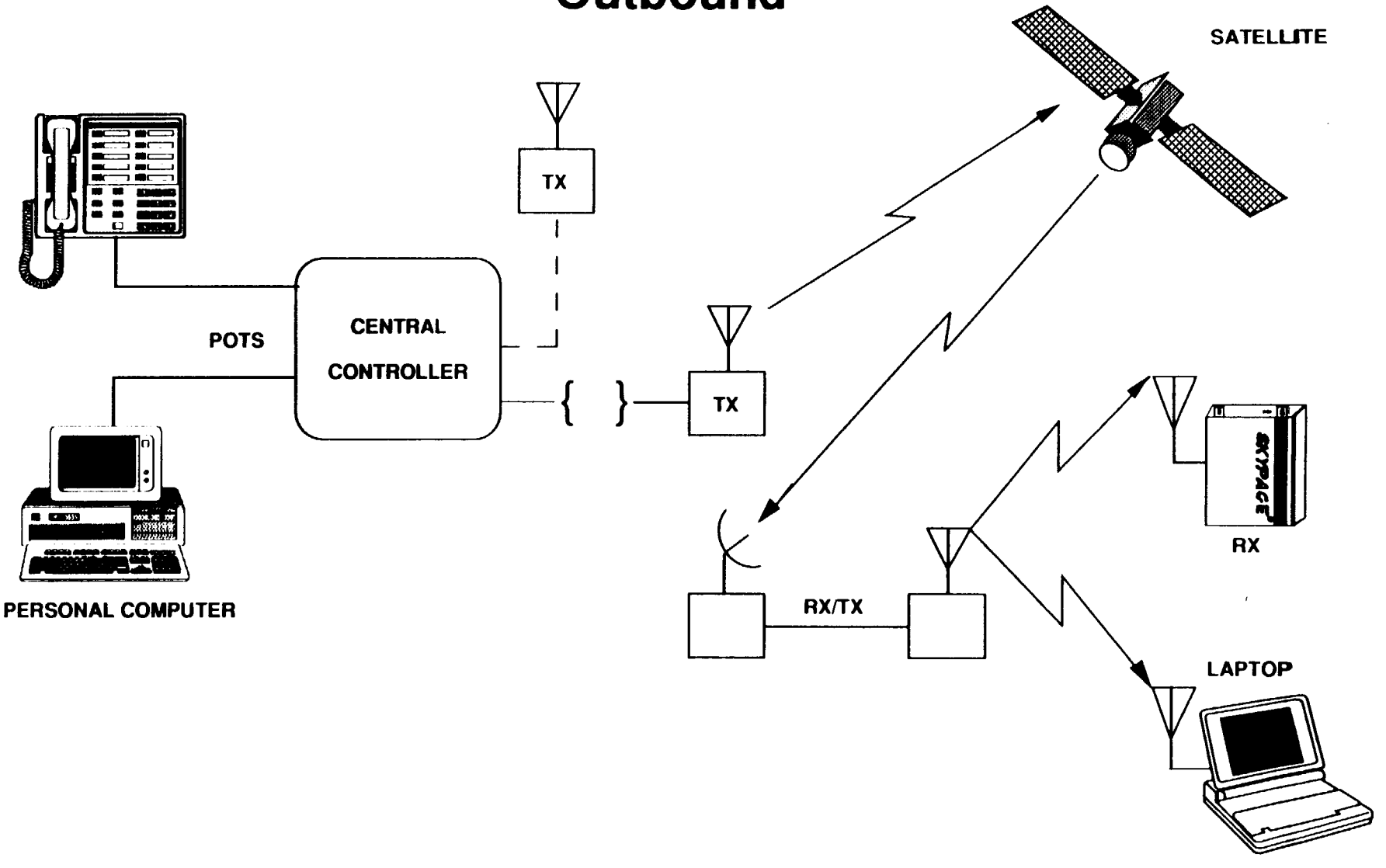

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FIGURE A3

Outbound Combined National/ Zonal Data Transmission

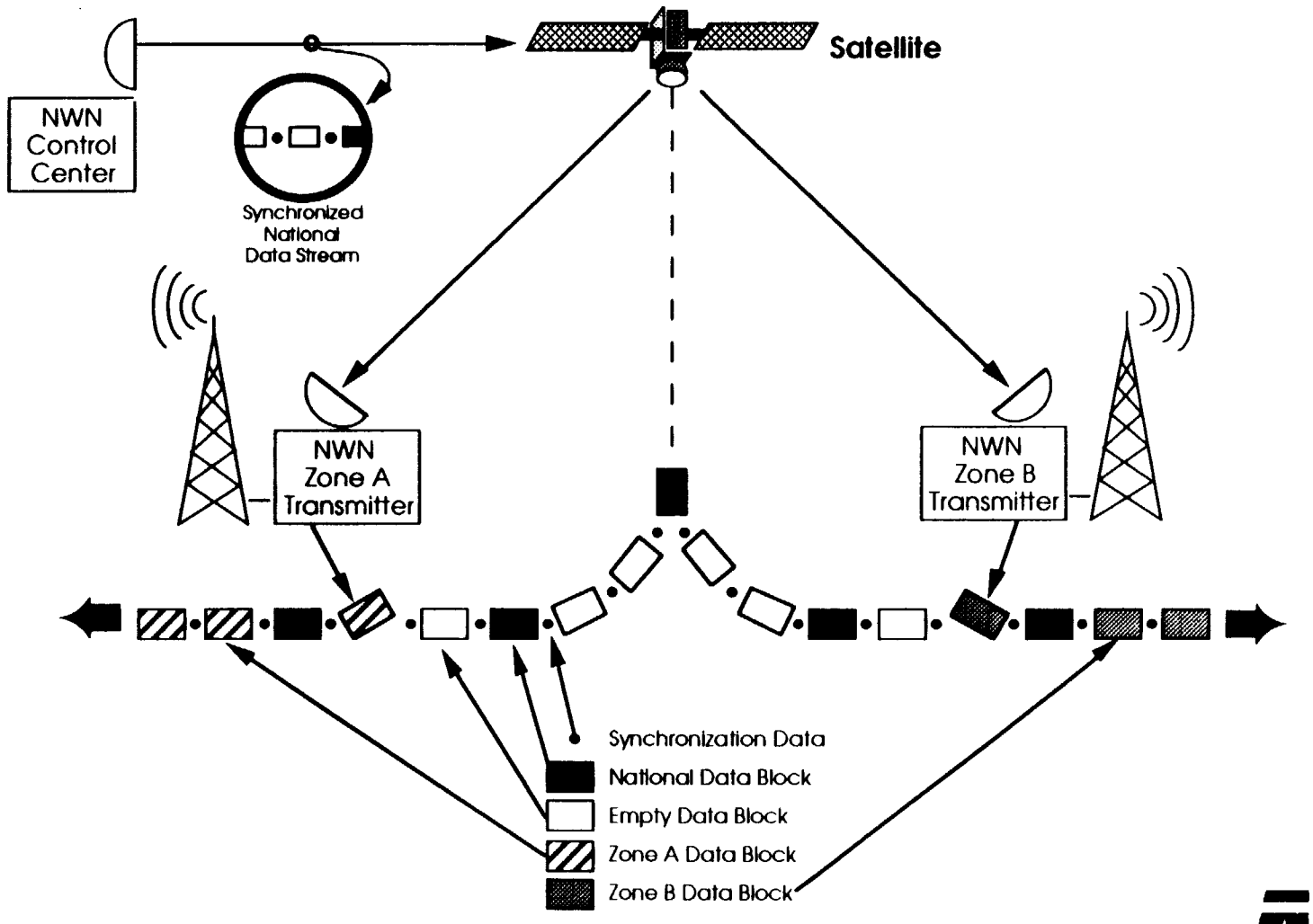

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FIGURE A4

Forward Channel NWN Transmissions

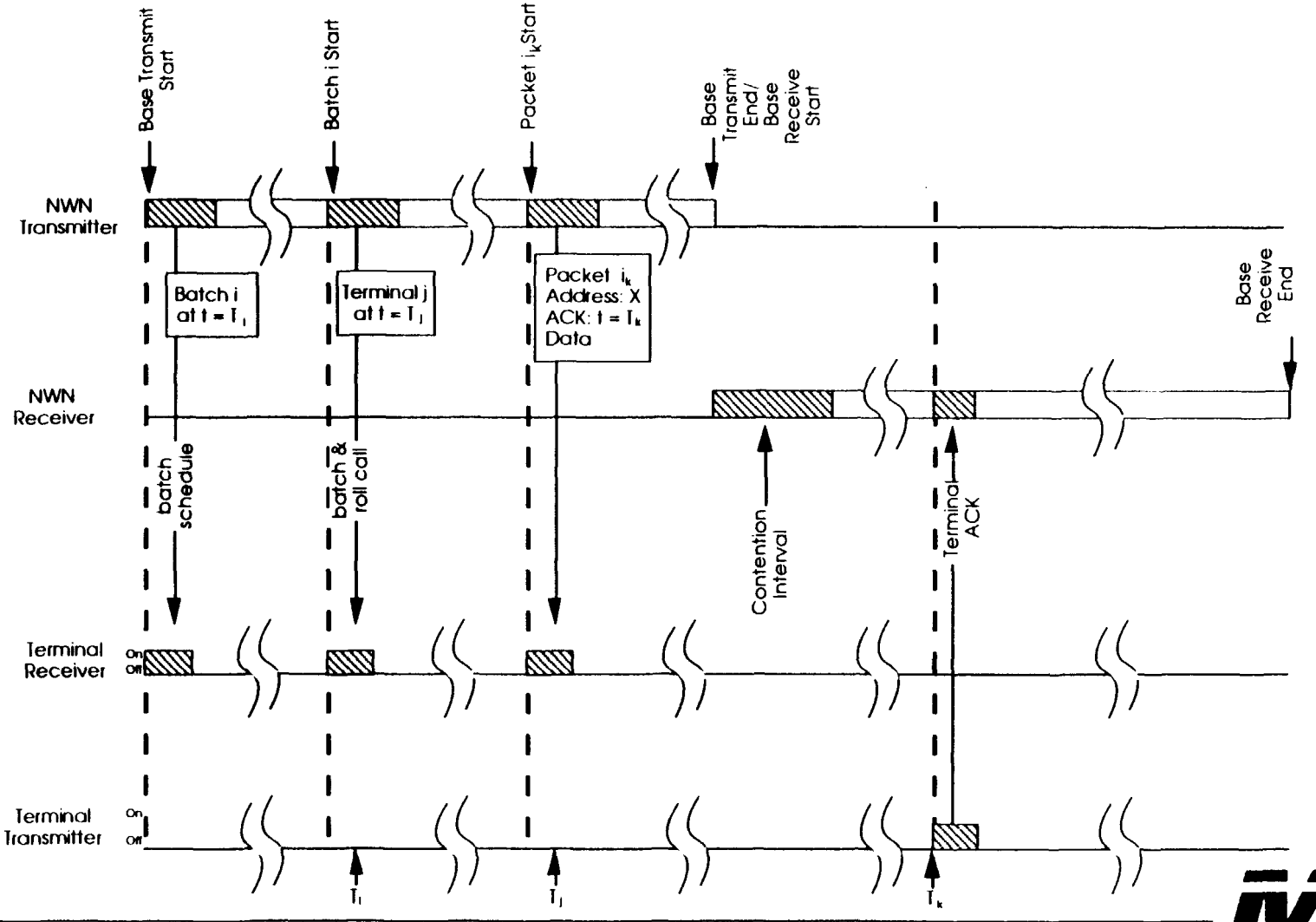

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FIGURE A5

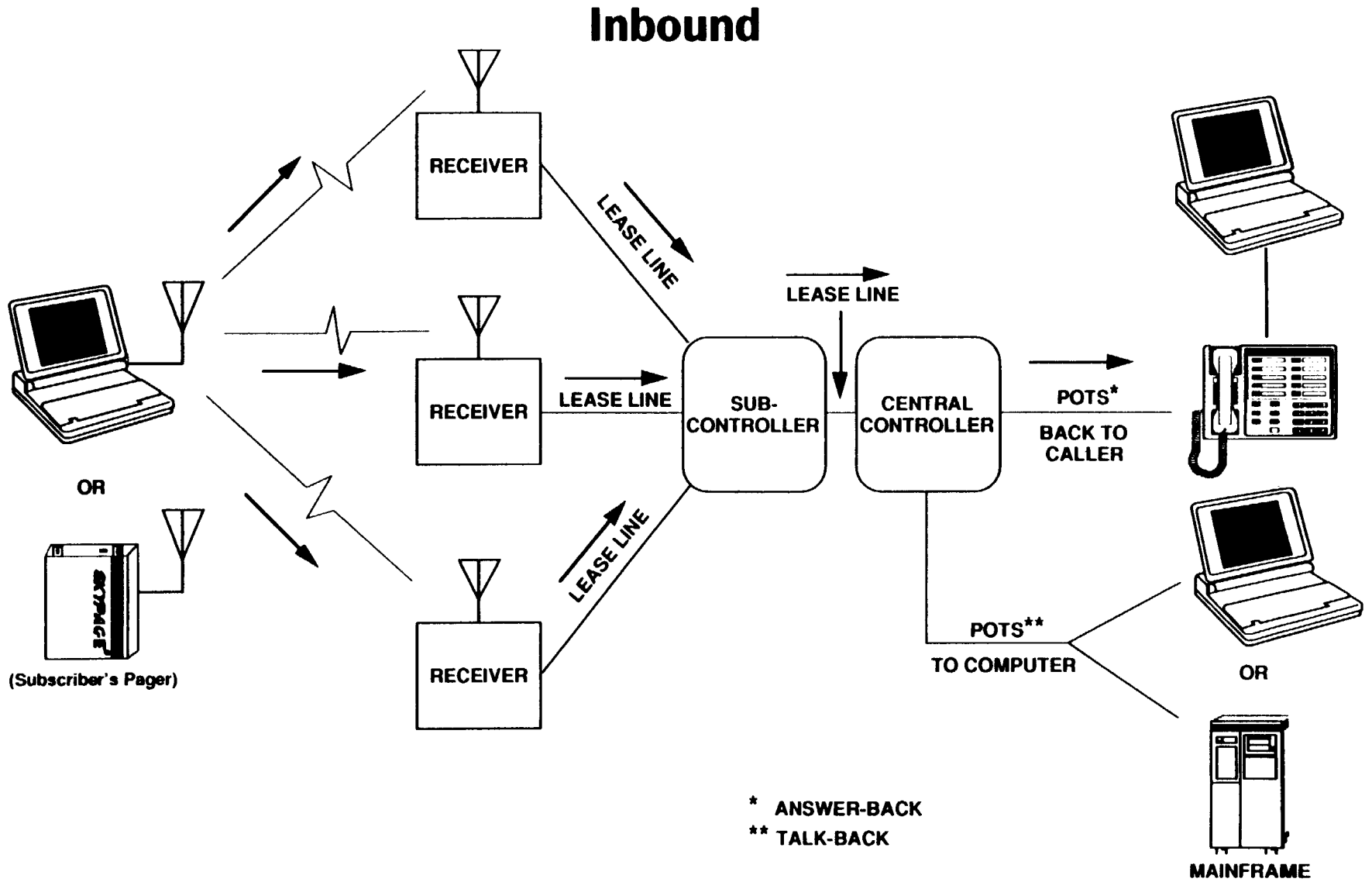

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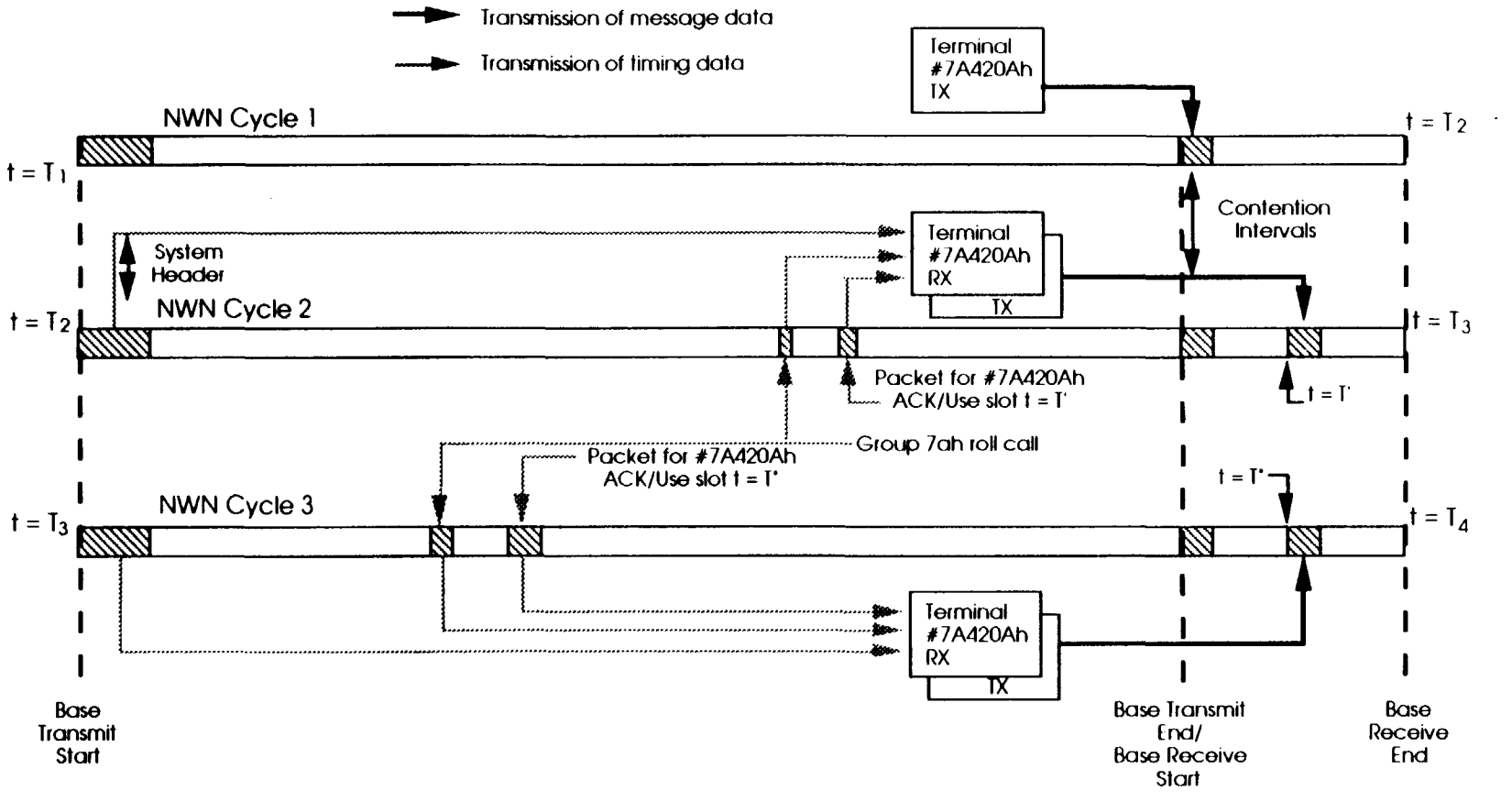
FIGURE A6

Reverse Channel NWN Transmissions



This figure shows the first three cycles of a terminal initiated data transfer from a hypothetical terminal with address 7A420Ah. For simplicity, the end of the transmit subcycle is located at the same time in each cycle. In an actual NWN system, the forward reverse time division will be dynamic.

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B

APPENDIX B

Simulcast Network Primer

Simulcast technology originally was developed to extend coverage modestly beyond that which could be obtained from a single transmitter. Over time, however, simulcasting has evolved