Collision Free MAC Protocols for Wireless Ad Hoc Networks based on BIBD Architecture

Pietro Camarda and Orazio Fiume

Politecnico di Bari – Dipartimento di Elettrotecnica ed Elettronica (DEE)
Via E. Orabona, 4 - 70125 Bari (Italy)
Email: (camarda, o.fiume)@poliba.it

***Abstract*—Wireless Ad hoc networks represent a powerful telecommunication infrastructure that is being exploited for enabling general wireless networking connectivity for a variety of significant applications, e.g., military applications, industrial automation, sensor networks, vehicular networks, applications in case of disaster, etc.**

The distributed and flexible architecture of wireless ad hoc networks is a key factor, however, their wide deployment relies on protocols able to provide energetic optimization, high channel utilization, support for real time traffic, etc. In such a context, recently a Collision Free MAC protocol (CF-MAC), based on the theory of Balanced Incomplete Block Design (BIBD), has been proposed. Its effectiveness has been already investigated showing significant improvements compared to the Standard IEEE 802.11, in terms of throughput, one-way packet delay, energy consumption and support of real time traffic.

In this paper enhanced versions of CF-MAC have been considered with significant novelties regarding the introduction of variable time slot dimension, different management of Power Saving (PS) mechanisms, more efficient utilization of channel bandwidth, etc. The performance of these variants have been investigated by simple analytical models, in terms of energy saving, channel utilization, average access delay, etc., highlighting their improvements over basic CF-MAC protocol. In addition, computer simulations have been exploited to study the suitability of the proposed schemes to support VoIp applications.

***Index Terms*—Wireless Ad Hoc Networks, Power Saving, Collision Free MAC Protocols, Balanced Incomplete Block Design (BIBD).**

I. Introduction

Wireless ad-hoc networks are suitable to be widely adopted to provide a distributed, self-configuring communication infrastructure for a large variety of significant applications, e.g., military applications, industrial automation, sensor networks, vehicular networks, applications in case of disaster, etc., either in environments where a wired network cannot be easily set up, or more general as an extension of infrastructure based wired/wireless networks [1].

The distributed and flexible architecture of wireless ad hoc networks, usually composed by smart wireless mobile nodes with battery supply and finite lifetime, that communicate to each other via a shared radio channel, is a key factor. However, due to the scarce energy resources available at each station, much efforts must be devoted to find out energy efficient circuits, protocols, and algorithms [2] capable to extend as much as possible network lifetime while providing an acceptable Quality of Service (QoS). Specifically, innovative and energy efficient clustering techniques in addition to power control mechanisms and MAC algorithms are required in order to reduce energy consumption while providing acceptable throughput and delay.

In particular, the trade-off between energy-saving and QoS requirements becomes a critical issue when the ad-hoc network has to support time-critical applications, such as voice over IP (VoIP) [3–5] or industrial automation applications [6]. In fact, power efficient protocols are usually based on keeping Wireless Network Interface Card (WNIC) turned off as much as possible thus affecting packet delays. All the layers of the protocol stack are involved in this challenging issue [7].

The design of innovative MAC protocols, in such a context, is a very challenging issue. The well-known Distribute Coordination Function (DCF) in IEEE 802.11 [8], is not power efficient because, being CSMA-based [9], it keeps wireless network interfaces sensing the channel for a large fraction of the time. Moreover, due to collisions and frame retransmissions, energy consumption increases with the offered load. For these reasons, several improved contention-based MAC schemes for wireless ad hoc networks have been proposed. Some of them aim at reducing as much as possible packet losses due to collisions; others are based on keeping network interfaces in awake state (i.e., turned on) only for short time intervals, that is when there are pending data to transmit or receive, and in doze state (i.e., turned off) otherwise. Recent studies [10] have shown that batching frames helps to reduce the number of contentions and the ACK overhead.

Other approaches tackle the power saving issue using collision free TDMA-based protocols, which achieve

This paper is an extended version of the paper "P. Camarda, O. Fiume, and G. Marraffa "BIBD Based Collision Free MAC Protocols for Wireless Ad-Hoc Networks" Radio and Wireless Symposium (RWS), 9-11 January 2007, Long Beach, CA-USA"

© 2007 ACADEMY PUBLISHER

power saving by avoiding overhead, overhear, and collisions. A drawback of these scheme is their low bandwidth utilization [11].

Recently a Collision Free MAC protocol (CF-MAC) has been proposed. CF-MAC is based on the theory of Balanced Incomplete Block Design (BIBD) [12], which has been widely studied in the field of combinatorial mathematics. Its effectiveness has been already investigated showing significant improvements compared to Standard IEEE 802.11, in terms throughput, one-way packet delay, energy consumption and support of real time traffic [13-15].

In this paper enhanced versions of CF-MAC, still based on BIBD, have been proposed considering several significant novelties that regard the introduction of variable time slot dimension, different management of Power Saving (PS) mechanism, more efficient utilization of channel bandwidth, etc. The performance of these variants have been investigated, for various traffic types, by simple analytical models and by simulations, highlighting their improvements over basic CF-MAC protocol.

Combinatorial design theory has been applied to various aspects of communications [16, 17], but to the best of our knowledge, the approach followed by the authors of this paper is the first to apply BIBD theory to design collision free MAC protocols in wireless ad hoc networks.

