DEPARTAMENTO DE ELETRÓNICA, TELECOMUNICAÇÕES E INFORMÁTICA

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ASSIGNMENT GUIDE NO. 1

CONNECTIVITY PERFORMANCE OF MULTI-HOP WIRELESS NETWORKS WITH MOBILE TERMINALS

Assignment Guide No. 1

1. General Description

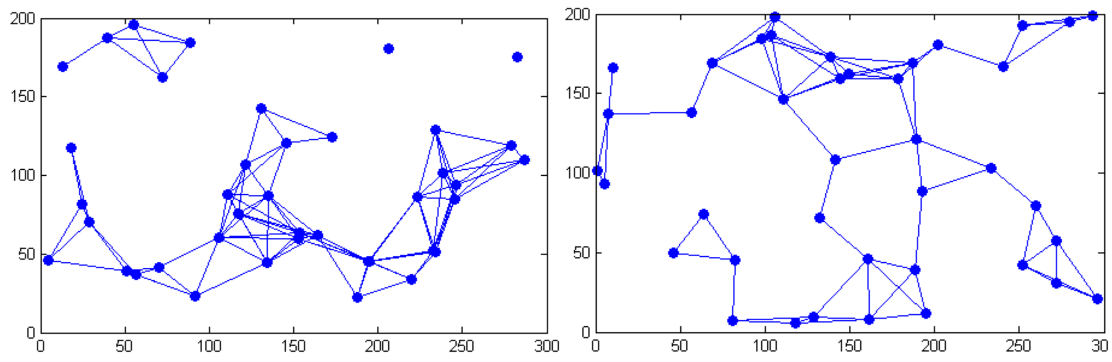
The aim is to conduct a simulation analysis of the connectivity performance of a multi-hop wireless network with mobile nodes (i.e., nodes moving around over time) on a rectangle area of 300 horizontal meters by 200 vertical meters representing a possible university campus or city park.

In the first part, the assignment addresses the ad hoc variant of such networks. In this case, a set of wireless mobile nodes establishes a network between them without connectivity to the outside world.

In the second part, the assignment addresses the variant where the wireless network provides access to the wired network through AP (Access Point) nodes. In this case, each node is connected to the network if it can communicate with at least one AP.

In both cases, consider a given radio range W such that any two nodes establish a direct connection if the distance between them is not higher than W. In multi-hop networks, nodes are able to perform routing, i.e., they can forward data received from other nodes and destined to other nodes. Therefore, two nodes can communicate between them (i.e., they are connected) as long as there is at least one path of direct connected nodes between them.

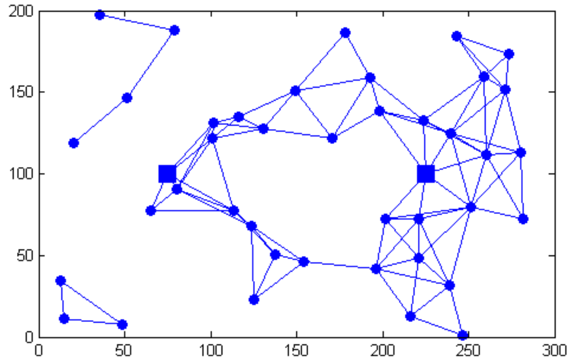
For illustration purposes, consider an ad hoc network with 40 nodes and a radio range of $W = 50$ meters. Fig. 1(a) illustrates a time instant where there is no full connectivity and Fig. 1(b) illustrates a time instant where the network is fully connected (in both figures, node pairs whose distance is not higher than 50 meters are connected with a line). Since the number of nodes is 40, there is a total of 40 × 39 / 2 = 780 node pairs. In the case of Fig. 1(a), there is a group of 33 connected nodes, a group of 5 connected nodes and 2 isolated nodes. In this case, the number of connected node pairs is 33 × 32 / 2 + 5 × 4 / 2 = 538. Therefore, the percentage number of connected node pairs is 538 / 780 × 100% = 69%. Obviously, in the case of Fig. 1(b) the percentage number of connected node pairs is 100%.

