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A comprehensive methodology to evaluate the performance of a cooperative wireless network

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Abstract: Performance evaluation of a cooperative wireless communication network depends on several parameters. Many of the studies, in fact, take a limited number of performance metrics individually to reach a conclusion about the performance of a network. Besides, in general, some performance metrics might be in conflict. Thus, ignoring the combined effect of all performance criteria in the network may lead to an incorrect conception of the overall communication performance of the network. Therefore, in this study, a comprehensive evaluation methodology in terms of various metrics is proposed to calculate the performance of a cooperative wireless communication network deployment using a real terrain map. The proposed methodology, based on desirability functions, is discussed in terms of signal quality, signal quality with hopping, average number of hopping, hopping duty, and deployment altitude. In addition to individual scores for each performance criterion, an overall performance score is also obtained. Furthermore, the effects of the desirability function's ambition factor, terrain characteristics, and connectivity requirement rate on the score are also presented. The simulation results show that the desirability function-based performance evaluation approach could support a flexible evaluation as well as provide an agreement on the conflicting performance metrics.

Key words: Connectivity, hopping, propagation loss, desirability functions, wireless networks

1. Introduction

Unlike cellular networks, a typical wireless communication network may consist of many devices that have to communicate with each other without utilizing a base station. Communication between any two devices is provided when the receiver is within the transmission range of the transmitter. Conversely, a direct link among all the devices hardly exists due to propagation losses and terrain characteristics; however, as a cost-effective solution, a cooperative wireless network that allows multihop transmission may be employed to connect all the devices in the network [1–4].

Cooperative wireless networks may be found in both civil and military applications [5]. For example, for disaster relief, randomly deployed communication devices are essential and probably the only solution to provide communication in an emergency situation. On the other hand, the predefined deployment plan may be the primary and permanent aspect for the network. Thus, if redeployment of the devices in the network is not possible, a cooperative wireless network that allows multihop transmission is the only solution.

In the literature, coverage and the number of devices are generally the most common performance indicators to define the performance of a wireless network via optimization algorithms. In [6], quality of

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coverage and the number of sensors are used for the performance evaluation of a wireless sensor network on three-dimensional terrain. In [7] the performance of a communication network over a real terrain is calculated based on two different metrics. The first metric considers the coverage, whereas the second metric computes the average signal quality. In [8] coverage is used as the main performance metric of a wireless sensor network and mobility is considered on a synthetically generated terrain. In [9] the performance metric is chosen as coverage. Although some studies such as [10] took the effect of propagation loss and the characteristics of a real environment, there is a lack of studies that take the performance evaluation problem of a cooperative wireless network in terms of overall communication activity in an aggregated manner.

An accurate performance evaluation of a cooperative wireless network is critical for the success and maintainability of the communication activity in the network. Since several parameters can be used to calculate the performance of a network, in many cases these parameters may have different units and they may conflict with each other [1, 11]. Derringer and Suich [12] introduced individual desirability functions to evaluate multiple responses, which is a simple and flexible solution to obtain a fair adjustment among several metrics. After calculating individual scores for different performance parameters, an overall desirability score is obtained by considering all the metrics [13].

The scope of this study is to propose a methodology to evaluate the performance of a wireless cooperative communication network in which the devices are already deployed and relocating the devices is not probable or desired. Accordingly, devices are randomly deployed over an environment by using a real terrain map having latitude, longitude, and altitude information. Since the performance of a wireless network mainly depends on the communication link efficiency, a detailed propagation loss calculation considering the characteristics of the terrain is performed. Performance parameters are defined as signal quality, signal quality with hopping, number of hops, hopping duty, and deployment altitude. With respect to these performance parameters, desirability functions are defined to calculate the individual scores. However, evaluating these performance metrics individually may be contradictory or misleading. Thus, one may prefer to evaluate the overall performance score of a cooperative wireless communication network. To the best knowledge of the authors, performance evaluation of a cooperative wireless network deployment over an environment using a real terrain map in this manner has not been deeply studied in the literature.

The organization of this study is as follows. In Section 2, we discuss the cooperative wireless communication network model in terms of propagation loss, connectivity matrices, and desirability functions. The proposed performance evaluation approach is also given in Section 2. The simulation parameters and results are given in Section 3. Finally, results of this study are concluded in Section 4.

