A Distributed CDMA Scheme in Wireless Mobile Ad-Hoc Networks

Mehdi Gheisari

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Mehdi gheisari
Islamic Azad University

Abstract

CDMA is a spread spectrum multiple access scheme in which a transmitter spreads the information signal in a wide frequency band by using a spreading code. In this paper, we have designed a code assignment algorithm for clustered wireless mobile ad-hoc networks with unknown traffic parameters. In this algorithm, the interference-free inter-cluster communications are organized by cluster-heads using a CDMA scheme. Therefore, to design such a algorithm, we encounter two important problems, namely cluster formation and code assignment. In this paper, we propose two phases algorithm to solve the addressed problems based on learning automata. In the first phase of proposed algorithm, the wireless hosts are grouped into non-overlapping clusters. Then in the second phase of the algorithm, an interference-free code is assigned to each cluster. The learning automata residing in each cluster head allocates a code to its cluster head. We have implemented the system in network simulator "GloMoSim". In addition, we have rigorously evaluated the performance of our proposed solution by performing a variety of experiments through the extensive simulation experiments. The performance of proposed algorithm is measured, and the results are compared with CS-DCA, LACAA and Hybrid-DCA protocols in terms of the number of used codes, code spatial reuse, blocking rate, waiting time for packet transmission and throughput. Simulation results show that the proposed method outperforms the existing methods in terms of almost metrics of interest under the same conditions.

Keywords: CDMA, Code assignment, Mobile ad-hoc networks, Learning automata, GloMoSim.

1. Introduction

CDMA is a spread spectrum multiple access scheme in which a transmitter spreads the information signal in a wide frequency band by using a spreading code. A receiver uses the same code to retrieve the received signal as well. This approach provides multiple accesses by allowing the simultaneous transmission by different nodes, and is employed to reuse the bandwidth and to reduce the interferences. In CDMA scheme, each group of nodes can be given a shared code. Many codes occupy the same channel, but only nodes associated with a particular code can understand each other. If the codes are orthogonal, or nearly so, so that any bit errors caused by co-channel interference can be handled by forward error correction, multiple nodes may occupy the same band. In the spread spectrum CDMA system, each node needs to know which code must be used for transmitting or receiving a particular packet. Indeed, the receiver should be set to the same code as the designated transmitter. Since the number of available codes is limited, it is impossible to assign a unique code to each transmitter or receiver, and so the concept of the code spatial reuse seems to be promising. In a clustered network, this means that two or more non-neighboring clusters can be assigned the same code. An interference-free code assignment problem is similar to the vertex coloring problem in which the neighboring nodes (clusters) are refrained from choosing the same colors (codes). Graph coloring problem is known to be NP-hard [1].

In CDMA scheme, simultaneous transmissions can be isolated by using different spreading codes. However, a node in a spread spectrum CDMA system needs to know which code should be used for transmitting or receiving a particular packet. In this scheme, a unique code is assigned to each transmitter and this is a trivial problem if the network size is small. But, when we employ the CDMA scheme in a large multi-hop ad-hoc network, the code assignment becomes an intractable problem. The concept of the code spatial reuse is a well-known solution reported in the literature ([2],

[3]) by which a host of connections can be handled with a minimum number of codes. Another promising approach to solve the code assignment problem is using the CDMA/TDMA technique [3], [4]. To design a CDMA scheme, two following issues must be considered. First, grouping the hosts into a number of non-overlapping clusters and second, assigning a code to each cluster so that no two neighboring clusters have the same code.

Many studies have been carried out on the CDMA/TDMA scheme in cellular networks [5], [6], [7] and [8], while in ad-hoc networks; it has not received the attention it deserved. Moreover, Richard lin and Gerla in [9] introduced a network architecture in which the nodes are organized into non-overlapping clusters. In this method, the clusters are independently controlled and are dynamically reconfigured as the nodes move. In [10], the authors also proposed a distributed cluster formation algorithm. The cluster heads act as local coordinators to resolve channel scheduling, perform power measurement/control, maintain time division frame synchronization, and enhance the spatial reuse of time slots and codes. Using a CDMA scheme, an interference-free code is assigned to each cluster, and a TDMA scheme is used within the clusters. In [11], authors also proposed a CDMA/TDMA based scheme for multimedia support in a self-organizing multi-hop mobile network. They introduced a network architecture in which the nodes are organized into non-overlapping clusters. In this method, the clusters are independently controlled and are dynamically reconfigured as the nodes move. In [11], an interference-free channel access scheduling method is proposed to handle the inter-cluster communications based on graph coloring problem. Due to the node clustering, the proposed method provides spatial reuse of the bandwidth. Furthermore, the bandwidth can be shared or reserved in a controlled fashion in each cluster. Yang and Chang in [12] proposed a dynamic code assignment algorithm for hybrid Multi-Code CDMA/TDMA systems. The proposed code assignment scheme takes into account the time-varying traffic characteristics of the mobile users. In this algorithm, the base station assigns more codes to the mobiles during the congestion period. The extra codes are then released when the congestion subsides. In this method, the congestion is predicted based on the queue length of the mobiles.