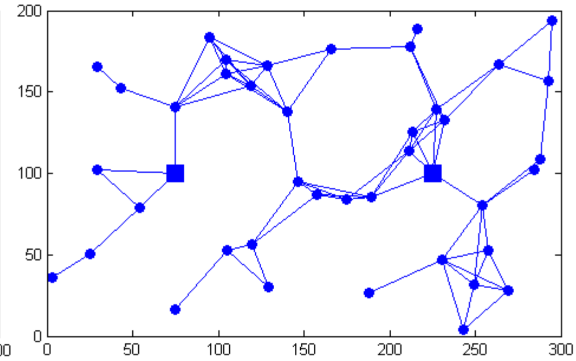


(a) (b)

Fig. 1 – Ad hoc network in a time instant where there is no full connectivity (a) and where the network is fully connected (b)

Now, consider the previous example of with 2 AP nodes providing node connectivity to the wired network. Fig. 2(a) illustrates a time instant where there is no full connectivity and Fig. 2(b) illustrates a time instant where the network is fully connected (the two AP nodes are represented by squares and are fixed, i.e., their location does not change with time). In the case of Fig. 2(a), there are 7 nodes that have no connectivity to any of the AP nodes. Since the total number of nodes is 40, the number of connected nodes is 40 – 7 = 33 and, consequently, the percentage number of connected nodes is 33 / 40 × 100% = 82.5%. Obviously, in the case of Fig. 1(b) the percentage number of connected nodes is 100%.





(a) (b)

Fig. 2 – Mobile wireless network with two AP nodes (square nodes) in a time instant where there is no full connectivity (a) and where the network is fully connected (b)

The simulation analysis aims are:

- In ad hoc networks (first part of the assignment): for different radio range values W, the aim is to determine the minimum required number of nodes to obtain an acceptable connectivity performance level of 99%.
- In wireless mobile networks with Access Points (second part of the assignment): for different radio range values W and different number of nodes, the aim is to determine the required number and location of AP nodes required to obtain an acceptable connectivity performance level of 99%.

Both cases are continuous time systems (i.e., the list of connected nodes varies continuously with time). To develop a proper simulator, time is discretized in time instants with equal time difference between consecutive instants. Then, the simulator computes only the state of the system at each discrete time instant (the time difference value between consecutive time instants is a trade-off between simulation running time and results accuracy).

Fig. 3 illustrates the results of a simulation run for the ad hoc network case shown in Fig. 1 and Fig. 4 illustrates the results of a simulation run for the wireless mobile network with 2 AP nodes shown in Fig. 2. In both cases, the time difference was 1 second and the total simulated time was 1 hour (= 3600 seconds). The blue line gives the connectivity performance at each discrete time instant and the red line gives the evolution of the average connectivity performance (the final performance value is the value of the red line at the end of the simulation).

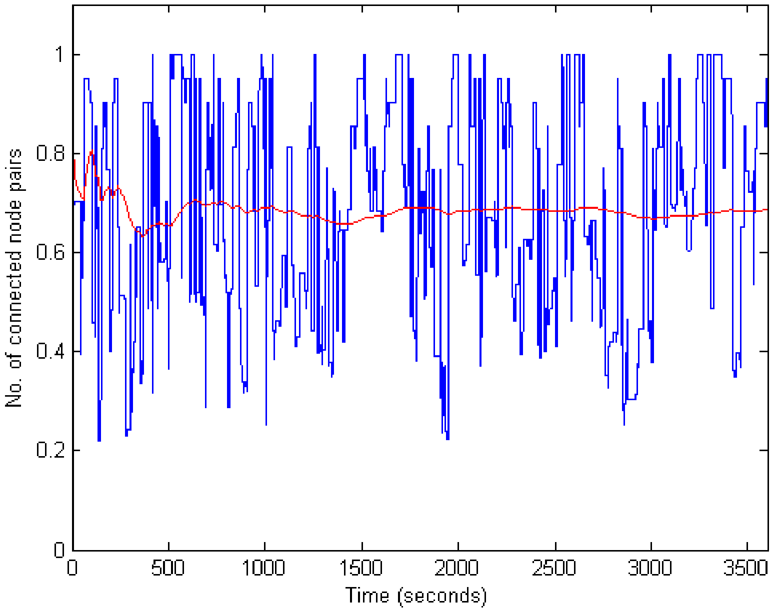


Fig. 3 – Simulation run of an ad hoc network
(time interval = 1 second, total simulated time = 1 hour)