2. Materials and methods

2.1. Network model

A wireless network consisting of n equivalent devices having the same transmission powers and antenna heights is considered in this study. All communication devices in the network can send and receive data among each other and they all have hopping capability. Therefore, multihop transmission is employed to provide connections among the devices when there is not a direct link between any two devices. The topology of a sample network having 10 nodes is given in Figure 1. In this figure the lines indicate the required connections.

A digital terrain elevation data (DTED) map [14] is considered to represent a real environment characteristics. Each point on the map is defined with $p(x, y, z)$, where x, y, and z show the latitude, longitude, and altitude values, respectively. Since the deployment of the communication devices in the network is performed randomly, there is no guarantee for the existence of a reliable communication link among the devices due to obstacles and the propagation loss.

A directed communication graph, $G(V, E)$, can be used to model the wireless network deployment. An edge $(i, j) \in E$ is a directed link from device i to device j. E is the set of all possible links in the network and devices $n_i \in V$ in the network are represented with the set of vertices, V. The haversine distance, considering the earth's curvature, between device i and device j is represented by $d(i, j)$ [10].

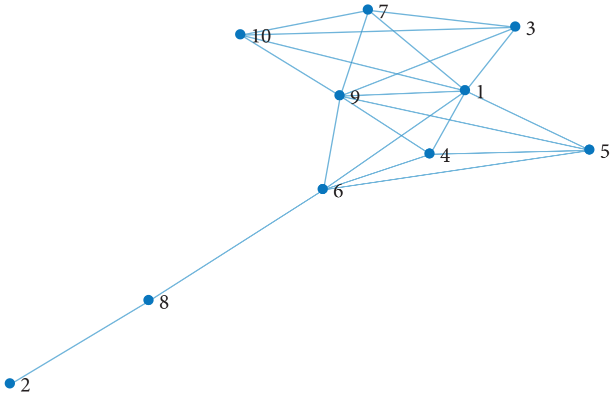

Figure 1. An example network topology representing desired connections among the devices.

The transmission range of a device determines the presence of a communication link between any two devices. Since the considered environment is a three-dimensional (3D) terrain, considering only the distance between the transmitter and receiver is not sufficient to describe the existence of a communication link. In this study, we employ the received power of the devices, which depends on the propagation loss between two devices, to determine the reliability of a communication link. Therefore, defining the received power at device j from the transmitter i as P_{ij} and a threshold power for a reliable communication as δ, the set of edges must satisfy the following condition to provide a communication link:

$$(i, j) \in E \leftrightarrow P_{ij} \geq \delta. \tag{1}$$

Although the main aim of a wireless communication network is to ensure that all devices are connected to each other, a communication link for all pairs of devices may not be obtained due to degradation in the received power. Therefore, a multihop transmission is considered as a low-cost solution rather than relocating devices. A maximum number of hops for each connection is defined not to increase the overhead in the network. With the help of multihop transmission, eventually we may have an all-connected communication network.

2.2. Propagation loss model

Line of sight (LoS) and terrain profile analysis are crucial while calculating the propagation loss in a terrain due to the obstacles through the propagation path. The locations and the number of obstacles are required to calculate the diffraction loss [15]. Since the locations of the devices may not be on the grid points, the interpolation method given in [16] is employed to calculate the latitude, longitude, and altitude values of any point between two locations defined in the gridded structure of the DTED maps.

We employ the propagation by the diffraction model recommended by the International Telecommunications Union [15], which is used to predict the propagation loss due to the obstacles existing in the terrain in addition to free space or flat earth path loss. Then the propagation loss, PL, is calculated as:

$$PL = max(PL_{free} + PL_{flat}) + PL_{diff}, \tag{2}$$

where free space and flat earth path loss are denoted by PL_{free} and PL_{flat}, respectively. PL_{diff} represents the diffraction loss due to the obstacles. Free space path loss is defined in (3), where d is the distance in kilometers between communication devices and f is the transmission frequency in MHz:

$$PL_{free} = 32.44 + 20\log_{10} d + 20\log_{10} f. \tag{3}$$

Similarly, flat earth path loss is given as:

$$PL_{flat} = 120 - 20\log_{10} h_{tx} - 20\log_{10} h_{rx} + 40\log_{10} d, \tag{4}$$

where h_{tx} and h_{rx} are the antenna heights of the transmitter and receiver devices, respectively. To calculate the diffraction loss, we obtain the path profiles and use the model described in detail in [15].