The rest of the paper is organized as follows. Section II summarizes the main features of system architecture based on BIBD design. Section III describes the enhanced versions of the MAC protocol based on BIBD. Performance results, exploiting analytical models have been reported in section IV, while computer simulation is exploited in section V to analyze VoIp applications. Finally, in section VI some conclusions are drawn.

II. SYSTEM ARCHITECTURE

In this section a system architecture based on the theory of Balanced Incomplete Block Design (BIBD) that allows the synthesis of new collision free MAC protocols, will be described [12].

Definition: *A BIBD is an arrangement of v distinct objects* $X=\{x_1, x_2, \ldots, x_v\}$ *into b blocks such that each block contains exactly k distinct objects, each occurring in exactly r different blocks; moreover every pair of distinct objects i and j occurs together in exactly l blocks.*

By definition, a specific BIBD is referred by the 5-tuple *(v, b, r, k, l)*. The five parameters are not independent, but the two basic relations that follows represent necessary conditions for the existence of a BIBD [12]:

$$bk = vr \quad (1)$$

$$r(k-1) = l\,(v-1) \quad (2)$$

The proposed system architecture considers a single hop wireless ad hoc network with the time axis divided into time slots, supposing that all stations are synchronized.

To this aim, we consider a BIBD architecture with parameters *(v, b, r, k, l)* as an arrangement of *v* stations into *b* slots. Each slot contains exactly *k* distinct stations, i.e., in each slot the access to the wireless medium is permitted only to *k* specified distinct stations. Considering a group of *b* slots, each station occurs in exactly *r* different slots, i.e., a given station can transmit/receive only *r* times. Moreover, each pair of distinct stations occurs together in exactly *l* slots, i.e., there are always time slots in which two distinct stations can communicate directly. The BIBD structure may be graphically represented; as an example, in Fig. 1 a BIBD system with parameters *(7, 7, 3, 3, 1)* is reported. In this simple case, there are seven stations, i.e.,(v = 7) in the network. There ere seven different time slots, i.e.. (b = 7) and in each of them only three distinct stations, i.e., (k = 3) accede to the channel; moreover, each station can access to the channel in three of these slots, i.e., (r = 3) and each pair of stations occurs together in one slot. i.e., (l = 1). Alternatively, the seven blocks can be explicitly enumerated. In the previous case we have:

$B_1=\{x_1, x_5, x_6\}$, $B_2=\{x_1, x_3, x_4\}$,

$B_3=\{x_1, x_2, x_7\}$, $B_4=\{x_2, x_4, x_6\}$,

$B_5=\{x_2, x_3, x_5\}$, $B_6=\{x_4, x_5, x_7\}$,

$B_7=\{x_3, x_6, x_7\}$.

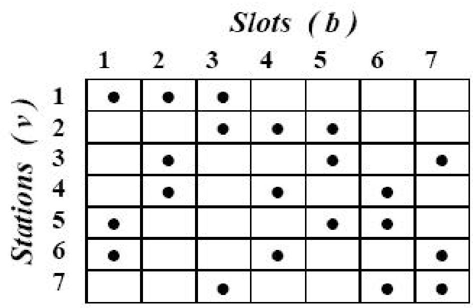

Fig. 1 Example of BIBD with parameters (7, 7, 3, 3, 1)

In general a BIBD arrangement can be described using an incidence matrix, which is a v by b binary matrix where the $a_{i,j}$ term is specified as follows:

$a_{i,j}$ = 1 if station i is contained in the group j, 0 otherwise.

The incidence matrix for the system described in Fig. 1 is reported below. Every incidence matrix, is constrained by the property of BIBD and therefore has r ones per row and k ones per column.

© 2007 ACADEMY PUBLISHER

$$\begin{bmatrix} 1 & 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & 1 \\ 0 & 1 & 0 & 1 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & 1 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 0 & 1 & 1 \end{bmatrix}$$

The BIBD incidence matrix can be derived by several methods. The most significant exploit the Hadamard Matrices and the Mutually Orthogonal Latin Squares (MOLS) [12]. The methods based on MOLS produce BIBD design only for relatively few values of v. Specifically, let n be a prime number or a power of a prime number, v can assume only the values: $v=n^2$ or $v=n^2+n+1$. As an example, a BIBD design can be obtained for the following values of $v<200$

$$v \in \begin{Bmatrix} 4, 7, 9, 13, 16, 21, 25, 31, 49, 57, 64, 73, 81, \\ 91, 121, 133, 169, 183 \end{Bmatrix}$$

More useful, in the context of this paper, appears the utilization of Hadamard matrices. A Hadamard matrix of order n (H_n) is a square matrix whose elements are +1 and -1 and such that $H\,H^T = n\,I$ [12], where I is the identity matrix and H^T represents the transpose of H. The value of n is not arbitrary, but only the values $n=1$, $n=2$, and $n \equiv 0 \bmod (4)$, can lead to Hadamard matrices.

