Reducing Interference in the Mobile Two-Tier Ad Hoc and Wireless Sensor Networks with the Help of Stochastic Chaotic Simulated Annealing

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Abstract—In this paper, a very efficient approach to reducing interference in mobile ad hoc and wireless sensor networks is proposed. The approach uses chaotic simulated annealing (CSA). The basic concept of this method was formulated as a channel assignment problem (CAP). The solution of the CAP problem is based here on neural networks which are able to find a conflict-free frequency assignment for the devices so that interference between channels is minimized. The proposed method is validated by means of computer simulation-based experimentations.

Index Terms—Ad hoc networks, wireless sensor networks, interference reduction, stochastic chaotic simulated annealing

I. INTRODUCTION

Ad hoc wireless networks [1] have attracted a lot attention over the last few years. The design of ad hoc wireless networks requires novel approaches, since they have peculiar characteristics which differ substantially from those of fixed networks or cellular networks. It is obvious that in these networks radiotransmission supports network mobility, hidden nodes and other factors, such as the quality of service, security fault-tolerance, etc.

Wireless sensor networks [2] represent a new type of a system which has emerged thanks to the technological progress in the intelligent sensor development. However, these networks are treated as a particular type of ad hoc networks [3], [4]. In the wireless sensor networks all nodes are 'smart sensors' which are equipped with advanced sensing functionalities (thermal, pressure, etc.).

Ad hoc and wireless sensor networks are often an element of mobile nodes referred to as mobile access points. These nodes are powerful nodes, both in their communication and processing capability and their ability to traverse the network. Some examples are manned/unmanned aerial vehicles, ground vehicles equipped with power generators, etc. The mobile access nodes retrieve the data from immobile nodes and deliver then to a remote control center.

Mobile ad hoc and sensor networks are often organized in two-tier networks (see Fig. 1). To the first tier belong all immobile nodes grouped into clusters. These nodes provide the gathered data to the clusterhead nodes. The second tier is formed by the clusterhead nodes and the mobile nodes. These nodes are responsible for delivering all data to a remote control center.

The building of wireless networks is associated with the radio channel assignment problem (CAP). According to the classification of the CAP [5] we can formulate two categories, i.e., CAP1 and CAP2. The former is associated with the minimization of the span of channels subject to demand and interference-free constraints. The CAP2 is used to minimize interference subject to demand constraints. In addition to this, in practical cases the one more useful is the CAP2 due to, among others, the high demand in mobile communications and the often used topology control protocols.

Interference is one of the main performance limiting factors in ad hoc and wireless sensor networks. Interference depends on the position of transmitting nodes, the power transmitted by each node, the fading distribution, etc. In general, interference in these networks belongs to the undesirable phenomena. Additionally, as far as these networks are concerned, a small interference helps in reducing the coding overhead. It means that the energy of battery-driven devices can be saved up. Thus, minimizing interference may increase the network lifetime.

The upper bounds of some of the interference problems have been obtained in a different context. Among others,
the problem of reducing the total amount of energy spent by the nodes in wireless ad hoc networks with connectivity requirements was given by G. Calinescu [6]. The positive aspect of this approach was prolongation of the lifetime of the ad hoc network.

The problem of reducing interference in ad hoc and sensor networks was studied by T. Moscibroda and R. Wattenhofer in the paper [7], in which a greedy algorithm for approximation to the interference with connectivity requirements was given. In recent papers presented by von Rickenbach [8], the problem of minimizing the maximum interference was studied. An $O(\sqrt{n})$ approximation algorithm to evaluate the interference was given.

The method of artificial intelligence was also used to minimize interference in wireless networks. Among others, minimizing the severity of interferences in the cellular radio was given by Kunz [9]. The author solved channel assignment problem by minimizing the energy or the cost function representing interference and channel assignment constraints. The same problem was resolved by K. Smith and M. Palaniswami [5] by means of the simulated annealing, a modified Hopfield neural network, and a self-organizing neural network. In a paper by L. Wang et al. [10], the authors studied the proposed stochastic chaotic simulated annealing to solve the traveling salesman problem and the channel assignment problem (CA) for cellular mobile communications. The CSA used by them restricts the random search to a subspace of chaotic attracting sets which is much smaller than the entire state space searched by stochastic simulated annealing (SSA).

The main goal of this paper is to introduce the new method of minimizing interference in mobile two-tiers ad hoc and wireless sensor networks. We use chaotic simulated annealing in order to solve the CAP2 problem. We applied only CAP2 because, in most cases, the interference-free lower bound is far greater than the number of the available channels. Our solution is able to make a dynamic change of node locations and for themselves to take into consideration the movement of the mobile nodes.