Now, PL_{ij} is the total propagation loss from device i to device j and the transmitter power of the device i is defined as P_i. Therefore, the received power at device j, P_{ij}, is given in (5):

$$P_{ij} = P_i - PL_{ij}. \tag{5}$$

In brief, the propagation loss simply depends on terrain elevation values, transmitter and receiver antenna heights, and transmission frequency.

2.3. Connectivity matrix model

The desired connectivity, actual connectivity, hopping connectivity, and accessibility matrices will be introduced to represent the directed communication graph.

Since all devices in the system are not necessarily required to communicate with each other, a desired connectivity matrix D is introduced to represent the required connections among the devices in the network. The diagonal elements of this matrix have a value of 0. The (i,j) entry of the matrix has a value of 1 if device i and device j are desired to be connected. On the other hand, the entries that take the value of 0 represent nonmandatory connections. Besides, the connectivity requirement rate of the network is also defined as the ratio of number of connections that are desired to the number of all possible connections in the matrix. For example, for a network consisting of n devices having $n(n-1)$ possible connections, and if only two connections are required, the connectivity requirement rate is equal to $2n/(n-1)$. The desired connectivity matrix D is given as:

$$D = \begin{bmatrix} 0 & 0 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 1 \\ 1 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 1 & 1 & 0 & 0 & 1 & 1 & 0 \\ 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 1 \\ 1 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 1 & 0 \end{bmatrix},$$

for the corresponding topology of the network given in Figure 1.

The actual connectivity matrix, C, is proposed to represent the actual connection status of the network. Therefore, each entry of the actual connectivity matrix can be obtained according to the threshold value and the received power at the corresponding device, as given in (6). In other words, if the received power at device j is greater than the threshold then this corresponding *(i,j)* entry is set to 1, whereas the entries of the matrix when the received power is less than the threshold are determined as 0. The diagonal elements of the matrix are also set to 0.

$$c_{ij} = \begin{cases} 1, & P_{ij} \geq \delta \\ 0, & P_{ij} < \delta \end{cases} \tag{6}$$

Now we will present a sample actual connectivity matrix with respect to (6) as follows:

$$C = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 & 1 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 & 1 & 0 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 & 1 & 0 & 1 & 0 & 1 \\ 1 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 & 1 & 1 & 0 & 1 & 0 \end{bmatrix},$$

for the same network discussed in Figure 1. The topology of the actual connectivity matrix is now given in Figure 2. Note that Figure 1 and Figure 2 only represent the desired and actual connections in the network, respectively, not the positions of the devices.

Besides, if any entry of the desired connectivity matrix has a value of 1 when the corresponding entry of the actual connectivity matrix is 0, this is a contradiction for the desired connectivity status. Since multihop transmission is a viable solution to get the desired connectivity, a hopping connectivity matrix H is introduced as:

$$H = C + C^2 + ... + C^k, \tag{7}$$

where $k \geq 2$ represents the maximum number of allowed hops to provide a connection between any two devices [17]. Namely, the H matrix is obtained by summing the C matrix with its square, third, and other kth powers. Thus, the entries of matrix H have nonzero integer values, which represent the number of available paths to provide the connection at entry *(i,j)*.

Since the hopping connectivity matrix does not give any information about which path should be selected, the Floyd–Warshall algorithm [18] is employed to find the shortest hopping route between transmitter i and receiver j. In this context, the shortest path is determined in terms of number of hops. An accessibility matrix A is introduced to represent the required number of hops for each *(i,j)* entry to obtain the connections in the desired connectivity matrix. If any entry of the C matrix is equal to 1, then the corresponding entry of the A matrix will also be 1 since there is a direct connection for these devices and no hopping is required for the corresponding link. On the other hand, if any entry of the C matrix is equal to 0, the corresponding entry of matrix A will be calculated by means of summing the kth powers of the C matrix. This summation can be