into a technique capable of providing superior performance and continuous coverage to hundreds or thousands of square miles. It is now possible to add capacity re-use to these extended systems by exploiting current technological opportunities such as high speed time division multiplexing and satellite based synchronization.

I. TRADITIONAL SIMULCAST SYSTEMS

Classical simulcast is simple -- additional transmitters, operating on the same frequency and transmitting the same information, are positioned to cover the extended areas (see Figure B1). In some cases the "extended area" is entirely enclosed within the coverage area of another transmitter -- *e.g.*, building interiors and valleys. In regions where one (and only one) transmitter dominates (*e.g.*, regions A, B, and C in Figure B1), it is obvious that simulcast will work -- the other transmitters do not significantly affect receivers in those regions. In the overlap areas (regions D and E in Figure B1), where the signals from two or more transmitters are approximately equal, however, problems can arise.

Early simulcasting experiments appeared to confirm the dire claims of pessimists that simulcasting will never work because there is destructive as well as

constructive summing of signals in overlap regions. Destructive interference occurs when the two signals are 180 degrees out of phase and cancel each other. While there were some successes, reliable design procedures were not available.

Experiments in synchronizing the carrier frequencies of all simulcast transmitters did not help because points at which destructive summing occurred persisted for long periods. To some extent, deliberately offsetting the carrier frequencies could ensure that destructive summing did not persist, but the slight errors displayed by high quality reference oscillators (*e.g.*, 20 Hz errors in 100 MHz signals or a few parts in 10^7), rendered deliberate offsetting unnecessary. Further, merely offsetting the carrier frequencies could not guarantee acceptable quality demodulation.

II. MODERN SIMULCAST TECHNIQUES

Simulcasting entered a new era when operators finally determined that the critical element of simulcasting was synchronizing the modulating signals at the equi-signal point between the two transmitters (see Figure B2, displaying the situation at, for example, point D when modulating waveforms are synchronized).[1] The slight offset of the carrier frequencies causes a slow drift of the relative phase of the two signals. When the signals are anti-phased (*e.g.*, the third bit in Figure B2), they will cancel each other, but slight differences in the carrier frequency ensure that such a

---

[1] For simplicity, the Figures show a continuous phase binary frequency shift keying (high frequency transmitted to send a binary "zero", lower frequency to send a binary "one"), with smooth (continuous phase) transitions between frequencies. More complex frequency modulations, including analog FM, would have similar results but result in more complex pictures.

condition does not persist. Only slight deviations from anti-phasing are required to yield adequate signals if both signals are well above the noise threshold, as can be seen in the lowest graph on Figure B2. At worst, the temporary dip in the signal may cause a few errors in a digital signal, which can be counteracted with an error correcting code, or a click in an analog signal, but the modulation will be correct on either side of the anti-phase.