Various methods have been developed to synthesize the Hadamard matrices [12]: iterative procedure, Williamson method, Paley construction, ecc. The iterative approach appears quite useful and is based on the property that the Kronecker product of two Hadamard matrices H_n and H_m is a Hadamard matrix of order $m \cdot n$. Example of Hadamard matrices derived by Kronecker product are:

$$H_2 = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

$$H_4 = H_2 \otimes H_2 = \begin{bmatrix} H_2 & H_2 \\ H_2 & -H_2 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix}$$

$$H_8 = H_2 \otimes H_4 = \begin{bmatrix} H_4 & H_4 \\ H_4 & -H_4 \end{bmatrix} =$$

$$\begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 & 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 & 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 & 1 & -1 & -1 & 1 \\ 1 & 1 & 1 & 1 & -1 & -1 & -1 & -1 \\ 1 & -1 & 1 & -1 & -1 & 1 & -1 & 1 \\ 1 & 1 & -1 & -1 & -1 & -1 & 1 & 1 \\ 1 & -1 & -1 & 1 & -1 & 1 & 1 & -1 \end{bmatrix}$$

$$H_{16} = H_2 \otimes H_8 = \begin{bmatrix} H_8 & H_8 \\ H_8 & -H_8 \end{bmatrix}$$

The BIBD incidence matrix of order v can be derived by the Hadamard matrix of order $n=v+1$. In fact , it can be shown the following result [19].

Theorem: A normalized Hadamard matrix of order n ($n \geq 8$) is equivalent to a symmetric BIBD design with $v=b=n-1$, $k=r=n/2-1$, $l=n/4-1$.

As an example, from the previous matrix H_8, the BIBD design (7,7,3,3,1) can be easily derived discarding the first row and the first column and replacing the values -1 by 0. The derived incidence matrix, after inessential permutations of rows and columns, is equal to the incidence matrix of the BIBD reported in Fig.2.

In the same way, the BIBD design (15, 15, 7, 7, 3) can be easily derived from H_{16}, with the following blocks [19]

$B_1=\{x_1, x_2, x_3, x_4, x_5, x_6, x_7\}$ $B_2=\{x_1, x_2, x_3, x_8, x_9, x_{10}, x_{11}\}$
$B_3=\{x_1, x_2, x_3, x_{12}, x_{13}, x_{14}, x_{15}\}$ $B_4=\{x_1, x_4, x_5, x_8, x_9, x_{12}, x_{13}\}$
$B_5=\{x_1, x_4, x_5, x_{10}, x_{11}, x_{14}, x_{15}\}$ $B_6=\{x_1, x_6, x_7, x_8, x_9, x_{14}, x_{15}\}$
$B_7=\{x_1, x_6, x_7, x_{10}, x_{11}, x_{12}, x_{13}\}$ $B_8=\{x_2, x_4, x_6, x_8, x_{10}, x_{12}, x_{14}\}$
$B_9=\{x_2, x_4, x_7, x_8, x_{11}, x_{13}, x_{15}\}$ $B_{10}=\{x_2, x_5, x_6, x_9, x_{11}, x_{12}, x_{15}\}$
$B_{11}=\{x_2, x_5, x_7, x_9, x_{10}, x_{13}, x_{14}\}$ $B_{12}=\{x_3, x_4, x_6, x_9, x_{11}, x_{13}, x_{14}\}$
$B_{13}=\{x_3, x_4, x_7, x_9, x_{10}, x_{12}, x_{15}\}$ $B_{14}=\{x_3, x_5, x_6, x_8, x_{10}, x_{13}, x_{15}\}$
$B_{15}=\{x_3, x_5, x_7, x_8, x_{11}, x_{12}, x_{14}\}$.

Extremely useful are also the following results [19].

Theorem 1: In a symmetric ($v=b$, $r=k$) BIBD with blocks B_1, B_2, ….., B_b and set of objects $X=\{x_1, x_2, \ldots, x_v\}$, for any i, the blocks B_1-B_i, B_2-B_i, ….., B_{i-1}-B_i, B_{i+1}-B_i, ….., B_b-B_i, form a BIBD with parameters ($v-k$, $b-1$, r, $k-l$, l)

Theorem 2: In a symmetric ($v=b$, $r=k$) BIBD with blocks B_1, B_2, ….., B_b and set of objects $X=\{x_1, x_2, \ldots, x_v\}$, for any i, the blocks B_1ÇB_i, B_2ÇB_i, ….. , B_{i-1}ÇB_i, B_{i+1}ÇB_i, ….., B_bÇB_i, form a BIBD with parameters (k, $b-1$, $r-1$, l, $l-1$)

As an example, from the symmetric BIBD *(7, 7, 3, 3, 1)*, by applying the *Theorem 1*, considering $i=7$, another BIBD with parameters *(4, 6, 3, 2, 1)* can be derived, with set of objects $X=\{x_1, x_2, x_4, x_5\}$, blocks:

© 2007 ACADEMY PUBLISHER

$\underline{B}_1 = B_1 - B_7 = \{x_1, x_5\}$, $\underline{B}_2 = B_2 - B_7 = \{x_1, x_4\}$,
$\underline{B}_3 = B_3 - B_7 = \{x_1, x_2\}$, $\underline{B}_4 = B_4 - B_7 = \{x_2, x_4\}$,
$\underline{B}_5 = B_5 - B_7 = \{x_2, x_5\}$, $\underline{B}_6 = B_6 - B_7 = \{x_4, x_5\}$,

and incidence matrix:

$$\begin{bmatrix} 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 1 \\ 1 & 0 & 0 & 0 & 1 & 1 \end{bmatrix}$$

Equivalent results can be obtained for any other value of i.

Exploiting the previous design theory results, it can be shown that a BIBD design exists for the practical values of v [12, 19]. As an example, a BIBD design for all values of v=200 have been reported in [18, 20].

III. CF-MAC AND ECF-MAC PROTOCOLS

The developed MAC protocols allow collision free transmissions over a shared wireless medium. It is supposed that the geographical coverage of the network is limited to a few hundreds of meters and thus a negligible propagation delay is experienced, considering a single hop ad hoc network.