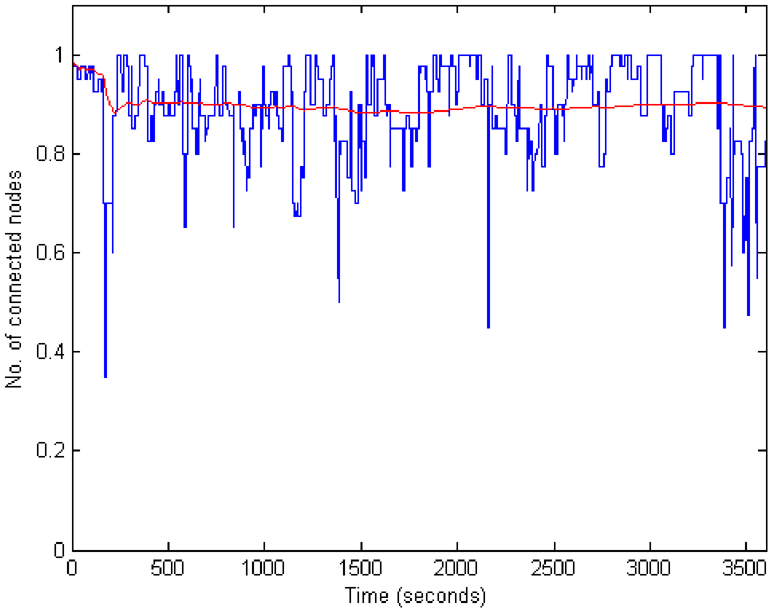


Fig. 4 – Simulation run of a wireless network with 2 AP nodes
(time interval = 1 second, total simulated time = 1 hour)

2. First Part of the Assignment

2.1. Simulator Development

Using the MATLAB main script proposed in Section 6, implement the required MATLAB functions to develop an ad hoc network simulator with the aim of estimating the average number of connected node pairs (see Section 4.1 describing a labelling algorithm to compute the number of connected node pairs). The simulator considers a given number N of mobile nodes constantly moving within a rectangle area of 300 horizontal meters by 200 vertical meters (consider horizontal coordinates between 0 and 300 and vertical coordinates between 0 and 200).

The initial horizontal and vertical coordinates of each node are randomly generated within the rectangle limits with a uniform distribution (see Section 5.1). The initial speed of each node is randomly generated with a uniform distribution between 0 and a maximum speed value S. The initial direction of each node is randomly generated with a uniform distribution between 0 and 2π radians (see Section 5.2).

The node movement follows a constant speed model as long as the node is within the rectangle. Then, when the node reaches a horizontal/vertical limit, the sign of its horizontal/vertical speed component is changed (if it is positive, it is changes to negative and vice-versa).

The input parameters of the simulator are:

- N number of mobile nodes
- W radio range (in meters)
- S maximum node speed (in Km/h)
- Δ time difference between simulated time instants (in seconds)
- T number of time instants to be simulated (i.e., the total simulated time is $T \times \Delta$ seconds)

2.2. Results Analysis

a) For each of the cases defined in the following *Table 1*, run 4 simulations and determine the average number of connected node pairs (run each simulation with $\Delta = 1$ second and $T = 3600$).

Table 1

Case	S (km/h)	W (meters)	N	No. of Connected Node Pairs (%)
A	3	40	50	
B	3	60	50	
C	3	80	50	
D	3	40	100	
E	3	60	100	
F	6	40	50	
G	6	60	50	
H	6	80	50	
I	6	40	100	
J	6	60	100	

