MAC PROTOCOL FOR WIRELESS NETWORKS IN TACTICAL ENVIRONMENTS*

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Abstract

A MAC protocol suitable for cellular wireless networks with motorized base stations operating in battlefield environments is described. The proposed scheme is a quasi-deterministic media access protocol based on disjunctive superimposed codes. Each wireless terminal is pre-assigned a unique code vector from a binary superimposed code whose parameters are computed from network specifications. A terminal transmits in slot k of each fixed length frame only if the the kth component of its assigned code vector is non-zero. This scheme guarantees each active terminal at least one collision free packet transmission per time frame. Additionally, this scheme is robust, does not require reassignment of code vectors, and obviates the need for explicit association procedures when users cross cell boundaries. These properties are important in environments where the coverage areas and intersections between cells vary dynamically as a consequence of base station mobility.

1 INTRODUCTION

Dynamic base station mobility coupled with user mobility are key considerations for wireless networks in battlefield environments. In such scenarios, some base stations will be mounted on vehicles such as tanks, trucks, etc; resulting in mobile cell sites. Consequently, the size, coverage areas, and relative positions of cells will change over time, thereby necessitating channel and traffic reassignment. Moreover, the mission critical nature of tactical situations mandate a communications infrastructure that has known deterministic performance bounds, and provides smooth and seamless coverage. These characteristics complicate the design of media access control (MAC) protocols for wireless networks operating in such environments.

In this paper, we describe a MAC protocol for cellular wireless networks in tactical environments. Over the last two decades, MAC protocols for wireless networks have attracted much attention within the published literature. See, for example, [2, 3, 5, 10, 12] and the references therein. Most of the prior studies that pertain to cellular networks implicitly assumed that cells are immobile. The network under consideration here consists of a set of possibly mobile overlapping cells. Each cell contains a base station (possibly mobile) and a set of mobile terminals. Mobile terminals can move freely between cells.

The MAC protocol is quasi-deterministic and is based on constant weight superimposed codes [7, 8, 1, 11, 6]. By quasi-determinism, it is to be understood that the scheme does not completely obviate packet collisions over the shared wireless medium. However, it has the interesting property that each wireless terminal is guaranteed at least one collision free packet transmission within a bounded time frame. Under this approach, each terminal is preassigned a unique constant weight binary vector from a disjunctive superimposed code whose parameters are derived from the specifications of the wireless network. A terminal transmits in slot k of each frame only if the kth component of its assigned code vector is non-zero. This protocol is characterized

* **To appear: MILCOM-96, October, 1996**

by the tuple (N, Δ, n), where N is the total number of terminals in the network (or an upper bound thereof), Δ is an upper bound on the maximum number of terminals in any given cell, and n is the frame size which corresponds to the maximum number of slots that a terminal can wait before conflict free transmission is assured. The relation between the network parameters (Δ, n, N) and the parameters of the constant weight superimposed code used for the MAC protocol is summarized in Theorem 3.1 of Section 3.

Use of a MAC protocol based on constant weight binary superimposed codes offer a number of desirable properties for wireless tactical communication systems:

- The scheme is fair, and permits terminal mobility without need for code reassignment. In other words, this approach facilitates seamless mobility. In particular terminals within a given cell can engage in peer to peer communications without consulting the base station for bandwidth reservation.
- Given any combination of Δ or less terminals in any given cell, each terminal is guaranteed at least one conflict free packet transmission in at most n time slots.
- As the number of terminals per cell decreases (less than Δ), the effective bandwidth available to each user increases.
- Superimposed codes throttle the effective packet injection rate into the network. In this regard, they act as a congestion control mechanism under high traffic situations.

The remainder of this paper is organized as follows. In Section 2 we describe the system model, introduce some notation, and summarize relevant properties of superimposed codes. In Section 3, we discuss the design considerations for the MAC protocol. Finally, Section 4 contains our concluding remarks.

2 SYSTEM MODEL

We consider a wireless network which is partitioned into a set of cells; $S = \{S_j : j = 1, 2, \ldots, Q\}$. The cells are induced by mobile base stations in the system. The cell system can be conveniently mapped onto the echelon structure of a tactical formation. The network contains a set $V = \{V_i : i = 1, 2, \ldots, N\}$ of wireless terminals which are permitted to move freely between cells. We assume that there are at most Δ terminals in each cell at any given instant in time. Thus, if we let A_j be a random variable representing the number of terminals in cell S_j, then it is supposed that $A_j \leq \Delta$ for $j = 1, 2, \ldots, Q$. Figure 1 depicts such a cellular system in a tactical environment.