A. CF-MAC Protocol Features

In CF-MAC [8,9], the time is partitioned into an endless sequence of fixed duration time slots. Each time slot is divided in an *access window* and a *data exchange window* (fig.2). The access window is split into k minislots, each one is assigned to one of the k stations that share the slot. The others v-k stations are supposed to be in *doze* state. If the station assigned to the first minislot has scheduled traffic to transmit, it sends a RTS (Request To Send) frame to the destination, which replies, if in awake state, with a CTS (Clear To Send) frame. Then the *data exchange window* starts immediately and the two stations can exchange data until the end of the slot. Obviously, the destination station is awake only if it is one of the k stations that share the current slot. The other k-2 stations, listening the RTS/CTS handshake, realize that the channel will become busy and, therefore, transit in doze state.

It may happen that the first station has no pending traffic and thus the RTS is not transmitted or the destination is in doze state and obviously it cannot transmit the CTS frame. In the previous situations, the station assigned to the second minislot can transmit its RTS and so on. Thus, as soon as a station performs the handshake, it gets the right to transmit during the current time slot.

The above outlined collision free access protocol privileges stations in the earlier minislots; therefore, some unfairness among stations can arise. This issue can be solved by assigning minislots in round robin fashion. Fig.3 shows such a round robin scheme for a single slot: in a sequence of $k{\cdot}b$ slots (a *superframe*), each station is assigned one time to the first minislot, one time to the second minislot, and so on.

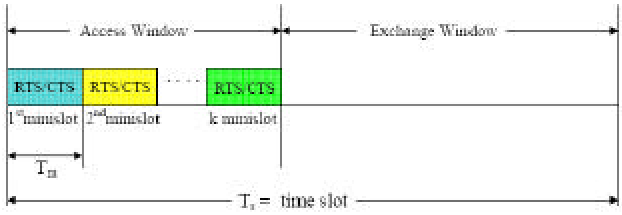

Fig. 2 Structure of a Time Slot

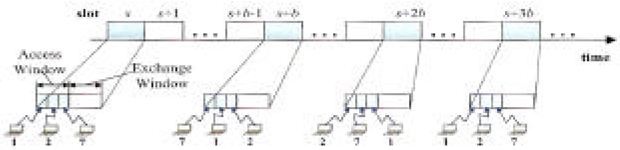

Fig. 3 Round robin scheme in the access window

A significant reduction of power expenditure respect to the first version of CF-MAC can be obtained by considering that BIBD matrices can be saved in a lookup table of each station. In this way, each awake station knows if its destination belongs to the other k-1 awake stations. Furthermore, in case of single hop and static stations the RTS/CTS transmission can be avoided. Therefore, a station assigned to a specific minislot, with pending traffic, can send data frames without undertaking the handshake procedure. When a transmission starts, the remaining k-2 stations transit in doze state until the next time slot.

A substantial modification of CF-MAC (called later ECF-MAC) can be obtained by imposing all stations to stay awake and ready to receive during the access window, while the BIBD schedule continues to be adopted to manage the right of medium access. Therefore, a transmitting station will surely find awake its destination station.

B. ECF-MAC Protocol Features

The enhanced CF-MAC protocol (ECF-MAC) keep the same basic infrastructure of CF-MAC. The k stations that share the slot have the right of transmission, while all the other ones *(v - k)* are awake in *idle* state. A generic station with the right of transmission in a given slot and pending traffic, exploiting the pertinent minislot, like in CF-MAC, sends a RTS frame to the destination station, which, being awake, can certainly replay, with a CTS frame. Then, the transmission starts immediately and the two stations can exchange data. Time slot dimension is not fixed, but can vary between two bounds: T_{min} and T_{max}. In the RTS and CTS frames, sender and receiver include information about the transmission duration thus all other *(v - 2)* stations, listening the RTS/CTS handshake, transit in doze state until a new time slot starts. If none of elected stations have pending traffic all v stations go in doze state for a time interval T_{Doze}.

© 2007 ACADEMY PUBLISHER

Also in this case, the RTS/CTS handshake is not essential if each station catches the access sequence from a lookup table stored in its own memory. Information about the transmission duration are specified in the *data* frame.

IV. Performance Evaluation

In this section, we will show some results about the efficiency of the proposed MAC protocols in case of:

1) traffic saturation with random destination;
2) perfect synchronization among stations;
3) single-hop network;
4) media occupation persisting until the following time slot.

A quite simple analytical model has been developed with the target to highlight the suitability of the BIBD architecture for achieving high channel utilization and substantial power saving.

A. CF-MAC protocols performance

In case of random traffic, i.e., for each slot all stations choose randomly and independently the destination, the probability to choose a station in doze state is:

$$a = \left(\frac{v-k}{v-1}\right) \quad (3)$$

Thus, the probability that in a generic slot the channel is occupied by a transmission, i.e., the probability of channel utilization , is given by:

$$p_u = 1 - a^k = 1 - \left(\frac{v-k}{v-1}\right)^k \quad (4)$$

Let T_m be the duration of a minislot, kT_m the duration of the access window, and T_s the duration of entire time slot.