In [9], the authors proposed a self-organized dynamic channel assignment scheme called CS-DCA to improve the spectrum efficiency for a TDMA microcellular system. The proposed scheme takes advantage of the channel segregation method introduced by [13]. In channel segregation scheme, the channels are shared and dynamically assigned to the neighboring cells. In this method, for each cell, a dynamic priority is associated with every channel. When a call arrives, the channel with the highest priority is selected. If the selected channel is in use by the neighboring cells, the priority of the selected channel decreases, the next-highest priority channel is selected, and the same operation is repeated for the remaining channels. Otherwise, the selected channel is assigned to the call and the priority of the channel increases. This process is repeated until a free channel is found. In [9] the authors proposed a greedy based dynamic channel assignment algorithm called GB-DCA for cellular mobile networks. The proposed algorithm reduces the call blocking probability and increases the traffic-carrying capacity of the entire network. GB-DCA dynamically allocates the channels based on a greedy method. It uses an exhaustive search scheme for finding the co-channels. However, GB-DCA is designed for the cellular networks, where the wireless communications are limited to the same cell. In this case, only the neighboring cells are refrained from using the same codes. The code assignment problem becomes significantly harder when the GB-DCA is applied in multi-hop ad hoc networks. In [3], the authors proposed a CDMA/TDMA scheme for clustered wireless ad-hoc networks in which GB-DCA is used to handle interference-free code assignments. Wu designed a dynamic channel assignment algorithm called Hybrid-DCA to make the best use of available channels by taking advantage of the spatial reuse concept. In this approach, the TDMA scheme is overlaid on top of the CDMA scheme to divide the bandwidth into smaller chunks. Hybrid-DCA forms the channel as a particular time slot of a particular code. It borrows the color-based cluster formation algorithm proposed in [2] for clustering the wireless ad hoc networks. It also uses the channel segregation-based dynamic channel assignment algorithm (CS-DCA) proposed in [4] to assign the collision-free intra-cluster channel accesses. In Hybrid-DCA, the increase in spatial reuse is achieved by GB-DCA [14] and the decrease in control overhead by CS-DCA ([4]).

To design the proposed algorithm, the following two important problems must be considered; Cluster formation and code assignment in CDMA scheme problems. In this paper, we propose a learning automata-based algorithm to solve the code assignment problem. By the proposed cluster formation algorithm, the network is partitioned into a small number of clusters, each with a cluster-head and a number of cluster members. Inter-cluster connections are handled by a CDMA scheme, in which an interference-free code must be assigned to each cluster. To do so, we propose a code assignment algorithm based on the vertex-coloring problem in which the neighboring clusters are refrained from choosing the same codes. By the proposed scheme, the following advantages can be achieved. This scheme organizes the channel access in groups, and so can be effectively used in scalable multi-hop ad-hoc networks. The number of required codes decreases to at most the number of groups, and exploiting the code spatial reuse concept, it can be minimized.

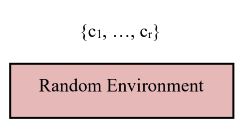
Through the extensive simulation experiments, the performance of the proposed CDMA scheme is measured and compared with CS-DCA [4] and Hybrid-DCA [3] in terms of the number of clusters, code and channel spatial reuse, blocking rate, waiting time for packet transmission, control overhead and throughput. The obtained results show that the proposed scheme outperforms others in almost all metrics of interest, specifically, under burst traffic conditions.

The rest of the paper is organized as follows. The next section introduces the learning automata concepts, and Section 3 describes the proposed overlaid CDMA scheme. Section 4 shows the superiority of the proposed scheme over the existing methods through the simulation experiments. Section 5 concludes the paper.

2. Learning Automata

A learning automaton ([15], [16], [17], [24], [25]) is a simple adaptive decision-making unit that improves its performance by learning how to choose the optimal action through the repeated interactions with a random environment. The action is chosen at random based on a probability distribution kept over the action-set and at each instance; the given action is served as the input to the random environment. The environment responds the taken action in turn with a reinforcement signal. The action probability vector is updated based on the reinforcement feedback from the environment. The objective of a learning automaton is to find the optimal action from the action-set so that the average penalty received from the environment is minimized. Learning automata have been extensively studied for the last three decades because of the applicability of such a probabilistic learning model in computer and communication problems. The results given in references [26], [27] show that the learning automata can be effectively used for solving the intractable optimization problems. In [24], several attempts have been also made to exhibit the capabilities of the learning automata in dynamic wireless ad hoc networks.

The environment can be described by a triple $E = \{\alpha, \beta, c\}$ where $\alpha = \{\alpha_1, \alpha_2, ..., \alpha_r\}$ represents the finite set of inputs, $\beta = \{\beta_1, \beta_2, ..., \beta_m\}$ denotes the set of the values can be taken by the reinforcement signal, and $c = \{c_1, c_2, ..., c_r\}$ denotes the set of the penalty probabilities, where the element c_i is associated with the given action α_i. if the penalty probabilities are constant, the random environment is said to be a stationary random environment, and if they vary with time, the environment is called a non-stationary environment. The environment depending on the nature of the reinforcement signal $\underline{\beta}$ can be classified into *P*-model, *Q*-model, and *S*-model. The environments in which the reinforcement signal can only take two binary values 0 and 1 are referred to as *P*-model environments. Another class of the environment allows a finite number of the values in the interval [0, 1] can be taken by the reinforcement signal. Such an environment is referred to as *Q*-model environment. In *S*-model environments, the reinforcement signal lies in the interval [a, b]. The relationship between the learning automaton and its random environment has been shown in figure 1.