This paper is organized as follows. In section II we formulate a stochastic chaotic simulated annealing related to the CAP problem. In section III, we present our method of minimizing interference by means of the stochastic chaotic simulated annealing. In section IV, we apply our method in order to assess the effectiveness of the mobile two-tier ad hoc and wireless sensor networks. Finally, in section V, we conclude this paper.

II. Stochastic Chaotic Simulated Annealing

The stochastic chaotic simulated annealing related to the CAP problem was described by L. Chen and K. Aihara [11], [12], [13] as the following equation, namely

$$x_{ik}(t + 1) = \frac{1}{1 + e^{-y_{ik}(t)/\epsilon}}$$  \hspace{1cm} (1)

$$y_{ik}(t + 1) = k \cdot y_{ik}(t) + \alpha \left( \sum_{l=1, i \neq j}^{N} \sum_{l=1}^{M} w_{ikjl} x_{ik}(t) + I_{ik} \right) - z(t)(x_{ik}(t) - I_0)$$  \hspace{1cm} (2)

$$z(t + 1) = (1 - \beta_1) z(t)$$  \hspace{1cm} (3)

$$A[n(t + 1)] = (1 - \beta_2) A[n(t)]$$  \hspace{1cm} (4)

where the variables are:

$N$ - number of call nodes;

$M$ - number of channels;

$x_{ik}$ - output of neuron $ik$;

$y_{ik}$ - internal state of neuron $ik$;

$I_{ik}$ - input bias of neuron $ik$;

$\alpha$ - positive scaling parameter for the inputs;

$z(t)$ - self-feedback neuronal connection height or refractory strength ($z(t) \geq 0$);

$\beta_1, \beta_2$ - damping factors for the time-dependent neuronal self-coupling and the added random noise ($0 \leq \beta_1 \leq 1, 0 \leq \beta_2 \leq 1$);

$I_0$ - positive parameter;

$\epsilon$ - steepness parameter of the neuronal output function ($\epsilon > 0$);

$n(t)$ - random noise injected into the neurons, with its actual value being in the range $[-A, A]$ and with a uniform distribution. $A[n]$ is the noise amplitude;

$w_{ikjl}$ - connection weight from neuron $ik$ to neuron $jl$, with $w_{ikjl} = w_{jlik}$ and $w_{iklk} = 0$.

The connection weights can be obtained from

$$\sum_{j=1, i \neq j}^{N} \sum_{l=1, l \neq k}^{M} w_{ikjl} x_{ik} + I_{jl} = -\frac{\partial E}{\partial x_{ik}}$$  \hspace{1cm} (5)

where $E$ is the energy function of the network or the cost function to be minimized in the formulated combinatorial optimization problem. In the absence of noise $n(t) = 0$ for all $t$ the problem is reduced to the mentioned above solution of the CSA given by Chen and Aihara [11], [12], [13].

In the absence of noise and damping of the self-neural coupling (i.e. $n(t) = 0$ for all $t$ and $\beta_1 = 0$), the Eq. (1) - (5) of the above given equation become the Aihara-Takaba-Toyoda chaotic neural network [14]. This network possesses several dynamic behaviours. Among others, this network can have static fixed points, periodic oscillations, and chaos depending on the value of the network parameters.
III. Minimizing Interference Using Stochastic Chaotic Simulated Annealing

In this section, we introduce a stochastic chaotic simulated annealing for minimizing interference in mobile ad hoc and sensor networks formulated as the CAP2 problem.

We assume that a hierarchical mobile ad hoc or sensor network has \( I \) immobile and \( J \) mobile nodes. The total number of the available channels is equal to \( M \). The channel requirements for the transmission inside and outside the cluster \( i \) are give by \( D_i \) and \( D_n \) (\( i = 1, \ldots, \phi_n, \; n = 1, \ldots, \Phi \)), respectively. Each element \( d_i \) in \( D_i \) or \( D_n \) represents the number of frequencies to be assigned to a call. The minimum distance in the frequency domain by which two nodes are separated in the frequency domain by which two nodes are separated in the frequency domain between the frequency assigned to call of node \( i \) and the frequency assigned to call of node \( j \). The co-channel constraint is represented by \( c_{ij} = 1 \), and the adjacent channel constraint is represented by \( c_{ij} = 2 \). \( c_{ij} = 0 \) indicates that calls of node \( i \) and \( j \) are allowed to use the same frequency. We recall that the CAP problem is formulated as finding a conflict-free frequency assignment with the minimum number of total frequencies, where the matrices \( C \) and \( D \) are given.