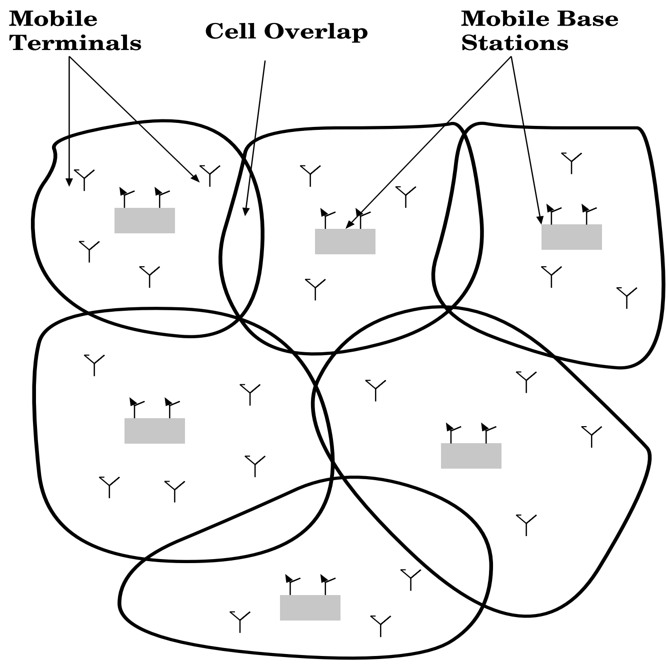

Figure 1: **Cellular System in a Tactical Environment**

A discrete time media access model is used in which time is divided into fixed length slots. A slot corresponds to the time required to transmit one packet plus a small guard interval. Such slotted systems are consistent with the current trend towards digitized battlefields. Time slots are grouped into fixed length recurrent frames. Each wireless terminal is assigned a unique binary vector (which we term its *deterministic access vector (DAV))* from a superimposed code whose parameters are a function of the network specifications. A wireless terminal transmits in slot k of each frame only if the kth component of its DAV is non-zero.

Since the MAC protocol depends on the properties of superimposed codes, let us first recall some basic facts concerning these structures. The interested reader is referred to [11, 1, 8] for additional details. Let C be a binary code and let $x = (x_1, x_2, \ldots, x_n)$, where $x_i \in \{0, 1\}$, be a code word in C. Given any two code words, $x, y \in C$, let $wt(x)$ and $d(x, y)$ denote the weight of x and the hamming distance between x and

y respectively. Let $c(x,y)$ denote the *correlation* between x and y which is equal to their inner product, i.e., $c(x,y) = \sum_{i=1}^{n} x_i y_i$. It is easy to see that the correlation between x and y is the number of bit positions they have a "1" in common. The maximum correlation for a given binary code C is defined as: $c = \max_{x,y \in C: x \neq y} c(x,y)$. The following definitions are standard in the theory of superimposed codes [11, 6].

Definition 2.1 *The superposition of two code words x and y denoted $x \vee y$ is defined as $z = x \vee y$ where:*

$$z_k = \begin{cases} 0 & \text{if } x_k = y_k = 0 \\ 1 & \text{otherwise} \end{cases} \tag{1}$$

The superposition of a set of code words $D = \{x^{(1)}, x^{(2)}, \ldots, x^{(r)}\}$ is given by $f(D) = x^{(1)} \vee x^{(2)} \vee \ldots \vee x^{(r)}$. The superimposed codes of interest for our current purpose belong to the class of *disjunctive codes* (also called *zero-false-drop codes*[11]). This notion is defined below.

Definition 2.2 *A binary code, C, of length n and size T is a disjunctive superimposed code of order Δ if each subset $D \subset C$ of cardinality $|D| \leq \Delta$ has the property that for each code vector $x \in D$ the following holds: $c(x, f(D)) = wt(x)$; whereas for each $y \in C \setminus D$ the following holds: $c(y, f(D)) < wt(y)$.*

The following theorem due to Kautz and Singleton [11] summarizes an interesting property of disjunctive superimposed codes.

Theorem 2.1 ([11]) *Suppose the code words of a code C are arranged as the rows of an $N \times n$ matrix $\mathcal{A}$. Then, C is a disjunctive code of order Δ if and only if every subset of $(\Delta+1)$ rows of $\mathcal{A}$ contains an $(\Delta+1)$ columned identity matrix.*

It is customary to denote the set of all disjunctive codes of length n, order Δ, and size T by $\mathcal{D}(n, \Delta, T)$. An important subclass of superimposed codes is the set of binary constant weight codes. A code C has constant weight if $\forall x \in C$, $wt(x) = w$ for some fixed integer constant w. A constant weight code is characterized by the parameter $T = A(n,d,w)$ which is defined as the number of binary vectors of length n, minimum hamming distance d, and fixed weight w. The set of constant weight codes of length n, weight w, correlation c, and size T is denoted $CW(n,w,c,T)$. Note that for a constant weight code, the maximum correlation, weight, and hamming distance are related by the formula: $d = 2(w - c)$. Every constant weight code is a disjunctive code. In particular, it can be shown that [8, 1]: $CW(n,w,c,T) \subseteq \mathcal{D}(n, \lceil \frac{w}{c} \rceil - 1, T)$.