When in a generic slot the i^{th} station starts the transmission after the RTS/CTS mechanism, the activity time (i.e., the time spent in the awake state) of all stations, T_a, is given by the sum of the activity time of the two stations (source and destination) that remain in active state for the entire slot, i.e. $2T_s$, and the activity time of the remaining *(k-2)* stations that transit in doze state at the end of i^{th} minislot, i.e. $(k-2)iT_m$. The average value of total activity time, after a little algebra, is given by [14]:

$$T_a = T_m\left[\frac{(1-a^k)(k-2)}{1-a} + 2ka^k\right] + 2T_s(1-a^k) \quad (5)$$

The previous quantities allow us to evaluate the energy saving of the proposed MAC scheme, E_s, compared with a scheme that does not implement a power saving mechanism (i.e., the stations are always active). Obviously, when all v stations are awake, the total activity time is vT_s. Thus:

$$E_s = 1 - \frac{T_a}{vT_s} \quad (6)$$

The efficiency of the CF-MAC protocol can be defined as the ratio between the average values of time spent on transmitting payload and the total time. In case of random traffic, such an evaluation can be limited to the single slot. When the i^{th} station gains the right of transmission, the useful time for the payload transmission in the slot is $u_i = T_s - iT_m$. Thus, we obtain [14]:

$$h = \frac{1}{T_S}\sum_{i=1}^{k} u_i p_i = 1 - a^k - \frac{T_m}{T_s}\frac{[1-a^k - ka^k(1-a)]}{1-a} \quad (7)$$

where

$$p_i = (1-a)a^i = \frac{k-1}{v-1}\left(\frac{v-k}{v-1}\right)^{i-1}$$

In fact, probability that the random destination station is found active is independent on the specific minislot and is given by *(k-1)/(v-1)* while $[(v-k)/(v-1)]^{i-1}$ represents the probability that all stations that precede the i^{th} station have chosen a doze destination.

The expressions (3)-(7) can be applied to the CF-MAC with or without the handshaking paradigm. When the RTS/CTS exchange is avoided, the substantial difference is the smaller duration of T_m that can be limited at the propagation time plus a guard time. The chosen value of T_m in this case is 1 µs without RTS/CTS and 30 µs in the other case.

Fig. 4 shows the energy saving of a network with a variable number of stations, for *Ts=3.4* ms. The energy saving increases monotonically with v and saturates at the astonishing value of 98%.

Fig. 5 shows the efficiency of CF-MAC for a variable number of stations, for *Ts=3.4* ms. The efficiency increases monotonically with v until saturates to a value very close to the unity, when v is about 25.

B. ECF-MAC protocols performance

The ECF-MAC imposes that all station are awake during the access window, although only k per time slot gain right to transmit. In this scenario the probability to choose a station in doze state becomes zero. Thus, the average value of the total activity time, can be easily obtained from (5) imposing $v=k$ and $a=0$:

$$T_a = (v-2)T_m + 2T_s \quad (8)$$

Starting from the expression (6), we obtain:

$$E_S = [(v-2)/v](1 - T_m/T_S) \quad (9)$$

The ECF-MAC protocol, like the previous case, in case of static network, allows to avoid the RTS/CTS handshake. In fact, the incidence matrices are known by all stations and those qualified to transmit in the current minislot can send immediately data frame to any station, being all awake. Fig.6 shows the energy saving for a network with a variable number of stations implementing the ECF-MAC protocol, exploiting for T_m and T_s the same values used previously.

The efficiency for the ECF-MAC protocol is independent of the number of stations and is simply given by the following expression:

© 2007 ACADEMY PUBLISHER

$$h = 1 - (T_m / T_s)\,. \qquad (10)$$

CF-MAC and ECF-MAC can be adopted in applications, like sensor networks, where the traffic load can be very light. In such a context, it can be useful to extend the time slot dimension, so that, during the *data exchange window*, the stations can stay in doze state for a larger amount of time, reducing energy expenditure. Specifically, in both protocols, when a certain number of consecutive time slots are empty, the Doze time duration, T_{Doze}, can be gradually increased in a bounded range between $T_{Doze-min}$, and $T_{Doze-max}$. In other words, the increase of T_{Doze} corresponds to the increase of T_s without varying the access window duration. In ECF-MAC, T_{Doze} can be set by a completely distributed procedure. As an example, T_{Doze} can be managed following a procedure similar to the TCP congestion control procedure.

In CF-MAC, instead, a certain number of RTS packets must be transmitted to ensure that all nodes of the network are synchronized with the current Time Slot duration.

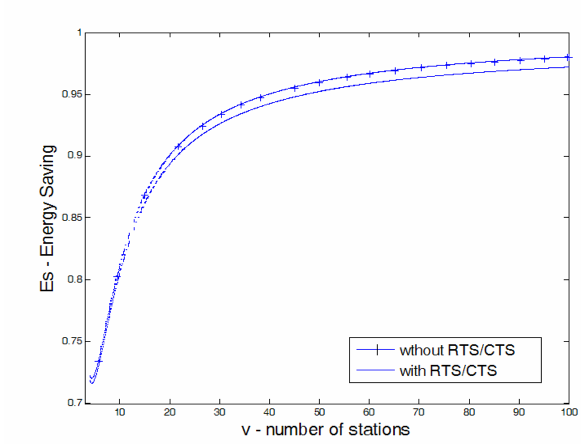

Fig. 4 Energy saving of CF-MAC (Ts=3.4 ms)