Slight shifts of the modulating waveform at the equi-signal point can be tolerated. Figure B3 shows a situation where the shift equals one-fourth of a baud interval. During the middle half of each baud, the two modulating signals coincide and successful demodulation can occur. During the misalignment periods, however, the summation contains an indeterminate mixture of the two modulating waveforms. If the misalignment of the modulating waveforms increases to a full baud interval (see Figure B4), successful demodulation is impossible. The periods of indeterminacy cover the entire baud interval. Empirically, Mtel has found that a misalignment of one-fourth of a baud interval is the maximum that can be tolerated without significant degradation of the demodulated signal.

The degree of modulation synchronization required appears trivial, but attaining this level in practice is considerably more complex. There are at least three sources of asynchroneity:

- timing shifts in the delivery of the modulating waveform;
- timing shifts internal to the transmitter;

- propagation anomalies.

In current commercial practice the summation of these three components results in time uncertainties of 200 microseconds, or baud rates of 1,250 baud.[2]

NWN has minimized the impact of the first two timing uncertainties by using store-and-forward transmission, distribution of synchronization signals by satellite, and meticulous transmitter design. Propagation anomalies, however, cannot be designed out of the system (see Figures B5 and B6). Figure B5 shows the ideal situation of a smooth earth where uniform attenuation of the signal strength from each transmitter occurs and the equi-signal boundary also is the equi-delay boundary. In the real world situation shown in Figure B6, various natural and manmade features attenuate the signal. The equi-signal boundary wanders and the two boundaries no longer coincide. Thus, the residual time uncertainty for NWN is approximately 80 microseconds, yielding a maximum baud rate of approximately 3000 baud.[3]

III. SIMULCASTING COMBATS MULTIPATH

Simulcast essentially is controlled multipath, which can successfully combat multipath. Most essential is the carrier offsets that are present in simulcast -- multipath causes persisting anti-phase situations because the carrier frequency of all components

---

[2] 1,250 baud = (1/4)/(200 μsec).

[3] (1/4) x (1/80 μsec) = 3,125 baud.

are identical, whereas in simulcast they are not. Thus, simulcast systems are able to cope with all but the most severe multipath situations.[4]

IV. SIMULCASTING VERSUS CELL BASED RE-USE PLANS

The classic alternative to simulcast for wide area coverage is assignment of orthogonal subdivisions of the available capacity to adjacent areas. Subdivisions can be made in time (*e.g.*, assigning different time slots to adjacent areas, as is done in the ERMES system), or in frequency (*e.g.*, broadcasting the same network programs on different channels in adjacent cities). There are two problems with such systems, however. First, orthogonal assignments require tuning the receiver to the assigned channel for the area in which the receiver currently resides. ERMES uses scanning pagers to detect the strongest signal for this purpose. In the broadcast services every traveler has experienced the frustration of finding the correct channel for their favorite programs. Simulcast operation avoids the need for scanning and re-tuning which can drive up terminal power consumption.

Second, and more serious, the orthogonal assignment approach consumes capacity -- anywhere from 3 to 7 or more orthogonal assignments are required to obtain continuous area coverage (see Figure B7). This waste of capacity is somewhat recouped if the same information is not needed throughout the service area. The

---

[4] Severe multipath, where the modulation mis-alignment approaches the baud interval (this situation is known as "inter-symbol interference" in multipath literature), will thwart even the corrective measures of simulcast. Severe multipath occurs, for example, when signals are reflected from distant mountains.

cellular radio service is the outstanding example of this capacity re-use principle -- the same frequencies are re-used in separated cells to carry different conversations. Identification of the specific area in which a subscriber is located is required to allow capacity re-use.

NWN has been designed to enjoy both the benefits of simulcast and capacity reuse (see Figure B8, showing the coverage areas of a number of transmitters for a simple NWN system). The service areas in Figure B8 are not distributed according to a theoretical pattern that has no relationship to the realities of propagation, but rather they are added wherever they are needed to insure complete coverage. Thus, for example, transmitters A and B have been added in the middle of other transmitter coverage areas in order to fill-in coverage holes, without requiring re-engineering of frequency assignments for adjacent transmitters. The only constraint is keeping the differential delay from all of the transmitters servicing an area within the nominal 80 microsecond limit.

Under the NWN simulcast system, a time slice of the system capacity is assigned to a nationwide service that is simulcast by all of the transmitters. This nationwide part delivers system wide messages and traffic destined to users who are (a) not in a zone or (b) did not acknowledge a message directed to their former zone. The nationwide service pervades all zones and therefore enjoys simulcast operation, with its multipath protection and building penetration, in the overlap areas between zones.

All time slices not dedicated to the nationwide service are assigned to zonal service. During zonal periods, each zone transmits unique information to subscribers within its boundaries. Subscribers are located via the receiver to which they respond. Each zone generally has multiple transmitters to fight multipath and increase building coverage (see Figure B9). Figure B9 shows the area of Figure B8 divided into three zones. In actuality, the zones proposed for NWN will be much larger than suggested in Figure B8. Thus, a zone will likely cover more than one state.