The CAP2 problem can be formulated here by means of using a neural network with \( N \times M \) neurons [5]. Thus, the output of each neuron \( x_{jk} \) is follows:

\[
x_{jk} = \begin{cases} 1, & \text{if node } j \text{ is assigned to channel } k \\ 0, & \text{otherwise} \end{cases} \tag{6}
\]

To measure the degree of interference between nodes \( j \) and \( i \) cost tensor \( P_{ji(m-1)} \) [5] is used, where \( m = k - l \) is the distance in the frequency domain between channels \( k \) and \( l \). The cost tensor \( P \) is defined as follows

\[
P_{ji(m+1)} = \max(0, P_{ji(m-1)} - 1), \text{ for } m = 1, \ldots, M + 1 \tag{7}
\]

\[
P_{ji} = c_{ji}, \; \forall j, i \neq j \tag{8}
\]

\[
P_{jj} = 0, \; \forall j \tag{9}
\]

The minimization interference regarding the demand constraints for wireless ad hoc/sensor networks can be defined by the following cost

\[
F(x) = \sum_{j=1}^{M} \sum_{k=1}^{M} x_{jk} \sum_{i=1}^{M} \sum_{l=1}^{M} P_{ji}(|k - l| + 1) x_{il} \tag{10}
\]

subject to

\[
\sum_{k=1}^{M} x_{jk} = D_j, \; \forall j = 1, \ldots, I + J, \tag{11}
\]

\[
\sum_{n=1}^{\phi_n} x_{jn} = D_n, \; \forall j = 1, \ldots, \Phi \tag{12}
\]

where \( F(x) \) is the total interference in the mobile network.

The computational energy function \( E \) can be defined as a sum of the interferences and constraints

\[
E = \frac{W_1}{2} \sum_{j=1}^{I+J} \sum_{k=1}^{I} (\sum_{j=1}^{M} x_{jk} - D_j)^2 + \frac{W_2}{2} \sum_{n=1}^{\phi_n} M \sum_{i=1}^{M} \sum_{j=1}^{M} x_{jk} \sum_{j=1}^{I+J} \sum_{i=1}^{I} P_{ji(k-l|+1)x_{il}} + \frac{W_3}{2} \sum_{j=1}^{I+J} \sum_{i=1}^{I} \sum_{l=1}^{M} x_{jk} \sum_{j=1}^{I+J} \sum_{i=1}^{I} P_{ji(k-l|+1)x_{il}} \tag{13}
\]

where \( W_1, W_2, W_3 \) are the weight coefficients corresponding to the constraints and interference, respectively.

Next, we derive the dynamics of the CSA for the CAP problem in wireless ad hoc and sensor networks as follows, namely

\[
y_{ik}(t+1) = k y_{ik}(t) - z(t)(x_{ik}(t) - I_0) + \alpha \{ -W_1 \sum_{h \neq j,k=1}^{M} x_{ih}(t) - W_2 \sum_{f \neq j,k=1}^{M} x_{jg}(t) \\
+ W_1 - W_2 \sum_{f \neq k=1}^{M} (x_{jg+1}(t) + x_{jg-1}(t)) f \} + n(t) \tag{14}
\]

IV. Simulation Results

In this section, we consider an experiments for assessing the effectiveness of our proposed method. The experiment involves the immobile and mobile nodes of the ad hoc/sensor network.

In the experiment we take into considerations the static location of two clusters with the clusterheads and eight immobile and one mobile nodes. In the experiment, we take into consideration the scenario with the single node which is harvesting the data from the network through the connection with the clusterhead node in the cluster. In our approach, only the transmission between the mobile node and the clusterhead node is possible. We have considered three moments in the movement of mobile node, namely: outside the cluster (Fig. 2), inside the cluster (Fig. 3), and outside the handoff zone (Fig. 4).
Fig. 2. The event corresponds to the scenario at time $t = 1$ where just one mobile node, labeled 11, outside the cluster communicates with the first clusterhead node.

Fig. 3. The event corresponds to the scenario at time $t = 2$ where a mobile node inside the cluster communicates with the first clusterhead node.

Fig. 4. The event corresponds to the scenario at time $t = 3$ where a mobile node outside the handoff zone communicates with the second clusterhead node.
Table I. The parameters used in simulation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value of parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N$</td>
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</tr>
<tr>
<td>$M$</td>
<td>28</td>
</tr>
<tr>
<td>$k$</td>
<td>0.8</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>0.02</td>
</tr>
<tr>
<td>$I_0$</td>
<td>0.35</td>
</tr>
<tr>
<td>$z(0)$</td>
<td>0.25</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>$5 \times 10^2$</td>
</tr>
<tr>
<td>$\beta_1 = \beta_2$</td>
<td>$5 \times 10^{-3}$</td>
</tr>
<tr>
<td>$W_1 = W_2 = W_3$</td>
<td>1</td>
</tr>
</tbody>
</table>

The number of required frequencies for all the nodes was determined before the simulation. Our neural network for chaotic simulated annealing was built of 312 neurons. In Table I we give the specification of our problem.