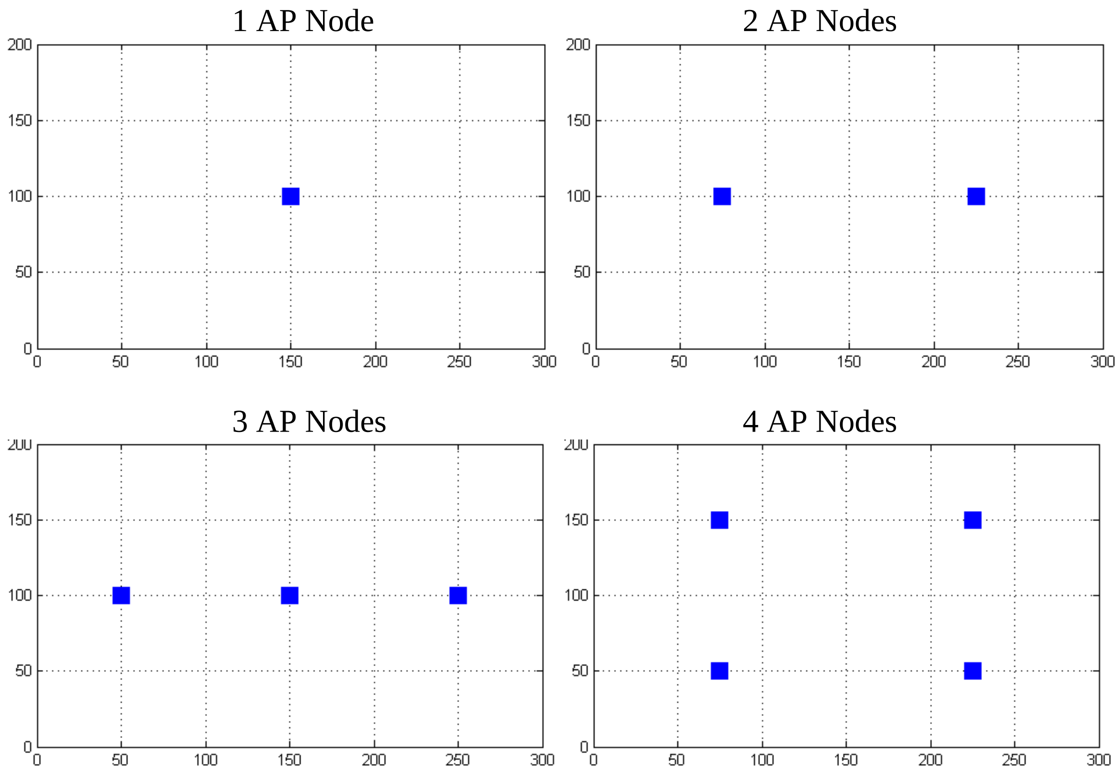
b) Based on the previous simulation results, take conclusions about the influence of the maximum speed S, radio range W and number of mobile nodes N on the connectivity performance of the ad hoc network.

c) Assume that the maximum speed of each node is S = 5 Km/h. For each of the 3 radio range values W of 40, 60 and 80 meters, determine the minimum number of mobile nodes N, in multiples of 10, such that the average number of connected node pairs is not lower than 99%. For better results accuracy, run 10 simulations for the cases of interest.

3. Second Part of the Assignment

3.1. Simulator Development

Using MATLAB, develop a simulator of a wireless mobile network with Access Points to estimate the average number of connected mobile nodes (see Section 4.2 describing a labelling algorithm to compute the number of connected nodes). Consider all input parameters of the previous simulator. In addition, consider as input a given set of AP nodes and their location coordinates. The sets of AP nodes of interest are:



3.2. Results Analysis

d) Consider in all cases that the maximum speed of each node is S = 5 Km/h. For the cases defined in the following *Table 2*, run 4 simulations and determine the average number of connected nodes (as before, run each simulation with $\Delta = 1$ second and $T = 3600$).

Table 2				
Case	No. APs	W (meters)	N	No. of Connected Nodes (%)
A	1	40	30	
B	1	60	30	
C	1	80	30	
D	1	40	50	
E	1	60	50	
F	2	40	30	
G	2	60	30	
H	2	80	30	
I	2	40	50	
J	2	60	50	
K	3	40	30	
L	3	60	30	
M	3	80	30	
N	3	40	50	
O	3	60	50	
P	4	40	30	
Q	4	60	30	
R	4	80	30	
S	4	40	50	
T	4	60	50	

e) Based on the previous simulation results, take conclusions about the influence of the number of APs, radio range W and number of mobile nodes N on the connectivity performance of the wireless network.

f) Are the suggested AP locations the best choice for each number of APs? Check possible alternatives.

g) Assume again that the maximum speed of each node is S = 5 Km/h. For each of the 3 radio range values W of 40, 60 and 80 meters and each of the number of mobile nodes N of 30, 50 and 70, determine the minimum required number of APs (and locations) such that the connectivity performance is not lower than 99%. For better results accuracy, run 10 simulations for the cases of interest.