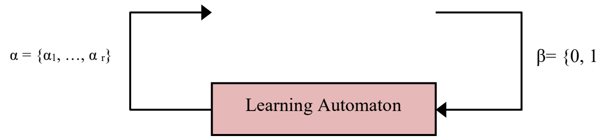


Fig. 1. The Automaton-Environment feedback loop

Moreover, Learning automata can be classified into two main families [15]: fixed structure learning automata and variable structure learning automata. Variable structure learning automata are represented by a triple $\langle \underline{\beta}, \underline{\alpha}, \underline{T} \rangle$ where $\underline{\beta}$ is the set of inputs, $\underline{\alpha}$ the set of actions, and *T* learning algorithm. The learning algorithm is a recurrence relation, which is used to modify the action probability vector. Let *α(k)* and $\underline{p}(k)$ denote the action chosen at instance *k* and the action probability vector on which the chosen action is based, respectively. The recurrence equation shown by (1) and (2) is a linear learning algorithm by which the action probability vector $\underline{p}$ is updated. Let $\alpha_i(k)$ be the action chosen by the automaton at instant *k*.

$$p_j(n+1) = \begin{cases} p_j(n) + a.(1 - p_j(n)) \\ p_j(n) - a.p_j(n) & \forall j \quad j \neq i \end{cases} \tag{1}$$

When the taken action is rewarded by the environment (i.e., *β(n)=0*) and

$$p_j(n+1) = \begin{cases} (1-b).p_j(n) & j = i \\ \left(\dfrac{b}{r-1}\right) + (1-b)p_j(n) & \forall j \quad j \neq i \end{cases} \tag{2}$$

when the taken action is penalized by the environment (i.e., *β(n) =1*). *r* is the number of actions that can be chosen by the automaton, *a*(k) and *b*(k) denote the reward and penalty parameters and determine the amount of increases and decreases of the action probabilities, respectively. If *a(k)=b(k)*, the recurrence Eqs. (1) and (2) are called linear reward–penalty ($L_{R\text{-}P}$) algorithm, if *a(k)>>b(k)* the given equations are called linear reward–*ε* penalty ($L_{R\text{-}\varepsilon P}$), and finally, if *b(k) =0* they are called linear reward–inaction ($L_{R\text{-}I}$). In the latter case, the action probability vectors remain unchanged when the taken action is penalized by the environment. In the multicast routing algorithm presented in this paper, each learning automaton uses a linear reward–inaction learning algorithm to update its action probability vector. In the following, some convergence results of the learning automata are summarized.

Definition 2.1. The average penalty probability *M(n)*, received by a given automaton is defined as

$$M(n) = E[\beta(n) \mid \zeta_n] = \int_{\alpha \in \underline{\alpha}} \zeta_n(\alpha) f(\alpha)$$

Where $\zeta : \underline{\alpha} \to [0,1]$ specifies the probability of choosing each action $\alpha \in \underline{\alpha}$, and $\xi_n(\alpha)$ is called the action probability.

If no priori information is available about *f*, there is no basis for selection of action. So, all the actions are selected with the same probabilities. This automaton is called *pure chance automaton* and its average penalty is equal to

$$M_0 = E[f(\alpha)]$$

Definition 2.2. A learning automaton operating in a *P*-, *Q*-, or *S*-model environment is said to be *expedient* if

$$\lim_{n \to \infty} E[M(n)] < M_0$$

Expediency means that when automaton updates its action probability function, its average penalty probability decreases. Expediency can also be defined as a closeness of $E[M(n)]$ to $f_l = \min_\alpha f(\alpha)$. It is desirable to take an action by which the average penalty can be minimized. In such case, the learning automaton is called *optimal*.

Definition 2.3. A learning automaton operating in a *P*-, *Q*-, or *S*-model environment is said to be *absolutely expedient* if $E[M(n+1) \mid \underline{p}(n)] < M(n)$ for all n and all $p_i(n)$.

Absolute expediency implies that $M(n)$ is a super martingale and $E[M(n)]$ is strictly decreasing for all n in all stationary environments. If $M(n) <= M_0$, absolute expediency implies expediency.

Definition 2.4. A learning automaton operating in a *P*-, *Q*-, or *S*-model environment is said to be *optimal* if

$$\lim_{n\to\infty} E[M(n)] = f_l$$

Optimality implies that asymptotically the action for which penalty function attains its minimum value is chosen with probability one. While optimality appears a very desirable property, certain conditions in a given situation may preclude its environment. In such cases, a suboptimal performance is desirable. Such property is called ε-optimality and is defined in the following definition.

Definition 2.5. A learning automaton operating in a *P*-, *Q*-, or *S*-model environment is said to be ε-optimal if

$$\lim_{n\to\infty} E[M(n)] < f_l + \varepsilon$$

can be obtained for any $\varepsilon > 0$ by a proper choice of the parameters of the learning automaton. ε-optimality implies that the performance of the learning automaton can be made as close to the optimal as desired.

2.1. Variable action-set learning automata

A variable action-set learning automaton is an automaton in which the number of actions available at each instant varies with time. In comparison with a variable action-set learning automaton, learning automaton with a fixed action-set is much easier to deal with. Fixed action-set learning automata are also easier for analysis. Therefore, the variable action-set learning automata have not received the attention they deserve. However, a learning automaton with a changing number of actions is absolutely expedient and also ε-optimal, when the reinforcement scheme is L_{R-I}. Such an automaton has a finite set of n actions, $\alpha = \{\alpha_1, \alpha_2, \ldots, \alpha_n\}$. $A = \{A_1, A_2, \ldots, A_m\}$ denotes the set of action subsets and $A(k) \subseteq \alpha$ is the subset of all the actions can be chosen by the learning automaton, at each instant k. The selection of the particular action subsets is randomly made by an external agency according to the probability distribution $q(k)=\{q_1(k), q_2(k), \ldots, q_m(k)\}$ defined over the possible subsets of the actions, where

$$q_i(k) = prob[A(k) = A_i \mid A_i \in A, 1 \le i \le 2^n - 1]$$

$\hat{p}_i(k) = prob[\alpha(k) = \alpha_i \mid A(k), \alpha_i \in A(k)]$ is the probability of choosing action α_i, conditioned on the event that the action subset $A(k)$ has already been selected and also $\alpha_i \in A(k)$. The probability of choosing the disabled actions is set to zero and the scaled probability $\hat{p}_i(k)$ is defined as

$$\hat{p}_i(k) = p_i(k) / K(k) \tag{3}$$

Where $K(k) = \sum_{\alpha_i \in A(k)} p_i(k)$ is the sum of the probabilities of the actions in subset $A(k)$, and $p_i(k)=prob[\alpha(k)=\alpha_i]$.

