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PACKET RADIO NETWORKS UNDER DYNAMIC JAMMING

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The purpose of this report is (a) to briefly review and classify the various research efforts developed so far in the broad area of Spread Spectrum (S^2) Random-Access Packet-Radio Networks (sometimes referred to as "Code-Division Random-Access" or CDRA) and (b) to point out certain directions that we perceive as being important to the Army, particularly in relation to the intelligent jamming of such networks. Furthermore, we will indicate the new areas and concepts that we wish to pursue further.

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INTRODUCTION

The purpose of this report is (a) to briefly review and classify the various research efforts developed so far in the broad area of Spread-Spectrum (S^2) Random-Access Packet-Radio Networks (sometimes referred to as "Code-Division Random-Access" or CDRA) and (b) to point out certain directions that we perceive as being important to the Army, particularly in relation to the intelligent jamming of such networks. In so doing, we will also put in perspective our efforts so far in this direction, under the auspices of the Army Research Office. Furthermore, we will indicate the new areas and concepts that we wish to pursue further.

We will start by outlining the various options and choices faced by the **COMMUNICATORS**, followed by those of the **JAMMER**. In each case, a thorough classification will be provided, along with a list of references that contain relevant material. Although we have tried to be as detailed as possible, the variety of available sources precludes us from being totally exhaustive in covering every possible reference. Also, there will be repetition of certain references in many cases, because they include material and assumptions that fall in more than one categories. For a good review of the various important aspects of CDRA, as applied to military packet radio, the following references can be consulted: [KaGrBuKu78], [Sass82], [Jubi85], [ShTo85], [Purs87], [Toba87], [PoSi87].

A. COMMUNICATORS

The possibilities associated with the network users, from now on collectively referred to as the "communicators", are the following:

(1). Number of Hops:

The network under consideration, consisting of a collection of modems (nodes), can either be of the *Monohop* or the *Multihop type*. In the first case, messages are to be transmitted only one hop away, implying that all source/destination pairs are within hearing distance from each other; otherwise, there will be more than one hop required to transfer a message from a source to a destination, leading to the multihop scenario and the associated routing issues. We note that the number of required hops is one facet of the important notion of **network topology**, others being the "connectivity" and the "modem availability", as described below. References on the topic include [SiKl83], [SiLe83], [SuLi85], [Toba87], [PoSi87], [Chen87].

(2). Connectivity:

A multi-node network can be either *Fully-Connected* or *Partially-Connected*. A fully-connected network means that every node can hear every other node, although not necessarily with the same quality. Typically, however, the notion of full connectivity implies that there is a direct link between any source and any destination which, in the absence of excessive multi-user noise and/or jamming, would be capable of sustaining communication. A prerequisite for full connectivity is a monohop network; when the network under consideration is multihop, it is necessarily partially connected, exactly because there is at least one source/destination pair that cannot communicate directly. However, there exist monohop networks that are not fully connected. An example can be found in Fig 1(a), whereas Fig.1(b) shows how the same node collection of TRs and RCVRs can be connected fully. Most of the references in [PoSi87] are about full connectivity (see also the models and references in [Purs86], [PrPo87], [StFo89]). An example of a partially connected monohop network can be found in [SuLi84].

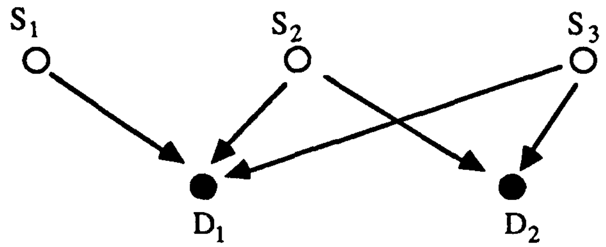

Figure 1(a). An example of a monohop, partially-connected network.

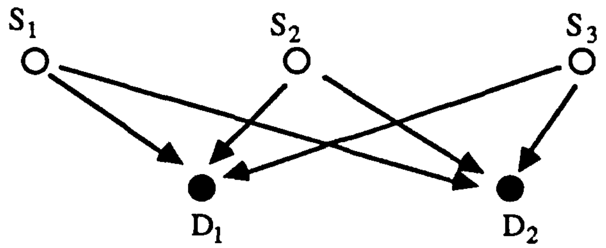

Figure 1(b). An example of a monohop, fully-connected network.