Signals to subscribers in each zone are transmitted simultaneously. Although there will be interference between different zonal signals in the overlap areas between zones (*i.e.*, the areas with double shading in Figure B9), reliable transmissions to users in those areas would take place during the nationwide service. Clearly, it is advantageous to minimize the number of messages sent to the overlap areas, so overlap areas are engineered to fall on areas of low subscriber density. Subject to that constraint, it will be possible to further subdivide zones. Thus, if zone II were approaching saturation, the lower three transmitters in zone II could be broken out as a separate zone. If this were to occur in the actual implemented system, a zone comprising more than three transmitters would likely be created.

The only constraints on this process are minimizing the number of subscribers in zone overlaps, keeping multiple transmitters in each zone to provide simulcast benefits, and minimizing the number of zones that must be administered.

In NWN, a system built out to 34 zones will allow 34 fold reuse of all of the capacity assigned to zonal operation, which is effectively most of the cycle.

During the zonal time slice, all transmitters are simultaneously transmitting information that is unique in each zone. Thus, the combination of: (1) the high re-use during zonal periods; (2) the reversion to the nationwide service if the subscriber does not acknowledge a zonal message; and (3) the simplicity of locating subscribers by noting where the acknowledgement is received make for a simple and robust system with high capacity capabilities.

FIGURE B1

Arrangement of Simulcast Transmitters

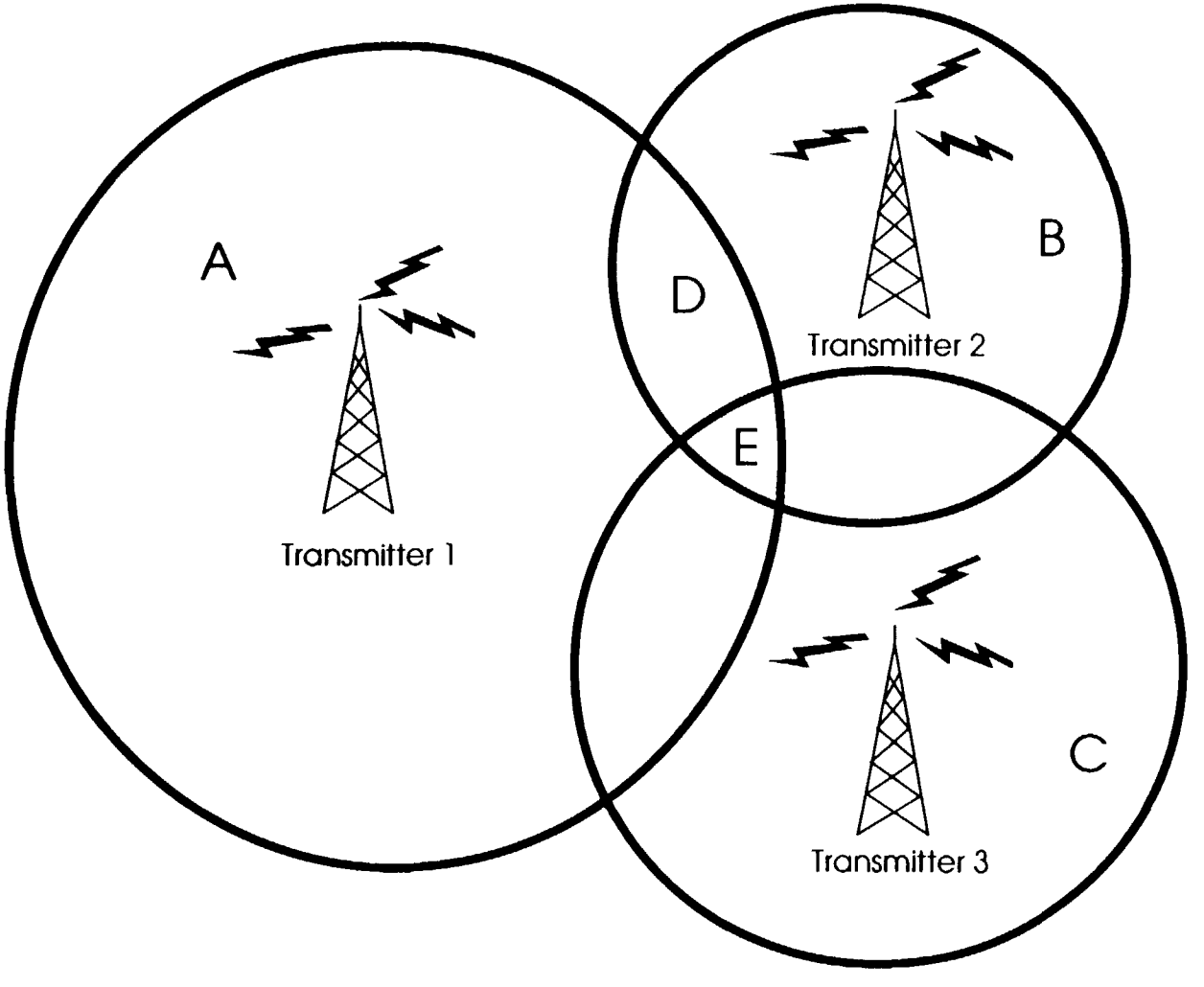

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FIGURE B2

Modulation Waveforms Synchronized

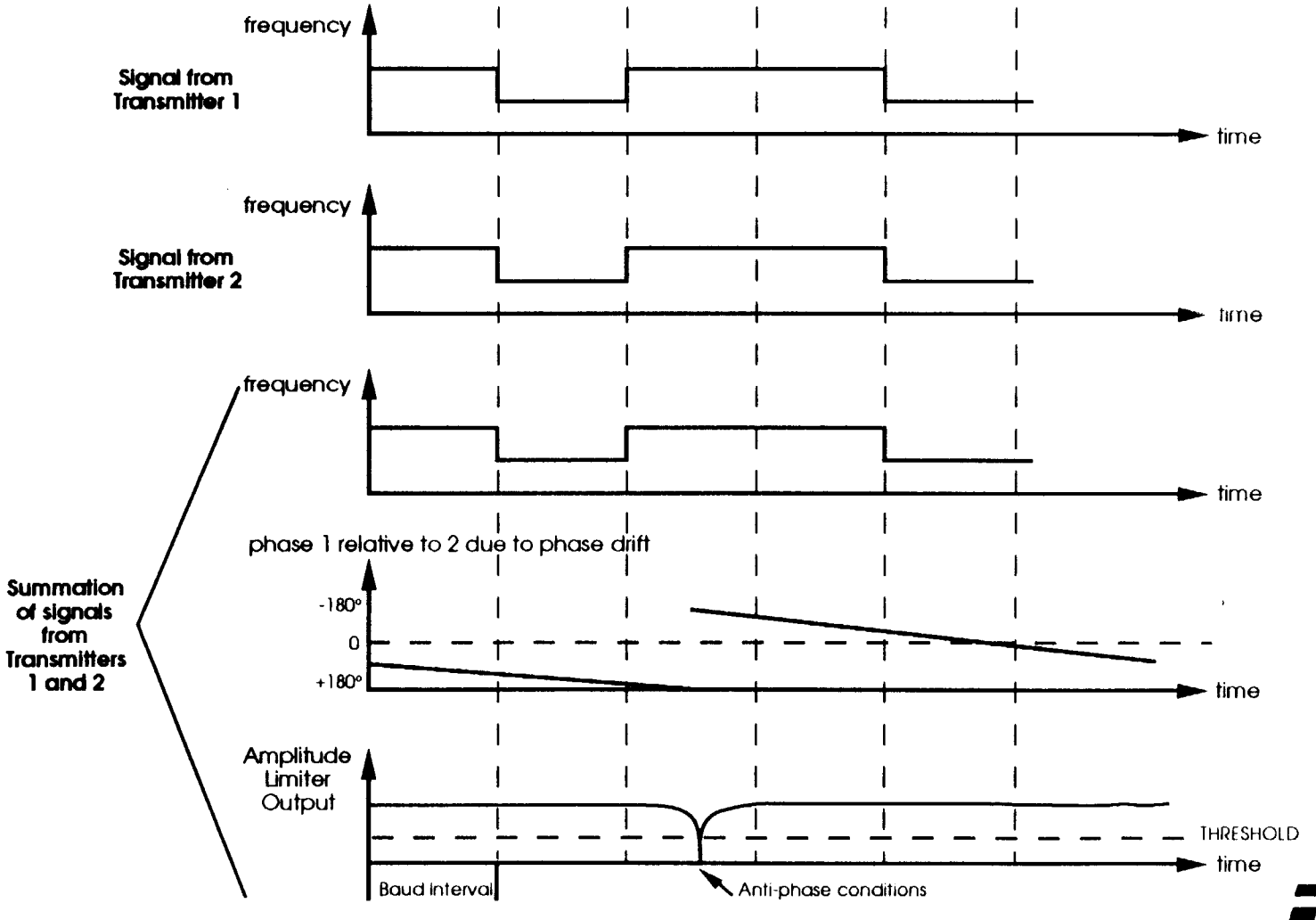

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FIGURE B3

Modulation Waveforms Offset by 1/4 Baud

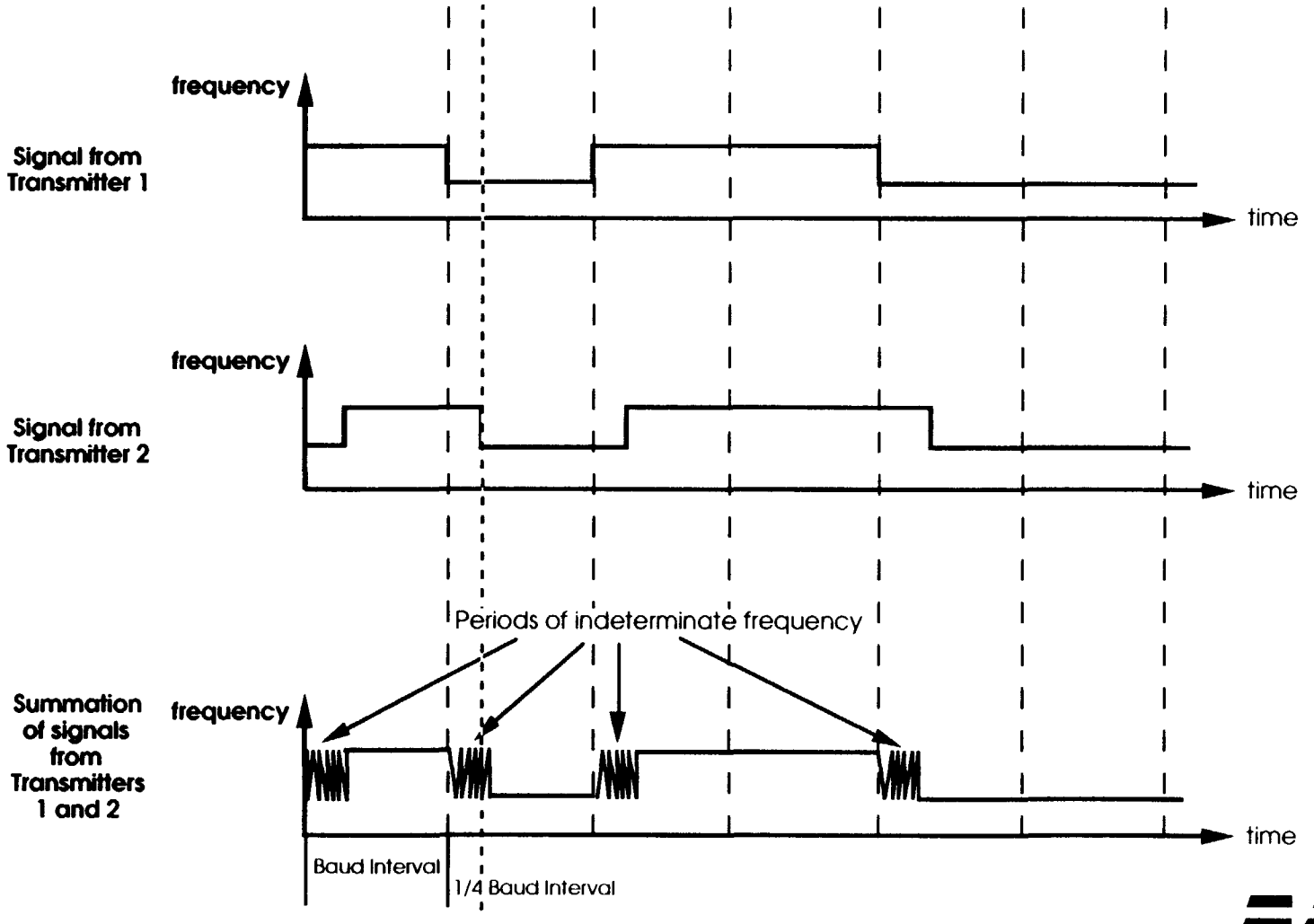

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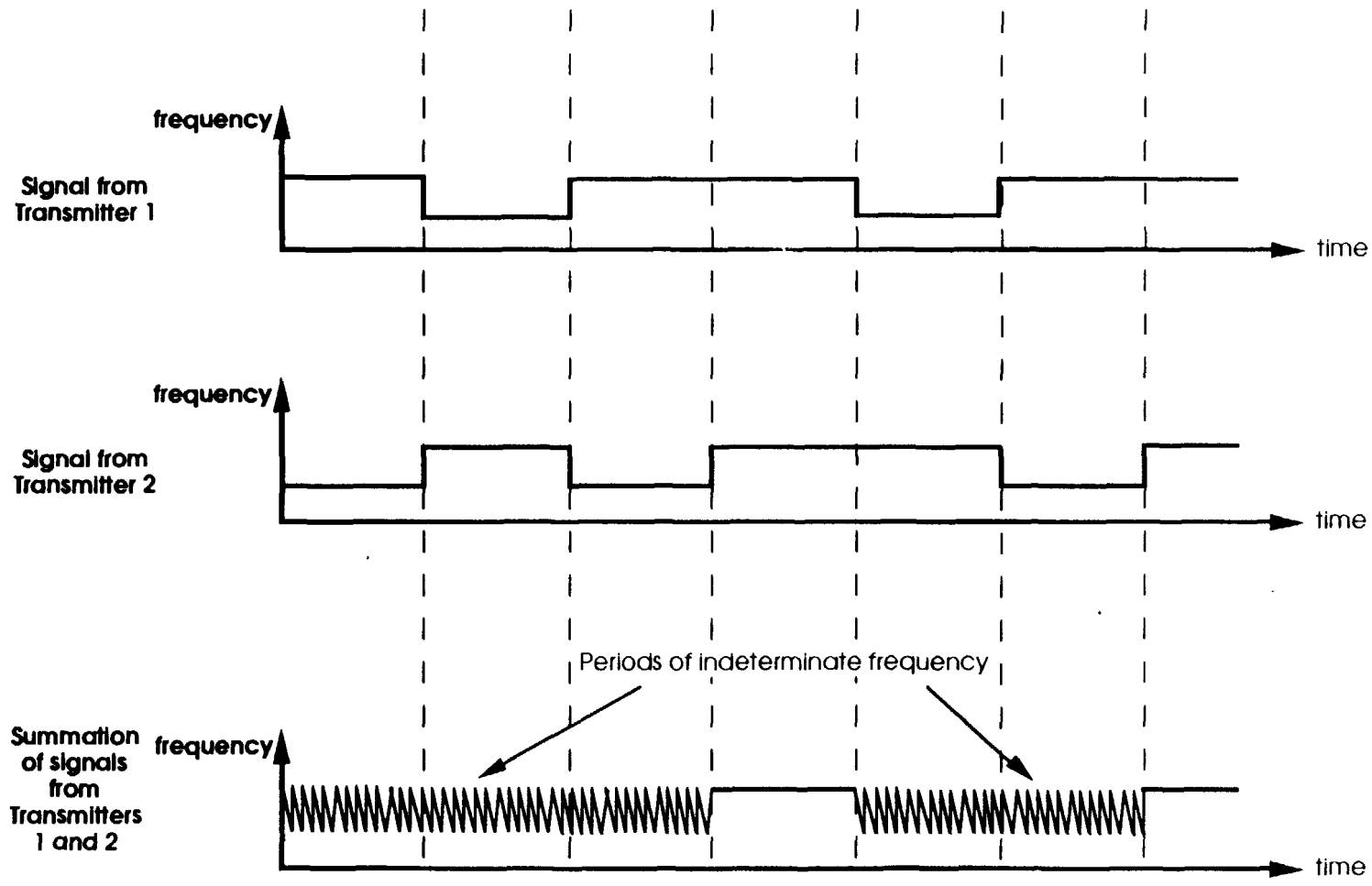
FIGURE B4

Modulation Waveforms Offset a Full Baud



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