The procedure of choosing an action and updating the action probabilities in a variable action-set learning automaton can be described as follows. Let *A(k)* be the action subset selected at instant *k*. Before choosing an action, the probabilities of all the actions in the selected subset are scaled as defined in Eq. (3). The automaton then randomly selects one of its possible actions according to the scaled action probability vector $\hat{p}(k)$. Depending on the response received from the environment, the learning automaton updates its scaled action probability vector. Note that the probability of the available actions is only updated. In some cases, we need to enable the removed actions again. To do so, the probability vector of the actions of the chosen subset is rescaled as $p_i(k+1) = \hat{p}_i(k+1)K(k)$, for all $\alpha_i \in A(k)$.

3. The proposed CDMA scheme

To design a CDMA scheme for clustered wireless ad-hoc networks, we encounter the following two intricate problems. The first problem is dividing the network into a minimum number of non-overlapping clusters. The second problem is to assign an interference-free code to each cluster considering the concept of the maximum code spatial reuse. That is, this problem is assigning the minimum number of codes to the clusters so that no two neighboring clusters are assigned the same codes. This problem is similar to the graph (vertex) coloring problem in graph theory, which is known to be NP-hard [1]. Therefore, we design two phases algorithm to solve the mentioned problems. In the first phase of our algorithm, we propose a learning automata-based clustering algorithm as the entire network is partitioned in to non-overlapping clusters with one cluster-head for each cluster. In the second phase, the CDMA scheme proposes a learning automata-based solution. Each of the above mentioned problems are described in detail below.

3.1. Phase 1: Learning automata based cluster formation algorithm

In ad-hoc networks, the theoretical analysis [18] shows that even under the optimal circumstances, the throughput of each host rapidly declines as the network size increases. Among the solutions proposed for solving the scalability problem in ad hoc networks, network clustering has attracted a lot of attention. The main idea behind the clustering approach is to group together the network hosts that are in physical proximity. The clusters provide a hierarchical structure to abstract the large scale networks which can be simply and locally organized [19], [20]. A clustering algorithm is a method for dividing the network into clusters so that each cluster includes a number of cluster members and a cluster-head (CH) with which the members can directly communicate. Due to the host mobility, strict resource limitations (e.g., bandwidth and power limitations), and hard to predict topology changes, clustering in ad hoc networks aims at dividing the network hosts into a minimum number of groups with the maximum stability.

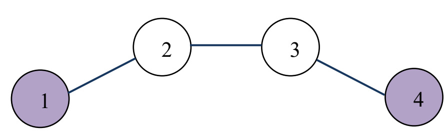
In this section, we propose a learning automata-based algorithm for clustering the wireless ad-hoc networks. In this algorithm, a network of learning automata isomorphic to the network graph is formed by assigning each host h_i a learning automaton A_i. Since we associate a learning automaton with each host, hereafter, host h_i may be called as learning automaton A_i and vice versa. The resulting network of learning automata can be described by a duple $< \underline{A}, \underline{\alpha} >$, where $A=\{A_1, A_2, \ldots, A_n\}$ denotes the set of learning automata corresponding to the vertex set of the network graph, and $\underline{\propto} = \{\underline{\alpha_1}, \underline{\alpha_2}, \ldots, \underline{\alpha_n}\}$ denotes the set of action-sets, in which $\underline{\alpha_i} = \{\alpha_j^i | h_i \text{ is a neighbor of } h_j \text{ or } i = j\}$ defines the set of actions can be taken by learning automata A_i. The action-set of host h_i (or learning automaton A_i) includes an action for each of its neighboring hosts as well as an action for itself. Choosing actionα_i^j by host h_i means that host h_i selects host *hj* as its cluster-head. That is, each host can chooses one of its neighboring hosts or itself as its cluster-head. The proposed cluster formation algorithm consists of a number of stages, and at each stage, each host picks its cluster-head among its neighbors or declares itself as a cluster-head. The following steps briefly describe a sample stage of the proposed cluster formation algorithm that is executed at host h_i.

This algorithm is a fully distributed algorithm in which each host chooses its cluster-head based solely on the local information received from its neighboring hosts. The algorithm is independently run at each host, and the information upon which the CH selection decision is based is confined to the neighborhood of the host. Furthermore, in the proposed algorithm, the hosts need not to be synchronized, and the neighboring hosts locally form the clusters.

In this algorithm, when a host joins the network, it initially broadcasts a *JREQ* (i.e., join request) message and then waits for a certain period of time. If a CH receives the *JREQ* message, it replies by sending back a *JREP* (join reply) message. If the newly joining host receives a *JREP* message, it chooses the sender of the *JREP* message as its CH, and sends a *CH-SEL* message to it. Otherwise, it chooses the neighboring host with the higher ID number as its CH. In this case, the new cluster-head calls CDMA algorithm (described later) to receive a code. If the newly joining host receives more than one *JREP* message, it selects the sender with the higher ID number as its CH.