4. Labelling Algorithms for Connectivity Computation

4.1. Number of Connected Node Pairs in Ad Hoc Networks

Consider a set of nodes $i = 1, 2, \ldots, N$. At a particular time instant, consider a list of node pairs $(i, j) \in L$, with $i < j$, with a direct connection between them. A labelling algorithm to compute the number of connected node pairs them is as follows:

Step 1: Assign label 1 to node 1, label 2 to node 2, and so on until node N.

Set REPETIR with TRUE

Step 2: Set REPETIR with FALSE

Compute all node pairs $(i, j) \in L$ in the following way: if the label of i is different to the label of j, assign the label of i to all nodes that have the label of j. If at least one label changes, set REPETIR with TRUE.

Step3: Stop the algorithm if REPETIR is FALSE; otherwise, return to Step 2

At the end, the labels assigned to nodes define the solution in the following way: all nodes with the same label are connected between them while nodes with different labels cannot communicate between them.

To compute the number of connected node pairs, first, note that if there are *n* nodes with the same label, then, all combinations of 2 out of *n* nodes are connected, i.e., the number of connected node pairs is $n(n-1)/2$. So, to compute the total number of connected node pairs, sum the number of connected node pairs for each different assigned label at the end of the above algorithm.

Consider an example with 10 nodes. In Step 1, the assigned labels are:

Nodes:	1	2	3	4	5	6	7	8	9	10
Labels:	1	2	3	4	5	6	7	8	9	10

At the end, if the assigned labels are:

Nodes:	1	2	3	4	5	6	7	8	9	10
Labels:	1	5	1	1	5	5	1	1	9	9

it means that nodes 1, 3, 4, 7 and 8 are connected (they have the same label 1), nodes 2, 5 and 6 are connected (they have the same label 5) and nodes 9 and 10 are connected (they have the same label 9). The total number of connected node pairs is $\frac{5\times4}{2} + \frac{3\times2}{2} + \frac{2\times1}{2} = 14$. Since the total number of node pairs is $\frac{10\times9}{2} = 45$, then the number of connected node pairs, in percentage, is $\frac{14}{45} \times 100\% = 31.1\%$ (i.e., 31.1% of the total number of node pairs are connected).

4.2. Number of Connected Nodes in Wireless Networks with Access Points

Consider a set of mobile nodes $i = 1, 2, \dots, N$ and a set of AP nodes $i = N + 1, N + 2, \dots, N + A$. At a particular time instant, consider a list of node pairs $(i, j) \in L$, with $i = 1, 2, \dots, N$ and $j = i + 1, i + 2, \dots, N + A$ (i.e., between each mobile node and both types of nodes, mobile and AP) that are connected between them.

A labelling algorithm to compute the number of mobile nodes that have connectivity to at least one AP is as follows:

Step 1:	Assign label 1 to the AP nodes and label 0 to mobile nodes Set REPETIR with TRUE
Step 2:	Set REPETIR with FALSE Compute all node pairs $(i, j) \in L$ in the following way: if the label of one end node is 1 and the label of the other end node is 0, assign the label 1 to the end node with label 0. If at least one label changes, set REPETIR with TRUE
Step3:	Stop the algorithm if REPETIR is FALSE or if all labels are set to 1; otherwise, return to Step 2

At the end, all mobile nodes with label 1 are connected to at least one AP node while mobile nodes with label 0 have no connectivity to none of the AP nodes.

Consider an example with 10 mobile nodes and 2 AP nodes. In Step 1, the assigned labels are:

	Mobile nodes										AP nodes	
Nodes:	1	2	3	4	5	6	7	8	9	10	11	12
Labels:	0	0	0	0	0	0	0	0	0	0	1	1

At the end, if the assigned labels are:

	Mobile nodes										AP nodes	
Nodes:	1	2	3	4	5	6	7	8	9	10	11	12
Labels:	1	0	1	1	0	0	1	1	1	1	1	1

it means that nodes 1, 3, 4, 7, 8, 9 and 10 are connected to the network. The other nodes (2, 5 and 6) have no path of direct connected nodes between each of them and at least one of the AP nodes. In this case, the number of connected nodes, in percentage, is $\frac{7}{10} \times 100\% = 70\%$ (i.e., 70% of the total number of mobile nodes are connected to the network).