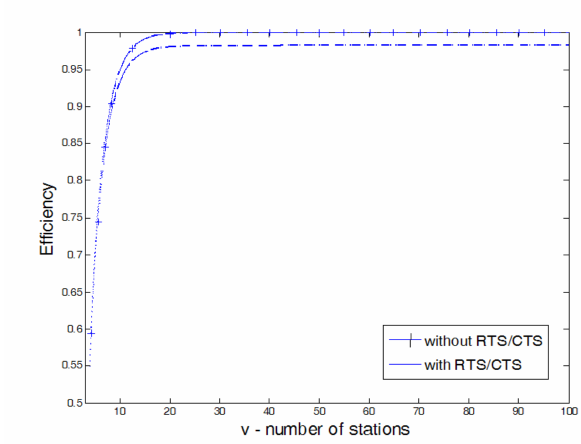

Fig. 5 Efficiency of CF-MAC (Ts=3.4 ms)

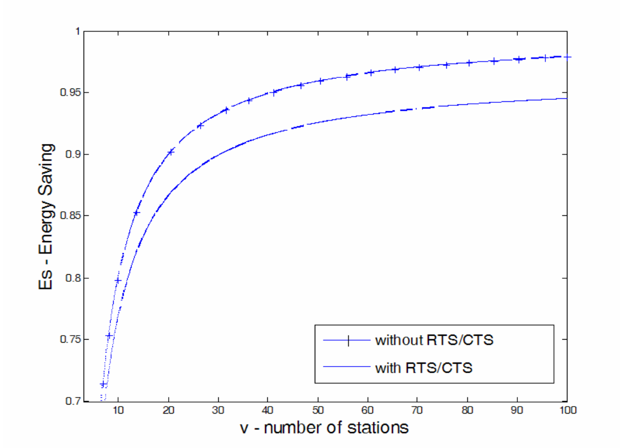

Fig. 6 Energy saving of ECF-MAC (Ts=3.4 ms)

V. CF-MAC AND ECF-MAC FOR VOICE COMMUNICATION

In this section, the ability of CF-MAC and ECF-MAC protocols to support VoIP traffic is investigated. For such a purpose, an event driven ad-hoc simulation tool has been developed in C language using libraries proposed in [21].

Our investigation considers a single-hop ad-hoc network with the following BIBD parameters (15, 15, 7, 7, 3), (31, 31, 15, 15, 7) or (39, 39, 20, 20, 10), considering an ideal radio channel behaviour.

We have focused on the one-way packet delay as a function of time slot duration *Ts* in the range [1 ÷ 2:5 ms]. For each considered scenario, we simulate one hour of the ad hoc network behaviour, running 10 simulations, each one with a different seed for the random number generator. Therefore, each reported result is evaluated as the average of these 10 repetitions in order to filter out statistical fluctuations.

Each station chooses randomly its destination and, after the end of a call, a new communication starts immediately toward a new randomly chosen station. Call duration is exponentially distributed with mean of 2 minutes. For voice calls, the G.729 codec (i.e., source rate is 8 kbps) with two frames per packet is considered. Thus, taking into account the protocol stack (i.e.,RTP/UDP/IP/LLC/MAC), packets are 86 bytes long.

In order to evaluate perceived speech quality, we used the ITU E-model [22], widely adopted for estimating speech transmission quality under various impairments. The major advantage of this model is that it separates the perceptual effects caused by the single impairment, allowing their analysis distinctly. The output of the E-model is the transmission rating factor *R*, defined as follows:

$$R = R_O - I_S - I_d - I_{e-eff} + A \qquad (15)$$

where *Ro*, *Is*, and *A* are factors associated with signal propagation; I_d is the delay impairment; I_{e-eff} is the equipment impairment (which captures the effect of information loss caused by encoding scheme and packet loss).

© 2007 ACADEMY PUBLISHER

To assess the effect of delay and packet loss on quality of speech transmission, it is a common practice to consider an ideal radio channel; thus, using default values of *Ro*, *Is*, and *A* given in [22], the eq. (15) becomes:

$$R = 93.2 - I_d - I_{e-eff}. \quad (16)$$

For the I_d factor we used the simplified equation obtained in [23] which gives an Id value of 1.2, 2.4, 3.6, 7.3 for a fixed delay of 50, 100, 150, 200 ms respectively. I_{e-eff} is evaluated considering the procedure suggested in [22, 24, 25]. In the context of this paper, where the packet loss can be neglected, I_{e-eff} @ *10* [15].

The *R* factor can be mapped in the well-known quality metric Mean Opinion Score (MOS) [24], which is defined as the arithmetic mean of a collection of subjective opinion scores given by users in an integer scale from 1 (bad) to 5 (excellent). Basing on the categories of speech transmission quality given in [25], a MOS value above 3.6 corresponds to satisfaction for almost all users. The mapping between *R* and MOS is reported in [22], with a maximum value for MOS equal to 4.5. In particular, considering no packet loss and a G.729 codec, the maximum ideal MOS achievable is 4.14.

Following recommendations in [22], the MOS has been evaluated periodically every 10 s, for each communication.

Fig. 7 shows the CDF of the one-way packet delay as a function of time slot size for CF-MAC with 38 active nodes (i.e., the scenario with the highest traffic load). The best results are obtained with small values of *Ts* (e.g., with *Ts* = 1.5 ms more than 94% of the packets have a delay under 100 ms), but we have acceptable delays also for larger values of *Ts*.