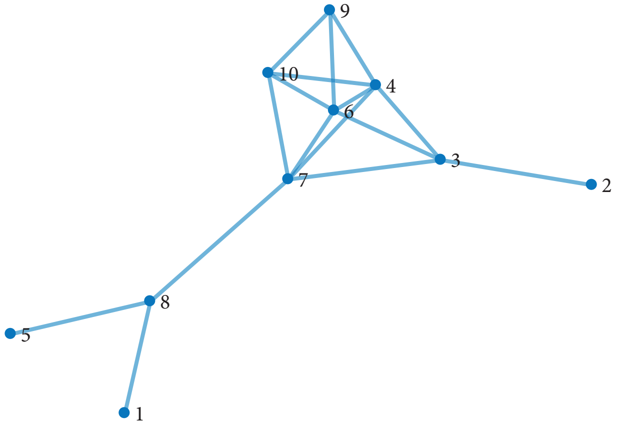

Figure 2. An example network topology representing actual connections among the devices.

done in two steps:

$$\left[H = C + C^2 + ... + C^{(k-1)}\right]_{ij} = 0, \tag{8}$$

$$\left[H = C + C^2 + ... + C^{(k-1)} + C^k\right]_{ij} \neq 0. \tag{9}$$

Namely, if (8) and (9) are both satisfied, then the corresponding entry of matrix A will be k; otherwise, it takes the value of 0. Therefore, the connection between device i and device j can be provided by *(k - 1)* hopping.

Since received power values of the devices are required to define the actual connectivity matrix, matrices for device-to-device received power, P, and end-to-end received power, E, are also introduced. The device-to-device received power matrix has a structure such that each entry represents the received power from the transmitter device i at the receiver device j for the corresponding *(i,j)* entry. On the other hand, entries of the end-to-end received power matrix describe the received power when multihop transmission is performed for the corresponding entries.

Although calculation of device-to-device received power is straightforward, as described in (5), end-to-end received power calculation depends on the individual received power of the devices that are utilized at the determined hopping route by the Floyd–Warshall algorithm. The end-to-end received power can be calculated as [19]:

$$E_{ij} = min\left\{P_{il_1}, P_{l_1 l_2}, ..., P_{l_{k-1}j}\right\}, \tag{10}$$

where $l_i \in Y \subset V$ and Y is the set of devices that are employed in the multihop transmission to provide a connection between device i and device j, in which there is not a direct connection between these two devices.

2.4. Desirability function approach

In this study, for a cooperative wireless communication network, signal quality, signal quality with hopping, number of hops, hopping duty, and deployment altitude are employed as performance metrics. Signal quality and signal quality with hopping performance metrics describe the average device-to-device and end-to-end received power values, respectively. Number of hops indicates the average number of hops performed whereas hopping duty represents the number of hopping tasks of the device that has the maximum number of hops in the network. Finally, the deployment altitude metric defines the ratio of the number of devices that are located above a specific altitude threshold to the total number of devices.

The performance metrics may have different aims, such as to be maximum or minimum; for example, average received power is desired to be as high as possible for good quality of communication whereas the hopping duty of a device is to be as low as possible to decrease the hopping load of the corresponding device. Therefore, we will first define two desirability functions for the criteria desired to be minimum or maximum, in (11) and (12), respectively. In the desirability function approach, *d(y)* takes the value of 1 for the most desired case whereas 0 represents an undesired result or a dissatisfaction of the requirement.

$$d_{min}(y) = \begin{cases} 1, & y < y_l \\ \left(\frac{y-y_u}{y_l-y_u}\right)^r, & y_l \leq y \leq y_u \\ 0, & y > y_u \end{cases} \tag{11}$$

$$d_{max}(y) = \begin{cases} 1, & y > y_u \\ \left(\frac{y-y_l}{y_u-y_l}\right)^r, & y_l \leq y \leq y_u \\ 0, & y < y_u \end{cases} \tag{12}$$

In (11) and (12), the exponent r is a user-defined ambition factor to determine the response of the desirability function. y_u and y_l are the upper and lower limits of the desirability functions, respectively [13].

Since we are proposing an aggregated performance evaluation, the individual desirability function scores of d_i can be employed in a geometric mean to calculate the overall desirability score, DS:

$$DS = \left[\prod_{i=1}^{m} d_i(y)\right]^{\frac{1}{m}}, \tag{13}$$

where m is the number of individual desirability functions scores.