(3). TR/RCVR Format:

The issue here is whether TRs and RCVRs act in a *dedicated* or *non-dedicated* fashion. A dedicated TR or RCVR performs just the respective function and no other. Contrary to that, a non-dedicated modem switches between the two functions according to some prespecified protocol. The latter case is more commonly known as the *half-duplex* case. Here, the modem can have a TR- mode priority or a RCVR- mode priority, depending on which function is preferred over the other at a particular point in time. Such a conflict can be of particular importance in unslotted system operation, where the need for a transmission and a reception job for a particular modem can overlap in time. In slotted operation, this issue is resolved rather easily: whenever an active transmission is scheduled in a slot, the modem switches to its TR mode. In all other (non-transmitting) slots, it remains an "active" RCVR (see below for terminology).

It is sometimes thought (erroneously) that the opposite of the half-duplex case is the *full-duplex* one, whereby a modem can perform both functions simultaneously. In other words, a unit consists of a separate TR plus a RCVR at the same time. In reality, however, the full-duplex case is just a special example of the dedicated scenario. To explain this further, we should distinguish between the concepts of *potential* and *active* TRs or RCVRs. Any unit that *can* and, at some time, *will* transmit, belongs to the set of "potential" TRs, whose size is fixed at N_T; the same goes for potential RCVRs (fixed size N_R). The term "active" is reserved for those units which indeed act in either capacity at a particular slot. For a random access model, the number of *active* TRs in any slot is a random variable denoted by M_T; thus, in general, M_T will be different than N_T. On the other hand, the picture regarding the number of active RCVRs is a bit more complicated: if the network is built with dedicated TRs and RCVRs, then *active* and *potential* RCVRs are identical notions, i.e., $M_R = N_R$. A satellite random-access application with many receiving beams would mostly fit in this category, as would a hierarchical type of network with devoted or "central" nodes/repeaters, whose only job is to receive messages at all times. If the units are non-dedicated, then obviously the number of active RCVRs is itself a random variable, and the equality $M_T+M_R=U$ holds. Within this framework, *full-duplex* units correspond to a special case of dedicated networks where the total number of units $U = N_T = N_R$, each including a potential TR and RCVR. In general (i.e., for an arbitrary network), N_T will not equal N_R; this is the case, for instance, in the single-star or connected-star topology. References on this topic include [SuLi85], [PoSi87], [PrPo87], [PoCh89].

(4). Code Distribution:

As explained in [Purs87], [PoSi87], [SoSi88], the networks can employ either a *common code,* a *TR-based* or a *RCVR-based* code system. *Hybrids* of those are also possible, wherein one set of codes are used in the synchronization preample (such as a common code heard by all or a RCVR-based code for the destination of a particular packet), and then another is used in the data portion (for instance, a TR-based code). Code distribution also affects the overall network topology, as detailed in [PoSi87].

(5). Physical-Level Modem Structure:

This refers to the particular choice of the *modulation/FEC coding/spreading* combination. Coherent or differentially coherent modulations are preferred with DS spreading, whereas noncoherent modulations, such as MFSK, are typical for FH. As of now, slow FH (at most one hop per encoded symbol) seems to be the design choice, although fast frequency-hopping might become a reality soon, as fast frequency synthesizers become more widely available. Both block and convolutional coding are used with DS, whereas the standard choice for FH seems to be the Reed-Solomon code (see details on the SINCGARS radio discussed in [Purs 87]).

With regard to the coding choice, we should distinguish between fixed and adaptive coding schemes. In the latter case, which might be incorporated into the design for the purpose of mitigating the effects of temporally and/or spatially selective jamming (such as the on-off type), we distinguish further between TR-adaptivity, where the FEC rate is adjusted to the channel conditions [KePo87], and the RCVR-adaptivity, such as the code-combining techniques [KePo89].

Another important option of adaptivity pertains to power-control, where the transmission radii are adjusted according to the channel conditions. This issue is not well understood yet, and is intimately connected to the concept of topology-adaptivity: as an example, the network connectivity might be adjusted according to the jamming threat, switching from a monohop, fully-connected network to a multihop one over time.