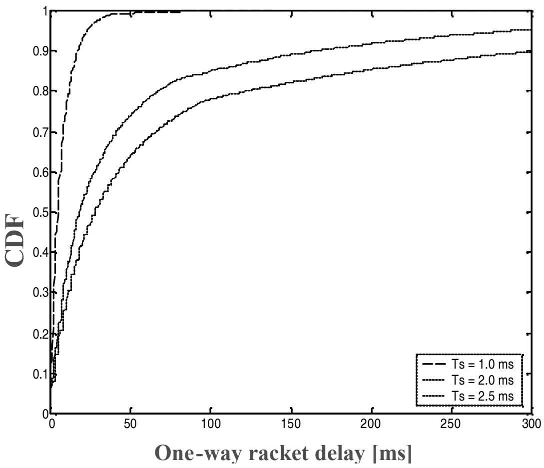

Fig. 7. CF-MAC: CDF of one-way packet delay vs. time slot size (38 active nodes).

Fig. 8 reports the cumulative distribution of one-way packet delay in the same network considered before but ECF-MAC based. It shows that, for a T_{Doze} interval of 10 ms, all packets are received within 40 ms. Moreover, for T_{Doze} larger than 60 ms, the cumulative function saturates to 1 with a delay of (T_{Doze} + 20) ms.

Fig.9 shows CDF of MOS for both protocols when total energy consumption is equal for both CF and ECF-MAC, that is when time slot duration is 1.5 ms for CF-MAC, and T_{Doze} is 100 ms for ECF-MAC.

The whole results have shown that, fixed the energy consumption level, ECF-MAC enables to reduce the one way packet delay with respect to CF-MAC. However, CF-MAC is more energy saving when traffic is very low, because it allows to be awake only *k* stations during the access window.

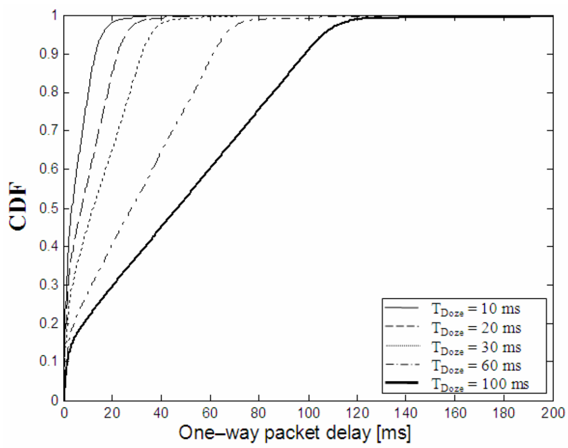

Fig. 8. ECF-MAC: CDF of one way packet delay of a 38 nodes network for several values of T_{Doze}.

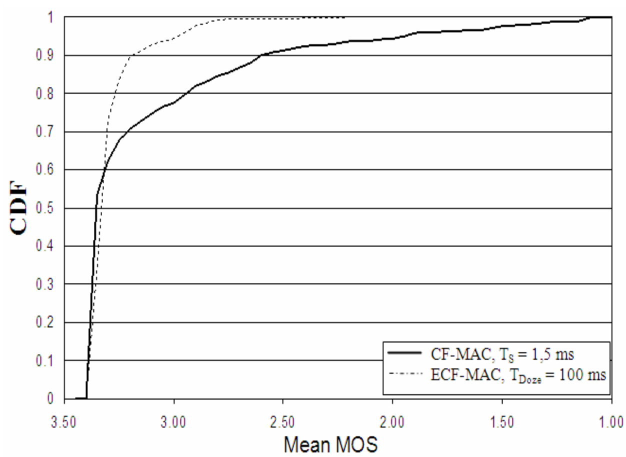

Fig. 9. Comparison of CDF of MOS index between CF and ECF-MAC adopted in 38 nodes network

VI. Conclusions

Starting from the theory of Balanced Incomplete Block Design (BIBD), in this paper we have investigated the effectiveness of two collision free MAC protocols for wireless Ad-Hoc networks, namely CF-MAC and ECF-MAC and their variants, with the target to enhance power saving and channel efficiency. The performance of the proposed MAC schemes have been analytically evaluated showing high efficiency and substantial savings of energetic resources. The suitability of the two MAC schemes to support VoIP applications has also been evaluated by computer simulation.

© 2007 ACADEMY PUBLISHER

The proposed MAC schemes based on BIBD can be extended in several directions. One of the most important extensions is represented by the utilization of several parallel wireless channels. In such a context, the resolvability aspect of a BIBD can be usefully exploited [28]. Another extension can be pursued by considering the application of BIBD structures to multihop wireless networks.

ACKNOWLEDGMENT

This work was supported in part by a grant from Apulia Region's Projects PE_074 and PS_092.

REFERENCES

[1] T. Rouse, S. McLaughlin, and I. Band, "Congestion-Based Routing Strategies in Multihop TDD-CDMA Networks", IEEE Journal on Selected Areas in Communications, Vol. 23, No. 3, March 2005.

[2] W. Stark, W. Hua, A. Worthen, S. Lafortune, and D. Teneketzis, "low energy wireless communication network design" IEEE Wireless communications, vol.9, n.4, pp. 60-72, 2002.

[3] A. K¨opsel and A.Wolisz, "Voice transmission in an IEEE 802.11 WLAN based access network," *Proc. of WoWMoM*, Rome, Italy, Jul. 2001.

[4] S. Garg and M. Kappes, "Can I add a VoIP call?" *Proc. of IEEE ICC*, May 2003.

[5] D. Hole and F. Tobagi, "Capacity of an IEEE 802.11b wireless LAN supporting VoIP," *Proc. of IEEE ICC*, Paris, France, Jun. 2004.