5. Generation of Random Values

5.1. Initial Node Coordinates

At the beginning, the initial horizontal and vertical coordinates of each node must be randomly generated within a rectangle area of 300 horizontal meters by 200 vertical meters. In MATLAB, the function `rand(N,M)` generates a matrix of `N` rows and `M` columns of random real values with a uniform distribution between 0.0 and 1.0. To generate the initial coordinates of `N` mobile nodes, run the MATLAB command:

```
pos = [300*rand(N,1) 200*rand(N,1)];
```

which generates matrix `pos` with `N` rows and 2 columns where the first column has the horizontal coordinates between 0 and 300 and the second column has the vertical coordinates between 0 and 200.

5.2. Initial Node Speed and Direction

At the beginning, the speed of each node must be randomly generated with a uniform distribution between 0 and a maximum speed value S. Also, the direction angle of each node must be randomly generated with a uniform distribution between 0 and 2π radians. To generate the initial speed and direction values of `N` mobile nodes, run the following sequence MATLAB commands:

```
S = 5/3.6;     % conversion to m/s
abs_val= S*rand(N,1);
angle_val= 2*pi*rand(N,1);
vel= [abs_val.*cos(angle_val) abs_val.*sin(angle_val)];
```

The first command converts the maximum speed value from Km/h into meters/second (everything after character `%` is ignored by MATLAB). The second command generates the speed values of all mobile nodes. The third command generates the direction values of all mobile nodes (angles randomly generated between 0 and 2π radians). The last command generates matrix `vel` with `N` rows and 2 columns where the first column has the horizontal speed component (mathematically given by the absolute value of the speed multiplied by the cosine of the direction angle) and the second column has the vertical speed component (mathematically given by the absolute value of the speed multiplied by the sine of the direction angle).

6. Proposed MATLAB Main Script for First Simulator

```
%Parameters initialization:
N= 50;         % Number of mobile nodes
W= 40;         % Radio range (in meters)
S= 3;          % Maximum speed (in Km/h)
delta= 1;      % Difference between consecutive time instants (in seconds)
T= 3600;       % No. of time instants of the simulation

S= S/3.6;               % Conversion of maximum speed to m/s
results= zeros(1,T);  % Initialization of the results array

% Generation of initial coordinates, speed and direction of mobile nodes:
[pos,vel]= InitialRandom(N,S);
% Visualize node positions:
figure(1)
plot(pos(:,1),pos(:,2),'o','MarkerEdgeColor','b','MarkerFaceColor','b')
axis([0 300 0 200])
hold on
% Simulation cycle running all time instants iter:
for iter= 1:T
    % Compute the node pairs with direct connections:
    L= ConnectedList(N,pos,W);
    % Compute the no. of connected node pairs of time instant iter:
    results(iter)= AverageConnectedNodePairs(N,L);
    % Update node coordinates and speed values:
    [pos,vel]= UpdateCoordinates(pos,vel,delta);
    % Visualize updated node positions:
    plot(pos(:,1),pos(:,2),'o','MarkerEdgeColor','b','MarkerFaceColor','b')
end
hold off
% Plot in a different window the simulation results:
figure(2)
plot((1:T)',results')
% Compute the final result:
FinalResult= average(results)

function [pos,vel]= InitialRandom(N,S)
 %Computes a matrix 'pos' of N rows and 2 columns with the coordinates of
 nodes (see Section 5.1) and a matrix 'vel' of N rows and 2 columns with
 the initial horizontal and vertical speed components of nodes (see
 Section 5.2).
end

function L= ConnectedList(N,pos,W)
 %Computes a matrix 'L' of 2 columns with the node pairs such that
 their distance is not higher than W.
end

function o= AverageConnectedNodePairs(N,L)
 %Computes a value 'o' with the no. of connected node pairs based on the
 input matrix 'L' of node pairs with direct connections (see Section 4.1).
end

function [pos,vel]= UpdateCoordinates(pos,vel,delta)
 %Updates the matrices 'pos' and 'vel' based on their input values and
 delta.
end
```