(6). Buffering:

This regards the issue of whether the different nodes in the network contain *buffers* which store packets before transmission, or are with *no buffer*. In the former case, the buffer is either modeled as having finite or infinite capacity. This buffering capability is important for the following two reasons: (a) storing newly generated packets before their first attempted transmission, or transient packets on their way to a final destination (that is when the node acts as a relay in a multihop network), and (b) storing packets that have failed their first transmission and are scheduled to be retransmitted (the so called *backlogged* packets). In the case of no buffering, transmitters are modeled as always *busy* (never *idle* with an empty buffer), implying that they are either in the *originative* mode (with a new packet) or in the *backlogged* mode. The following Fig. 2 provides a detailed diagram for the different modes that a modem can be in, as well as the associated nomenclature that we have adopted. The issue of buffer occupancy has been addressed extensively in [Chen87], extending the models of [SiLe83], [SuLi85]. An analysis of interacting queues can be found in [EpZh87], but not for CDRA.

(7). Access Protocol:

This refers to the way that a modem accesses the common spread channel. In Random Access, which has been the main feature in this packet radio under consideration, accessing is achieved with probabilistic means: an available packet will be transmitted in a specific slot with a certain probability p, which can be different for first transmission versus the re-transmission of a backlogged packet. If such a distinction is not made and all packets are transmitted with the same probability, we call it an *uncontrolled access protocol*, the opposite of which is *controlled accessing*. In the latter case we distinguish between static control and adaptive control techniques. For static control, the new-packet transmission probability is denoted by p_0, whereas the backlogged-packet transmission probability is denoted by p_r. Both p_0 and p_r are fixed throughout the system operation, although they can be chosen optimally [KlLa75], [DaGr80], [Rayc81], [PoSi87], [Chen87], [PrPo87], [PoCh89]. Contrary to that, the probability p_r changes continuously with time in the "adaptive-control" case, according to some channel observables (traffic levels, jamming etc.) [Haje82].

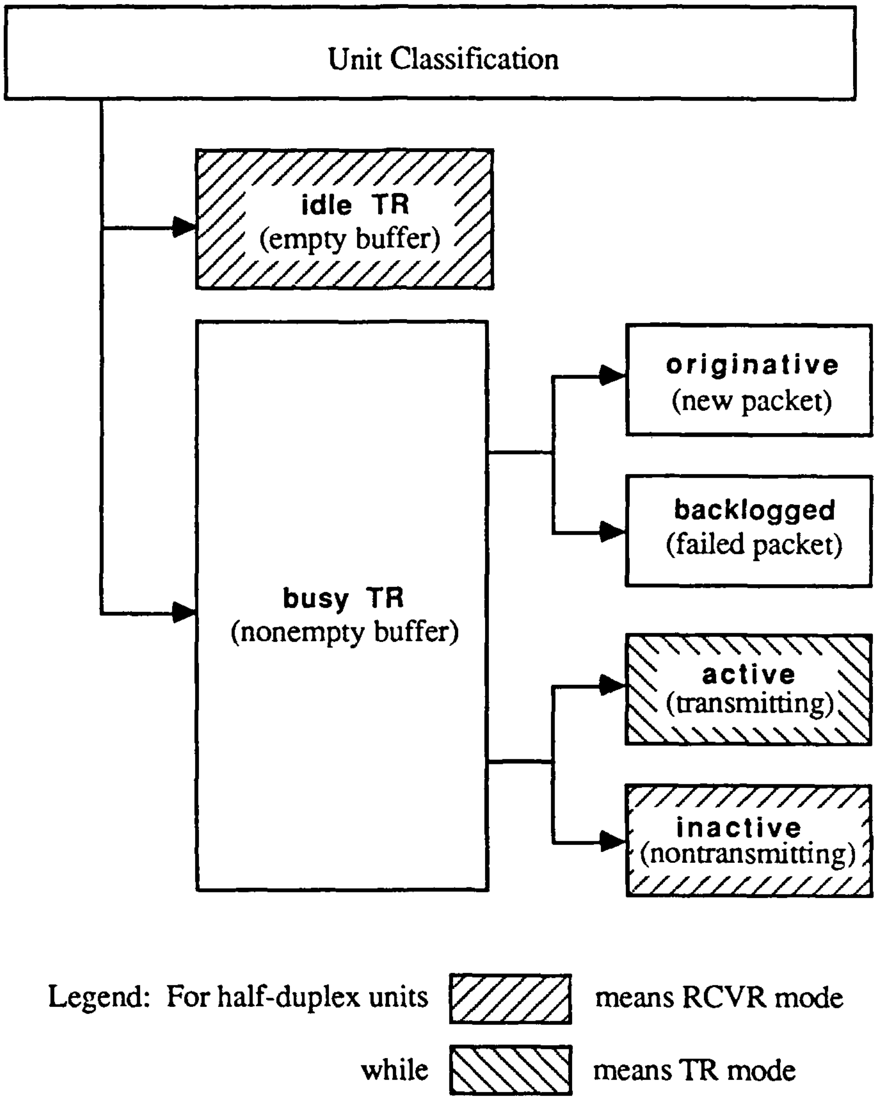

Figure 2. General classification of packet-radio unit status.