[6] G. Cena, I. Cibrario Bertolotti, A. Valenzano, and C. Zumino "Evaluation of Response Times in Industrial WLANs", IEEE Transactions on Industrial Informatics, Vol. 3, No. 3, August 2007.

[7] W. Stark, W. Hua, A. Worthen, S. Lafortune, and D. Teneketzis, "Low-energy wireless communication network design," *IEEE, Wireless Commun.*, vol. 9, no. 4, pp. 60–72, Aug. 2002.

[8] IEEE 802.11, Information technology- Telecommunications and Information Exchange between Systems- Local and Metropolitan Area Networks- Specific Requirements-Part11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, 1st ed. ANSI/IEEE Std.802.11, ISO/IEC 8802-11, 1999.

[9] D.S.Chan, T.Berger and R.Bridgelall "Energy saving of CSMA protocols for wireless packet switched networks", Wireless Communications and Networking Conference WCNC 2004, vol.1, March 2004, pp.447-452.

[10] Y.yuan, D.Guy, W.Arbaugh, and J.Zhang, "High performance mac for high-capacity wireless lans", International Conference On Computer Communications and Networks ICCCN 2004.

[11] Y.Wei, J.Heidemann, and D.Estrin, "Medium access control with coordinated adaptive sleeping for wireless sensor networks", IEEE/ACM Transactions on Networking, vol.12, no.3, june 2004.

[12] M. Hall, "Combinatorial Theory", 2nd ed. Wiley, 1998.

[13] G.Boggia, P.Camarda, O.Fiume, and L.A.Greco "CF-MAC e H-MAC Protocols for Energy Saving in Wireless Ad Hoc Networks" VTC'05 Spring, Stockholm, 2005

[14] G.Boggia, P.Camarda, M.Castellano, O.Fiume, L.A.Greco, and S.Mascolo "A Collision Free MAC Protocol for Energy Saving in Wireless Ad Hoc Networks" IWWAN'04, Oulu, Finland, 2004.

[15] G.Boggia, P.Camarda, R.Dell'Aquila, O.Fiume, and L.A.Grieco "CF-MAC Protocol for Voice Communication in Wireless Ad-Hoc Networks" Second IEEE Workshop on multiMedia Applications over Wireless Networks (MediaWiN 2007), July 1st 2007, Aveiro, Portugal.

[16] C.J. Colbourn, J.H. Dinitz, D.R. Stinson "Applications of Combinatorial Design to Communications, Cryptography, and Networking" Surveys in Combinatorics 1999 (J.D. Lamb and D.A. Preece, eds.), Cambridge University Press, pp. 37-100.

[17] S.A. Camtepe, B. Yener "Combinatorial Design of Key Distribution Mechanisms for Wireless Sensor Networks" IEEE/ACM Transactioins on Networking, Vol.15, No.2, April 2007.

[18] G. Marraffa, "MAC protocols for energy saving in Wireless Ad-Hoc Networks" Eng. degree thesis, *Politecnico di Bari*, April 2006.

[19] C.L. Liu, "Introduction to Combinatorial Mathematics", McGraw Hill, 1968.

[20] L. Nonnato "Prestazioni di Protocolli MAC basati su BIBD in Reti Wireless Ad-Hoc" Eng. degree thesis, *Politecnico di Bari*, Dec. 2006.

[21] M. H. MacDougall, *Simulating Computer System Techniques and Tools*, 1st ed. The MIT Press, 1987.

[22] Int. Telecommun. Union, *The E-model, a computational model for use in transmission planning*, ITU-T Recomm. G.107, Mar. 2003.

[23] R. Cole and J. Rosenbluth, "Voice over IP performance monitoring," *Computer Communication Review*, vol. 31, no. 2, pp. 9–24, April 2001.

[24] ——, *Methods for subjective determination of transmission quality*, ITU-T Recomm. P.800, Aug. 1996.

[25]——, *Definition of categories of speech transmission quality*, ITU-T Recomm. G.109, Sep. 1999.

[26] ——, *Transmission impairments due to speech processing; Appendix I: Provisional planning values for the equipment impairment factor Ie and packet-loss robustness factor Bpl*, ITU-T Recomm. G.113 Appendix I, May 2002.

[27] Telchemy Incorporated, *Estimates of Ie and Bpl parameters for a range of CODEC types*, ITU-T SG12 D.106, Jan. 2003.

[28] D.R. Stinson "Combinatorial Design, Construction and Analysis", Springer-Verlag, 2004.

Pietro Camarda graduated in Computer Science from the University of Bari, Italy, in 1978. Since 1986, he has been with the department of "Elettrotecnica ed Elettronica" at the "Politecnico di Bari", Italy, where he is currently Professor of Telecommunication. He was visiting scholar from October 1986 to December 1987 at Computer Science Department of the University of California, Los Angeles with the supervision of Prof. Mario Gerla. He has been involved in various research areas, mainly: LAN/MAN Architectures and Protocols, Optical Networks, Network Reliability, Cellular Radio Networks, Telecommunication Services, etc.

Orazio Fiume Graduated in Electric Engineering at Politecnico di Bari, Italy, in 2000. He attended, starting from 2002, the PhD school of Telecommunication under the guidance of Prof. Pietro Camarda. In 2005 he concluded his experience in the department of "Elettrotecnica ed Elettronica" at the "Politecnico di Bari" by receiving PhD degree with a thesis on Energy Saving Protocols for ad hoc and sensor networks. He, also, participated in researches areas about augmented reality and image segmentation for surgery applications.

© 2007 ACADEMY PUBLISHER