In mobile ad hoc networks, due to the node mobility and failures, the network topology frequently changes. Due to these dynamics, the network clusters may rapidly lose their validity, and the network must be clustered again. Re-clustering phase in many clustering algorithms reported in the literature is performed periodically for the entire network. In such algorithms, in predetermined time intervals, the normal operation of the network is interrupted, the clustering algorithm is performed on the entire network (producing a completely new clustered infrastructure) and then the normal operation of the network is resumed. Such periodical re-clustering schemes has a number of drawbacks. The very first problem with such schemes is that they consume too much energy because the re-clustering is performed on the entire network. Another problem is that the normal operation of the network is delayed until the re-clustering phase is over. Unlike such re-clustering schemes, firstly, the proposed re-clustering algorithm is performed locally and adaptively whenever it is needed. Secondly, by this method, the re-clustering is performed where the previous infrastructure is not valid anymore. In proposed algorithm, when a cluster-head decides to leave the network, it broadcasts a *REC-REQ* (re-clustering request) message, and asks its cluster members for a re-clustering process. Each cluster member that receives the *REC-REQ* message calls the algorithm for finding a new cluster-head. The re-clustering process is locally performed on demand, and the other clusters continue their normal operation during the re-clustering phase. If a cluster member decides to leave the cluster, it sends a *LREQ* (i.e., leave request) message to the cluster-head. Upon receiving the *LREQ* message, cluster-head removes it from the cluster member list.

The proposed cluster formation algorithm guarantees to cluster the entire network at each stage. In this algorithm, each host chooses its cluster-head, and so the network is partitioned into a number of non-overlapping clusters, in which each host is only associated with a unique cluster-head. As the algorithm proceeds, the number of cluster-heads decreases as the number of members in each cluster increases. Furthermore, in the proposed cluster formation algorithm, the cluster-heads are one, two or at most three-hops away. From clustering algorithm, it can be found that two clusters are not adjacent (or neighboring clusters), if their cluster-heads are four-hops or more away from each other. Hence, in a clustered network, some hosts have no cluster-heads, if the minimum distance between a given cluster-head and the other cluster-heads is more than three-hops. The following shows that his case does not occur in clustering algorithm. As shown in figure 2(a), cluster-heads 1 and 4 are three-hops away. Let us assume that (as shown in figure 2(b)) host 5 is located between hosts 2 and 3, i.e., cluster-heads 1 and 4 are four-hops away. This way, no cluster-head is associated with host 5, and this contradicts to the above assumption that in proposed algorithm each host selects its cluster-head. On the other hand, if we suppose that host 5 is associated with a cluster-head, this cluster-head must be (at most) three-hops away from cluster-heads 1 and 4. Therefore, by this algorithm, each cluster-head is at most three-hops away from (at least) another cluster-head.



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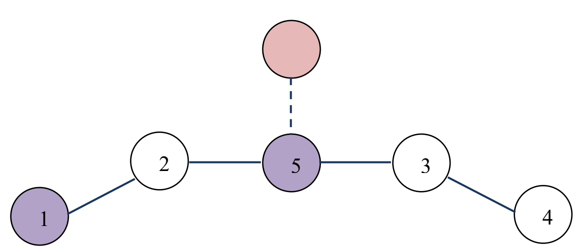

b

Fig. 2.Clustering a sample network by proposed clustering algorithm

3.2. Phase 2: learning automata-based code assignment algorithm

In the second phase of proposed method, we propose an algorithm for solving the code assignment problem in a clustered wireless ad hoc network based on learning automata concepts. The second phase aims to assign the minimum number of interference-free codes to the clusters. Since the number of available codes is limited, it is impossible to assign a unique code to each cluster, and so we take advantage of the code spatial reuse concept in our proposed algorithm. By this concept, two or more non-neighbor clusters can be assigned the same codes. Such a code assignment problem is similar to the NP-hard vertex-coloring problem in which no two neighboring clusters (or node) have the same code (or color). In our CDMA scheme, each host should send its ID and energy level to the cluster-head periodically. Then, the cluster-head call the following procedure for all inter cluster hosts repeatedly.

1. In the first step, the cluster-head sets the counter S_i to zero. Then, the cluster-head calculates the cost for each link as follows:

$$\mathrm{cost}(h_i) = \sum_{i=1}^{n} \frac{d^2(N_j^i, ch_i)}{\min(P_j^i, p_{ch_i})} \tag{4}$$

   In this equation, N_j^i is the number of j node in ith cluster, ch_i refers to ith cluster-head, P_j^i is the power of j node in ith cluster and P_{chi} is the power of ith cluster-head, and $d^2(N_j^i, ch_i)$ is the distance of node j from ith cluster.

2. In the second step, the cluster-head selects one of the accessible codes. This selected code is accordance with one of the learning automata actions in the cluster-head. The learning automata residing in the cluster-head acts as follows:
   - If the selected code by the cluster-head is against the selected code by neighboring cluster-heads, then the cluster-head rewards the desired node. Then, the counter S_i is increased by one unit. Moreover, the cluster-head removes the selected code from the list of available codes and after that, the cluster-head updates the action probability vectors of the learning automata.
   - Otherwise, the cluster-head penalizes the selected code.
3. The algorithm continues until the amount of S_i to reach a certain value. In the next section, we discuss on this value.

3.3. Calculation of the counter value

In this section, we explain the calculation of timer value, which we have used of it in three steps of our CDMA scheme. The proposed scheme is a multi-code assignment scheme. In multi-code assignment CDMA scheme, there is a queue with specific length. Therefore, in our CDMA scheme, we assign the codes in size of the queue length to the cluster-heads in each time. There are two thresholds: Low (L) and High (H) for each queue.