(8). Centrality:

In a large network where routing, connection and topology- setup, flow control and other network- management decisions have to be made, the burden of such decisions can either be assigned to specific central nodes, or it can be done collectively with all nodes participating. The first type of network falls under the *centralized* category, while the second type is referred to as a *decentralized* network. There can also be hybrid cases which imply a hierarchical structure: some nodes have a higher decision and organizational responsibility than others, although all nodes possess some degree of decision-making capability.

(9). Network Functions:

Among the many functions that a complex network must perform [KaGrBuKu78], we only mention here the following three: *routing*, *flow-control* and *information-exchange* [Chen87]. "Routing" refers to the task of finding the appropriate path(s) for a packet to follow from source to destination, and can be classified as deterministic, probabilistic and dynamic. In the first case, paths are fixed between each source/ destination pair. Furthermore, a deterministic routing algorithm can be of the single-path or diversity variety, depending on the number of paths that the same packet is sent through, in order to reach the destination. Probabilistic routing chooses the paths in a stochastic way in order to avoid deterministic obstacles and bottlenecks. However, the probabilistic law is typically stationary, i.e., it is not changing with time. Contrary to that, dynamic routing is concerned with finding the best routes in a dynamically changing environment, and utilizing those in a deterministic way. For the nodes to be able to find those best paths; however, they must be able to continuously monitor the quality of the channels and to exchange that information amongst themselves. This is where the notion of "information exchange" comes into play, with the associated issues of the frequency of exchanges, the types of messages exchanged, the choice of channel observables (see below) etc. On the other hand, "flow-control" is typically associated with dynamic procedures: the users adjust their accessing to the link (they control the flow of information into it) by reacting to the perceived level of congestion or channel quality, within a specific window of time.

(10). Observables:

The issue here is to identify the appropriate channel-quality monitoring schemes, whose conclusions are to be shared among nodes during the information exchange sessions. Typical such measures are the channel signal-to-noise ratio (SNR), the bit- or word- or packet-error rate over some observation interval, the number of retransmissions required to send a packet successfully, etc. These are obviously not unrelated statistics, and the selection of a proper subset of those upon which to base a channel-quality estimate (CQE) is an important open issue.

(11). Input Traffic:

The traffic requirements of a particular network, i.e., the amount of packets per second (or per slot) that the network can support on the average, is an external specification, much like the physical deployment of nodes in space. The nature of traffic is mostly a modeling issue, having to do with how traffic is being generated at the various nodes. As such, it is closely related to certain flow-control considerations. This traffic is the combined stream of new (original) packets as well as transient packets, as discussed above. The two immediate issues affecting performance evaluation are the *statistics* of the traffic and its *priority level.* With regard to statistics, typical models are the Bernoulli (for finite-user models) and the Poisson (for very large or infinite user-models). On the other hand, the notion of "prioritized traffic" refers to the case of integrated services, where both digitized voice and data are to be transported through the network. Such integration imposes different constraints on these heterogeneous traffic sources: voice can tolerate higher error rates (up to 10^{-3} bit-error-rates are typical for digitized voice), but it is very stringent on the delay requirements. For data transfer, these constraints are effectively reversed. The appropriate design of a secure, anti-jam network under such a mixture of requirements is an open issue.

B. JAMMER

Some of the choices related to the jammer's degrees of freedom are outlined below. Again, the list is not exhaustive, but it contains aspects that either have been, or will be addressed in the near future. As the project advances and other important parameters emerge, they can be incorporated in the list. Let us note that we deal here mostly with jammers that incorporate some minimal degree of randomness in their attack (stochastic jamming), for otherwise they would eventually become totally predictable: this would allow the network to perform its functions around them, thus rendering them ineffective. This randomness can vary from the simplest (random epoch of a periodic jammer), to the most advanced choices of the probabilistic jamming law. At this point, we make the assumption that the users cannot predict the jamming action (through, say, some advanced learning mechanism), but they can try to react to it adaptively once they sense it.

(1). Waveform/Time/Space Profile:

The most familiar jamming alternatives evolve around the particular signature of the jamming *waveform*. Thus, we talk about tone-jamming versus noise-jamming, partial-band versus full-band jamming, on-off (namely, two-level) versus multi-level jamming etc. [SiOmScLe85] .