2.5. Proposed performance evaluation methodology

The proposed performance evaluation methodology is summarized in Figure 3 in a flowchart. To verify that the required connections indicated by the desired connectivity matrix D are fulfilled, the entries of matrix H greater than 1 are set to 1 and defined as the H' matrix. As shown in the flowchart, we will first describe a desirability connectivity matrix, which represents the required or mandatory connections in the network. After calculating received power at each device according to the propagation loss, we will obtain the actual connectivity matrix. This matrix shows the connectivity status of the devices in the network. If all mandatory connections in the network are satisfied, the A, E, and H' matrices are constructed to calculate the performance of the network. Otherwise, the hopping process is performed and the same procedure is repeated.

Consequently, we define five different inputs, y_1, y_2, y_3, y_4, and y_5, for the desirability function scores, d_1, d_2, d_3, d_4, and d_5, respectively. It is preferable that the y_1 and y_2 input values be as high as possible, whereas the y_3, y_4, and y_5 input values are as low as possible.

High average received power in the network is essential for good quality transmission. Therefore, the signal quality desirability score shall be calculated by (12). The input of this function in terms of average device-to-device received power is determined as:

$$y_1 = \frac{1}{n(n-1)} \left[\sum_{i=1}^{n} \sum_{\substack{j=1 \\ i \neq j}}^{n} P_{ij} \right], \tag{14}$$

where $n/(n-1)$ represents the number of possible connections in the network.

The signal quality desirability score will approach 1, which indicates the most desirable performance, if y_1 is close to y_u, whereas the signal quality desirability score becomes zero when the average device-to-device received power value is less than y_l.

Then, since we assume that all the devices have hopping capability, after multihop transmission, we can propose the signal quality with the hopping desirability metric. This performance metric is also calculated by (12); however, now it depends on the average end-to-end received powers of the devices in the network. The input to the end-to-end received power desirability function is given in (15):

$$y_2 = \frac{1}{n(n-1)} \left[\sum_{i=1}^{n} \sum_{\substack{j=1 \\ i \neq j}}^{n} E_{ij} \right]. \tag{15}$$

Although multihop transmission eventually may provide all the required connections, a large number of hops will degrade the performance of the network. Therefore, for the hopping desirability score that will be calculated by (11) to indicate the performance of the network in terms of average number of hops, the input value is given in (16):

$$y_3 = \frac{1}{n} \left[\sum_{i=1}^{n} \sum_{\substack{j=1 \\ i \neq j}}^{n} (A_{ij} - 1) \right]. \tag{16}$$

The average number of hops performed in the network is calculated according to the accessibility matrix entries. Since allowing a high number of hops in the network will adversely affect the communication traffic, the hopping desirability function score is going to be decreased by the increasing number of hops.

Due to the characteristics of the environment, some of the devices in the network may have an excessive hopping duty to provide the connection. Therefore, a large number of hops for a single device will yield performance degradation in that device, which also degrades the performance of the whole system. In this context, the hopping duty desirability score shall be calculated by (11) and the input value is given as:

$$y_4 = \frac{max(m_i)}{n(n-1)}, i = 1, ..., n, \tag{17}$$

where m_i represents the number of hops performed for each device i. If the device has no hopping duty, the value of m for the corresponding device is set to zero. Consequently, for the input given in (17), the desirability function score increases when the hopping duty decreases. Finally, we define an altitude threshold because it