1. Every time, the length of queue is lower than L then, we consider the low condition.
2. When the queue size is between L and H values, then we report the medium condition.

3. When the length of the queue is more than the H value, we consider the high condition.

After repeated simulations and tests, we gain the best for these values. Therefore, the best of values for low and high are 4 and 20 respectively. The pseudo code of proposed algorithm is shown in the figure 3. The action of rewarding or penalizing performs based on learning rules (equation 2 and 3).

```
For each ch_i
{
    s_i = 0
    cost (h_i )=0
    For (j=1 to n_i )
    {
        A= d^2( N_j, ch_i)
        B= min (p_j. pch_i)
        cost (h_i) = cost( h_i) +(A/B)
    }
    While(s_i <= cost(h_i))
    {
        Select one code (C_i) from access code
        If (C_i <> C_j)
        {
                Reward(h_i)
                Delete C_i from access code list
                s_i = s_i + 1
                update (pch_i)
        }
        Else
        {
                Penalize(h_i)
        }
    }
}
```

Fig. 3. The pseudo code of proposed scheme

3.4. Convergence behavior of the proposed algorithm

As mentioned earlier, in the entire proposed algorithm each learning automaton operates independent of the others in a network of learning automata. In [15], [17] and [21], the convergence of such an automaton (with two actions) to the optimal solution in stationary or non-stationary environments has been proved. This convergence proof can be similarly generalized for a learning automaton with more actions. For the convergence speed of the learning automata-based algorithms, it should be noted that the convergence speed of a learning automaton is directly proportional to the learning rate, and its convergence rate to the optimal solution is inversely proportional to this parameter. When the learning rate decreases, the convergence speed also decreases (convergence rate increases), and the convergence speed significantly increases as the learning rate converges to one. This property of the learning automata enables us to make a trade-off between the costs (time complexity and message complexity) of algorithm and the optimality of the obtained solution. For instance, a trade-off between the number of clusters (or the number of used codes) and the number of iterations of algorithm (i.e., the running time of algorithm) can be made. In ad hoc networks, where the hosts suffer from the strict resource limitations (e.g., bandwidth or power), the communication and processing overheads should be kept as low as possible.

On the other side, a near optimal solution is usually sufficient in many applications of these networks. Therefore, by a proper choice of the learning rate, an acceptable solution can be provided for different applications in a reasonable time. That is, the running time of the proposed algorithms can be accommodated to the required optimality of the solution for different applications. In simulation experiments, we examined different learning rates and observed that 0.1 is a proper choice for optimizing different parameters by which the solution optimality and cost reached a compromise. In ad hoc networks, the obtained solutions rapidly lose their validity. Therefore, in our algorithm which is proposed for ad hoc networks, we sacrifice the optimality of the results in favor of the running time and message overhead (costs) of algorithm. Moreover, the proposed algorithm suffices to a near optimal solution of cluster formation and code assignment problems. Although, the simulation results shows that our proposed algorithm outperform the existing methods in almost all metrics of interest.

4. Experimental results

To study the performance of proposed CDMA scheme, we have conducted several simulation experiments. In these experiments, we compare the efficiency of proposed code assignment algorithm with the similar methods. We have implemented the proposed protocol by Glomosim simulator [22][23], a scalable discrete event simulator developed by UCLA.

4.1. Simulation settings

In our simulation scenario, an ad-hoc network consisting of *N* hosts is modeled in which the hosts are randomly and uniformly distributed within a two-dimensional simulation area of size 1000 m x 1000 m. The number of hosts ranges from 60 to 200 with increment step of 20. IEEE 802.11 is used as the MAC layer protocol, and two-ray ground as the propagation model. The wireless hosts communicate through a common broadcast channel of capacity 2 Mb/s using omnidirectional antennas. Each host is modeled as an infinite-buffer, store-and-forward queuing station. The radius of transmission range of all hosts is set to be the same, which is 250 m throughout the simulation process.

Each simulation experiment is executed for 1000 s. At each host, the arrival of the new connections is Poisson distributed with arrival rates of 5, 10, 15, and 20 (connections/min). Each host has a particular traffic load, which is defined by randomly choosing from the above-mentioned arrival rates at the beginning of each simulation. The duration of the connections is assumed to be exponentially distributed with mean 0.2.

The simulation results shown in this paper are averaged over 50 runs. In our experiments, we compare the results of the proposed algorithms with their counterparts of CS-DCA which is a channel segregation based channel assignment method proposed by Akaiwa and Andoh [4], Hybrid-DCA which is a dynamic channel assignment strategy proposed for clustered wireless ad-hoc networks [3], and LACAA [24] which is a hybrid CDMA/TDMA scheme based on learning automata.

4.2. Performance Metrics

In these experiments, the performance of the proposed algorithm is evaluated in terms of the following metrics of interest:

- **Code spatial reuse**: This metric is defined as the average number of times a code can be used. That is, code spatial reuse is the average number of clusters, which are assigned the same code. This metric is used to assess the performance of the code assignment algorithm.
- **Number of used codes**: It is defined as the number of codes, which are assigned to the clusters. This metric is inversely proportional to the code spatial reuse.
- **Blocking rate**: It is defined as the ratio of the number of the blocked connections to the total number of requested connections. This metric can be created due to no code. Moreover, this metric defines the rate of connections blocked due to the lack of available codes.
- **Waiting time for packet transmission**: This metric is defined as the average time each packet has to wait in the queue before transmission. This is the time between the arrival and transmission for each packet.