In this section, we have described the system model and reviewed some basic facts concerning superimposed codes and constant weight codes. In the next section, we focus on the design considerations for the MAC protocol.

3 DESIGN CONSIDERATIONS

Let $F = < t_1, t_2, \ldots, t_n >$ represent a fixed length frame consisting of a sequence of n time slots. Here, t_k denotes kth time slot in F. Suppose we assign a unique constant weight vector from a disjunctive superimposed code C of length n to each node. A wireless terminal transmits in slot t_k only if the kth component of its assigned binary vector is non-zero. For each $t_k \in F$, let $T(t_k) = (T_1(t_k), T_2(t_k), \ldots, T_N(t_k))$ be a *transmission indicator vector*, with the property that $T_i(t_k) = 1$ if terminal V_i transmits in slot t_k and $T_i(t_k) = 0$ otherwise. The following statement, which is easily verified, prescribes a necessary and sufficient condition to ensure at least one conflict free transmission for each terminal per time frame. Recall that A_p is the set of terminals in cell S_p.

Lemma 3.1 *To ensure that each terminal in a given cell, say S_p, is able to successfully transmit at least one packet per frame without conflict, it is necessary and sufficient that for each $V_i \in A_p$, there exists $t_k \in F$ such that $T_i(t_k) = 1$ and $T_j(t_k) = 0$ for all $V_j \in A_p$ $i \neq j$.*

Observe from Theorem 2.1 that if $A_p \leq \Delta$, then the above lemma is automatically satisfied if we use a disjunctive code from the class $\mathcal{D}(n, \Delta - 1, N)$ as a set of DAVs. Also, notice that the disjunctive code will satisfy the conditions of Lemma 3.1 provided the bound on the number of terminals per cell holds; regardless of the identity of terminals. Thus, wireless terminals can move between cells without need for bandwidth reassignment. For the same reason, so long as the bound on A_p is maintained, the coverage areas of cells can change over time. Additionally, since the DAVs are preassigned, base stations are not required to perform bandwidth allocation. Moreover, if the disjunctive code vectors have constant weight, then fair channel access is assured.

Kautz and Singleton [11] have shown that a disjunctive superimposed code (*zero-false-drop* code) of order Δ can be constructed from a constant weight code whose weight (w) and hamming distance (d) are related by the formula $d = \frac{2w(\Delta-1)+2}{\Delta}$. The following theorem, which is a consequence of the above result and the discussion following Lemma 3.1, provides a sufficient condition for a set of binary vectors from a constant weight code to act as DAVs for a given network configuration.

Theorem 3.1 *If* $d = \frac{(2w(\Delta-2)+2)}{(\Delta-1)}$ *and* $T = A(n,d,w) \geq N$ *then the constant weight code* C *with length* n*, minimum distance* d*, and weight* w *can be used as a set of deterministic access vectors for a network with* N *nodes in which the maximum number of terminals per cell is bounded from above by* Δ*.*

In the above display, the requirement that $A(n,d,w) \geq N$ is needed to ensure that each terminal can be allotted a unique code vector. Since use of superimposed codes guarantees each terminal at least one conflict free packet transmission per time frame, the guaranteed throughput per terminal is $1/n$. Additionally, since all code vectors have equal weight (which is equal to w), the maximum throughput per terminal is bounded from above by w/n. Consequently, it is desirable to make n as small as possible and w as large as possible. Thus, the design constraints are specified by the network parameters N and Δ; while the code parameters n and w are the results of a specific design. The performance of the MAC protocol then centers on the construction of efficient constant weight codes.

In general, construction of constant weight codes equipped with desirable parameters is a very difficult problem. However, it is known that constant weight codes can be derived from affine geometry codes, projective geometry codes, concatenated codes, permutation groups [4, 1], and simulated annealing [9]. Additionally, because constant weight codes have applications in diverse domains, updated tables of these codes are published regularly [4]. Regardless of the specific construction used, the steps required to derive constant weight superimposed codes for a given network configuration are summarized below.

1. **Given** a network with a maximum of N wireless terminals and a maximum of Δ terminals per cell, compute d and w such that $d \approx \frac{(2w(\Delta-2)+2)}{(\Delta-1)}$.
2. **Determine** the least n such that $A(n,d,w) \geq N$.
3. **Construct** a set of N superimposed code words of length n, constant weight w and minimum hamming distance d.
4. **Assign** a unique superimposed code word to each wireless terminal in the network.

The interested reader is referred to [4] where several examples of constant weight codes are displayed.

4 CONCLUSION

In this paper, we have described a MAC protocol suitable for wireless networks in tactical environments. The MAC protocol uses a quasi-deterministic access scheme based on constant weight binary superimposed codes. Use of constant weight superimposed codes guarantees that each terminal can have at least one collision free packet transmission within a bounded time interval. Additionally, use of superimposed codes permits seamless mobility. In particular, terminals within any given cell can engage in peer to peer communications without need to consult the base station for bandwidth reservation.

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