Another important feature is the *temporal* profile of the jammer, particularly in connection to the basic time-unit of the network, i.e., the slot-length. Here, as specific examples which do not exhaust all possibilities, we distinguish between the long-term, the Markovian and the slot-by-slot independent jammer [PrPo87]. In the first case, the jammer chooses very long blocks of time-intervals for its jamming actions, and the network is allowed to reach a dynamic equilibrium within each such block of time. In the Markovian case (another particular example within the jammer's probabilistic choices), these block-lengths are chosen according to a specific Markovian distribution. The last case of slot-by-slot independence implies that the jammer decides independently for every slot whether to jam or not. In all cases, a dominant parameter is the *temporal duty cycle* p_t, which quantifies in a coarse way the jamming options.

Finally, from a *spatial* viewpoint, the jammer has at his discretion the portion (fraction) of the total network that he chooses to jam [PoCh89]. This can either be a fixed fraction (a special case of which is "full-space" or "blanket" jamming) or a random fraction in each slot. In either case, a dominant parameter is the *spatial duty cycle* p_s, defined as the average portion of the total number of nodes jammed over time. This parameter provides a simplified quantification of the spatial options of the jammer, and it is a dual concept to p_t. In general, a complete description of the probabilistic jamming strategy requires the specification of the joint probability-mass distribution function of the jamming action over all nodes [PoCh89].

(2). Stationarity:

Any stochastic process is either *stationary* (time-invariant) or *nonstationary* (time-varying), depending on whether its probabilistic description changes over time or not. A stochastic jamming process is no exception, and this distinction applies here too. In the time-varying case we also distinguish between periodic and aperiodic jamming strategies [Chen87] .

(3). State Dependence:

This refers to whether the jammer adapts his strategies to certain channel measurements (see below), which provider him with some measure of the network state. If the jammer acts independently of any observations (i.e, if he is *state-independent*), we refer to him as a *static* jammer. If he does take into account these measurements (i.e, the actions at each point in time are *state-dependent*), we call him *dynamic*. Note that the distinction between "static" and "dynamic" is independent of the time-variability of the jammer: either one can be stationary or nonstationary, as defined above.

(4). Observables:

The actions of an adaptive (dynamic) jammer will depend on the values of certain chosen observables, much like the communicators' actions are modified by their own observables. Such candidates for jamming observables of the network status are the *traffic intensity* on the different monitored links, the *power level* employed by the users (in response to SNR and connectivity requirements), the *packet length* etc. The effectiveness of each of those observables is currently unknown.

Proposed Extensions/ Research Directions

We outline below some of the topics that we propose to examine, in the course of our continuing effort in this area under the sponsorship of the ARO.

1. Impact of partial connectivity in a monohop scenario versus the jamming strategy. Note that [PoSi87] and [PoCh89] dealt with fully connected monohop nets only.

2. Impact of FEC code-design for a FH radio versus the jamming spatial and temporal duty cycle.

3. Understand the ramifications of topology-adaptivity in response to a temporally and/or spatially selective jamming threat. This involves adjustments in possibly all the facets of network topology, such as the mono/multi-hop choice, full- versus partial-connectivity in the monohop case, dedicated versus half-dublex operation, and code distribution. This would entail an analytical understanding of the network performance in each stage of the topological transformation, as well as the dynamic aspects of the transition.

4. Perform a thorough examination and comparison of the various statistics that can be employed as measures of the channel quality for the communicators. Candidates for these channel-quality estimates (CQE) include the channel signal-to-noise ratio (SNR), the bit- or word- or packet-error rate over some observation interval, the number of retransmissions required to send a packet successfully, etc. In view of the fact that these are not independent statistics, the question is which ones (or what combination thereof) provides a reliable and concise description of the channel state at any point in time. The exact same issue should be addressed from the jammer's viewpoint, where the observables would now include the traffic activity (intensity) and the power level on the various monitored links, possibly the length of each transmission etc.

5. Examine appropriate design alternatives for a secure, anti-jam network under a mixture of requirements, pertaining to heterogeneous traffic sources such as digitized voice and data. This will include the possibility of different coding, accessing and routing choices for the different types of traffic, in order to accommodate the very

different error-rate/delay requirements for each of them.

6. Examine the interaction between adaptive users and adaptive jammers, namely, analyze the situation where both parties' actions depend on channel observables.

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