- **Throughput**: This metric is defined as the ratio of the average number of packets transmitted per slot to the total number of packets received. The traffic load of the various hosts is different in realistic scenarios.

4.3. Simulation results

In this section, we have evaluated our proposed algorithm CDMA based on the performance metrics. Then we have compared the results of simulations between our algorithm and LACAA [24], CS-DCA [4] and Hybrid-DCA [3].

In the first simulation, we have investigated the number of codes assigned in comparison with the number of hosts. figure 4 shows these results.

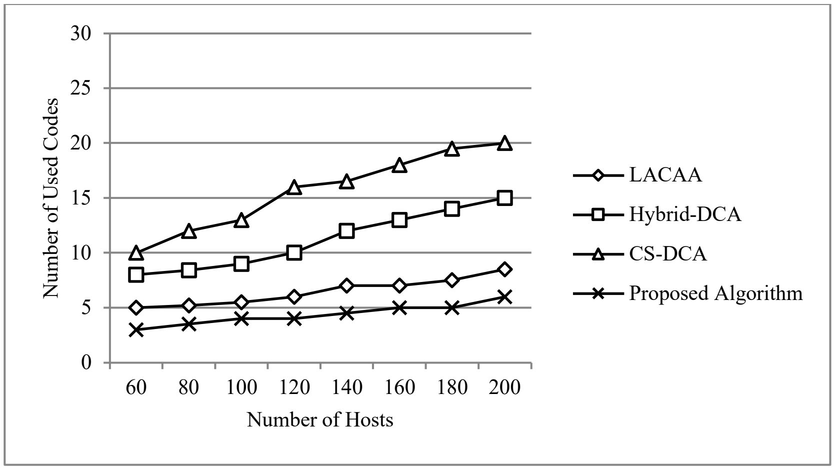

Fig. 4. The number of used codes versus the number of hosts.

Comparison between the results, which is shown in the figure 4, demonstrates the proposed algorithm has used fewer codes than LACAA, Hybrid-DCA and CS-DCA algorithms. The reason is that proposed algorithm performs the code assignment in distributed manner. Moreover, in the proposed algorithm, the cluster-head considers the minimum cost (equation 4) using learning automata for each host, while in the protocols CS-DCA, Hybrid-DCA and LACAA costs are not considered. It is clear that the number of used codes increases by the increase of hosts' number.

In the second experiment as shown in figure 5, proposed algorithm is compared with other protocols in terms of code spatial reuses with variation of number hosts.

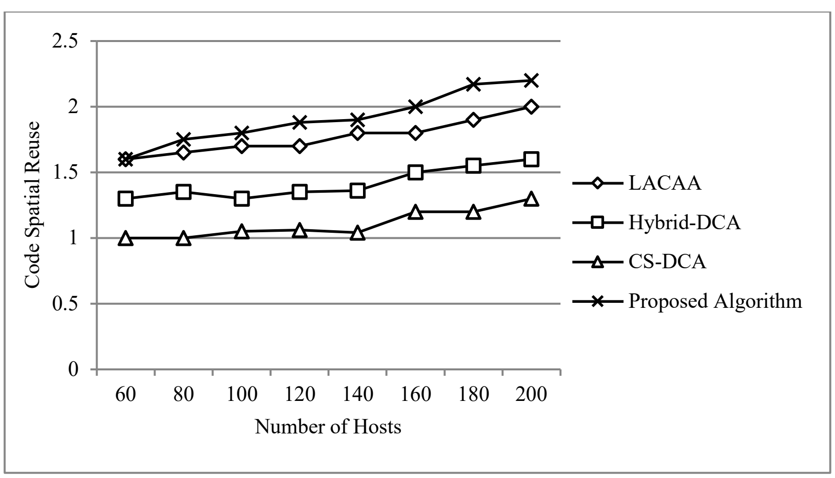

Fig. 5. The code spatial reuse versus the number of hosts

It is clear from the results shown in figure 5 that the code spatial reuses in each of four algorithms increases for increasing the number of hosts. However, the increasing trend of two protocols LACAA and proposed algorithm is higher than CS-DCA and Hybrid-DCA protocols. The LACAA protocol is improved the code spatial reuses rate by management of the clusters, as the number of assigned codes to the neighbor clusters is less. Therefore, the rate of code spatial reuses is increased. The proposed protocol decreases the number of assigned codes to each cluster by considering the cost of the link and uses of energy levels for assigning these codes. So, the proposed protocol increases the code spatial reuses to an acceptable level and outperforms the LACAA, Hybrid-DCA and CS-DCA protocols.

In the next experiment, we have evaluated the average waiting time for transmitting the data packets. Figure 7 shows the average time each packet has to wait for in the queue before transmission in comparison with variation of hosts' number.

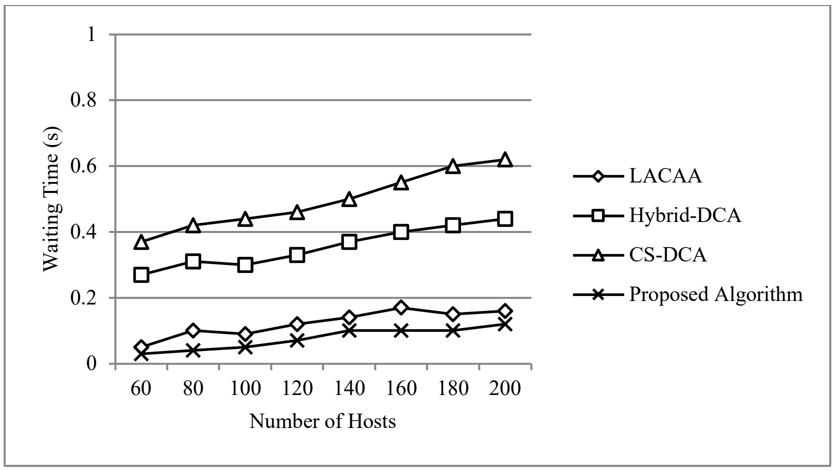

Fig. 7. The average waiting time for packet transmission versus the number ofhosts.