The constraint energy term in Eq. (13) imposes the demand constraint:

$$E_{\text{constraints}} = \frac{W_1}{2} \sum_{j=1}^{I+J} \sum_{j=1}^{I} \left( \sum_{k=1}^{M} x_{jk} - D_j \right)^2$$
$$+ \frac{W_2}{2} \sum_{n=1}^{\phi_n} \left( \sum_{k=1}^{M} x_{jk} - D^n \right)^2$$  \hspace{1cm} (15)

The interference energy term in Eq. (13) minimizes the interference

$$E_{\text{interference}} = \frac{W_3}{2} \sum_{j=I+1}^{I+J} \sum_{j=I+1}^{I} \sum_{k=1}^{M} x_{jk}$$
$$+ \frac{1}{M} \sum_{i=1}^{I+J} \sum_{i=1}^{I} \sum_{l=1}^{I} \sum_{h=1}^{M} P_{ji}(|k-l|+1)x_{il}$$  \hspace{1cm} (16)

To increase the chance of escaping from the local minima we include the chaotic dynamics in the single-neuron input term, namely

$$ky_{ik}(t) - z(t)(x_{ik}(t) - I_0)$$  \hspace{1cm} (17)

Then, the constraint input in Eq. (14) imposes the demand constraint

$$\alpha \left( -W_3 \sum_{h \neq k}^M x_{jh} + W_1 D_j \right) + \left( -W_2 \sum_{h \neq k}^M x_{jh} + D^n \right)$$  \hspace{1cm} (18)

Also, the interference input term in Eq. (14) minimizes interference

$$\alpha \left( -W_3 \sum_{f=1}^N \sum_{j \neq f}^M \sum_{h=1}^M \sum_{h \neq k} P_{ji}(|f-h|+1)x_{fh} \right)$$  \hspace{1cm} (19)

In the Figs. 5 - 7, we plot as the energy terms in Eq. (13) as a function of iteration steps in CSA: a) the total energy, b) the constraints term, and b) the optimization term.

Table II shows an example of all assigned frequencies for each node at time $t = 1, t = 2, t = 3$, respectively.
V. Conclusion

In this paper, we proposed a new method of reducing interference in mobile two-tier ad hoc and wireless sensor networks. We demonstrated that the chaotic simulated annealing is able to cause a dynamic change of node locations and for themselves to take into consideration the movement of some nodes. We then considered three constraints, namely: the constraint energy inside the cluster, the energy constraint outside the cluster, and the interference energy term. In the simulation study we investigated the assigned frequencies for the defined situations.

One may question whether it is realistic to rely on more sophisticated topologies of mobile ad hoc and wireless sensor networks. In a dynamic CAP, the demand is a function of time. The CSA is deterministic and is not able to overcoming all changing over time in mobile ad hoc and wireless sensor networks. Another direction is to solve the problem with constraints, e.g. limited capacity on the links, bounded distance between a node to mobile node, etc. Furthermore, a study of large size topologies and the deviation from the ideal curve of movement, as well as power of transmission can be a proper subject for a future study.

Table II. Assigned frequencies at time $t = 1, 2, 3$, respectively.

<table>
<thead>
<tr>
<th>Node</th>
<th>$t = 1$</th>
<th>$t = 2$</th>
<th>$t = 3$</th>
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<tbody>
<tr>
<td>1</td>
<td>38</td>
<td>27</td>
<td>52</td>
</tr>
<tr>
<td>2</td>
<td>17</td>
<td>12</td>
<td>16</td>
</tr>
<tr>
<td>3</td>
<td>23</td>
<td>9</td>
<td>43</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>3</td>
<td>22</td>
</tr>
<tr>
<td>5</td>
<td>1 8 11 47 53</td>
<td>24 33 39 48 42</td>
<td>13 31 34 37 49</td>
</tr>
<tr>
<td>6</td>
<td>29</td>
<td>21</td>
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</tr>
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</tr>
<tr>
<td>9</td>
<td>41</td>
<td>18</td>
<td>55</td>
</tr>
<tr>
<td>10</td>
<td>14 26 32 44 50</td>
<td>30 36 45 51 54</td>
<td>7 19 25 28 46</td>
</tr>
<tr>
<td>11</td>
<td>20</td>
<td>56</td>
<td>4</td>
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References