The results show that the average waiting time of proposed protocol for packet transmission is shorter than that of LACAA, Hybrid-DCA, and CS-DCA. Obviously, in this figure, the average waiting time for packet transmission increases as the number of hosts increases. However, this rate in proposed protocol has more decreases than the other protocols. This is due to the fact that in proposed protocol, each host based on learning automata residing in cluster head selects one accessible code and sends all packets immediately. So the data packets can be sent to selected paths quickly. Moreover, the proposed algorithm assigns the codes with respect to the cost of links and is a fully distributed algorithm. Therefore, the probability of the link failure decreases due to reduce energy level, while in other algorithms are given only the code assignment method and the broken links are not considered.

Figure 8 shows the number of connections blocked due to the lack of the codes versus the number of hosts. In this experiment, we have considered the minimum number of codes based on several performed simulations.

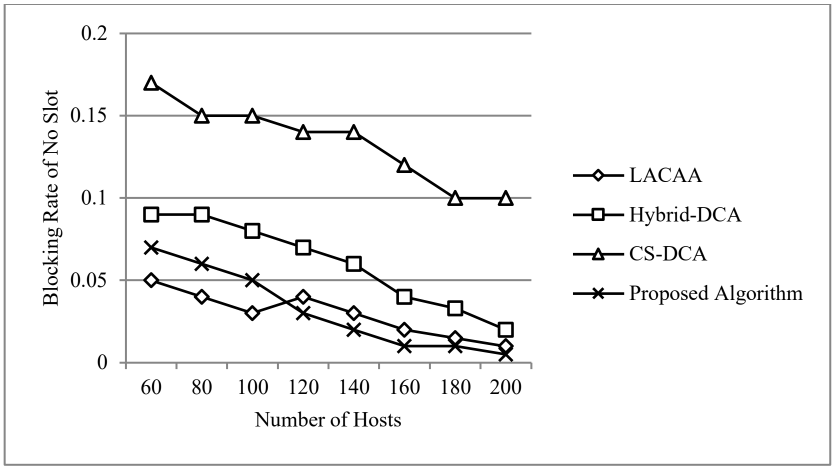

Fig. 8. The blocking rate due to the lack of the codes versus the number of hosts.

From the results shown in this figure, we conclude that in all algorithms the number of blocked connections decreases as the number of hosts increases. However, these rates for proposed algorithm and LACAA are less than CS-DCA and Hybrid-DCA algorithms. The proposed algorithm shows the higher blocking rate for the low number of hosts compared with the LACAA, but for high number of hosts (more than 120), the blocking rate is decreased than the LACAA Algorithm. Because the proposed algorithm uses the learning rules for code assignment and this makes the convergence rate be faster.

The last simulation depicts the throughput rate of the network in comparison with the number of hosts for four mentioned algorithms. Figure 9 shows these results.

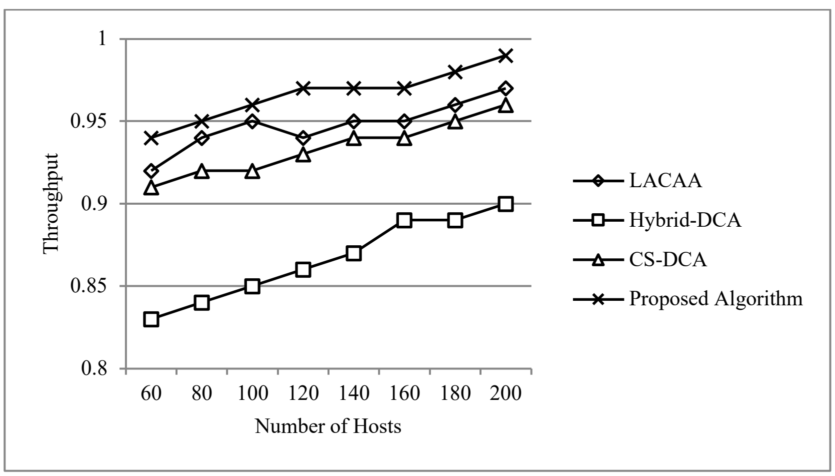

Fig. 9. Throughput versus the number of hosts.

From the results in this figure, it is observed that the throughput in all algorithms is increased for increasing the number of hosts in each of four algorithms. However, the proposed algorithm shows better performance than the LACAA, CS-DCA and Hybrid-DCA protocols, as for large number of hosts this rate is nearly one. The reason for these results is that proposed algorithm is a fully distributed algorithm, and uses the smaller number of control packets for code assignment.

5. Conclusion

In this paper, we have proposed a distributed code assignment scheme in clustered wireless mobile ad-hoc networks. The proposed protocol uses learning automata rules for assigning codes. To design this scheme, we proposed two learning automata-based algorithms for cluster formation and code assignment respectively. In this scheme, by clustering algorithm, the wireless hosts were first grouped in to a minimum number of non-overlapping clusters. Then, by proposed algorithm, an interference-free code was assigned to each cluster. Simulation results showed that the proposed CDMA scheme outperforms the existing methods LACAA, CS-DCA and Hybrid-DCA for almost all metrics of interest, specifically, under burst traffic conditions.

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