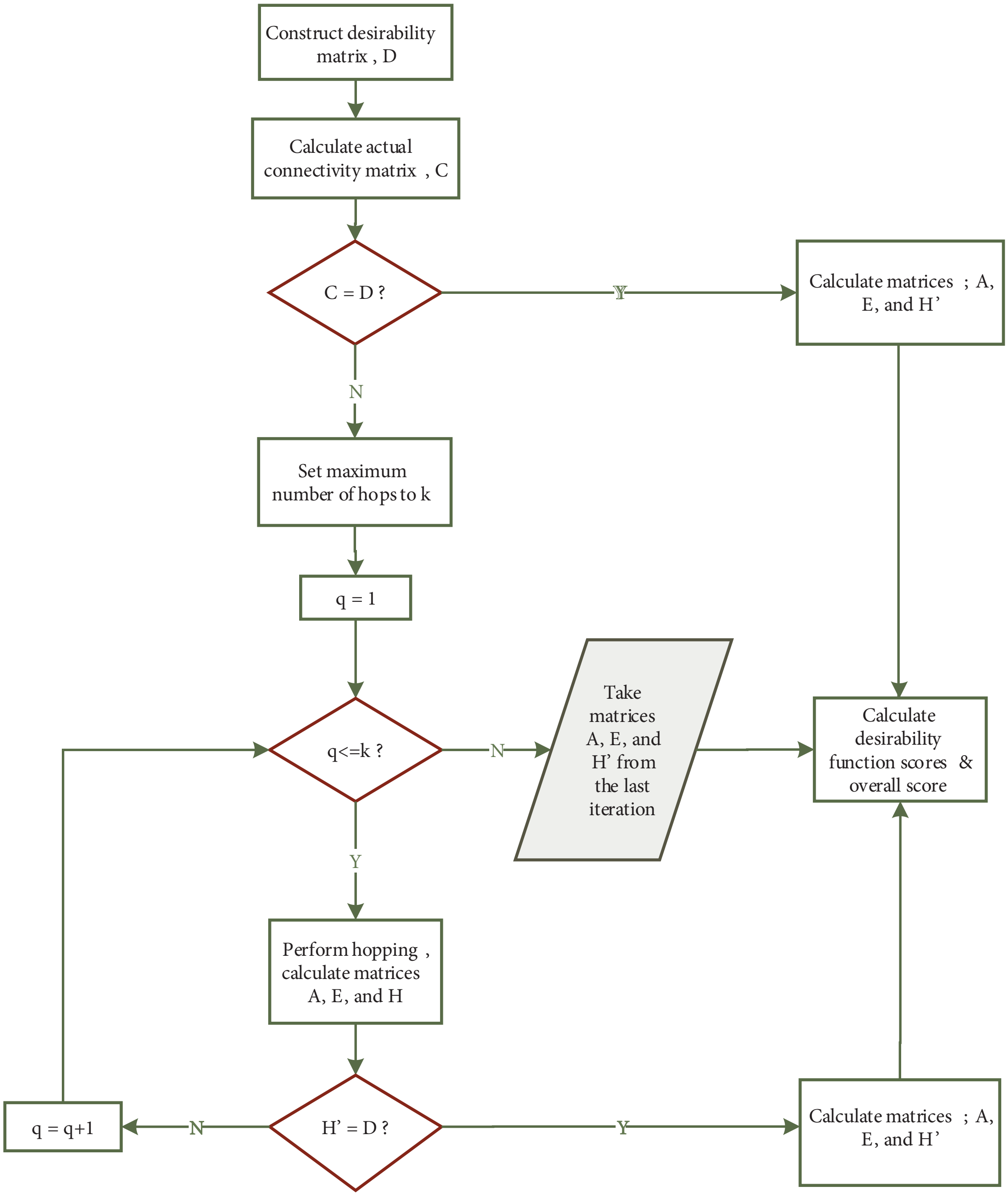

Figure 3. Flowchart of the proposed performance evaluation methodology.

is physically difficult to deploy the devices at high altitudes. Thus, it is preferable that the number of devices below the threshold be as high as possible. Therefore, for the altitude desirability score that will be calculated by (11), the input value is given as:

$$y_5 = \frac{n^{'}}{n}, \tag{18}$$

where $n^{'}$ represents the number of devices that are located above the threshold whereas n is the number of all devices in the network.

3. Results

Simulation results are given to show the effects of individual desirability scores on calculating the overall performance score of the cooperative wireless network as well as the impact of ambition factor, number of devices, and terrain characteristics. Random deployment of the devices over different terrain characteristics and various connectivity requirement rates are employed for different numbers of devices. Simulations are repeated 200 times and results are averaged. Simulation parameters are given in the Table.

Table. Simulation parameters.

Transmission power of the devices	20 W
Number of communication devices	30, 60, 120
Terrain dimensions	10162 m × 10286 m
Connectivity requirement rate, %	20, 40, 100
Maximum number of hopping	5
Power threshold for reliable communication link	–103 dBm
Transmission frequency	400 MHz
Desirability function ambition factors	0.3, 3
Signal quality and signal quality with hopping desirability function lower and upper limits	–125 dBm, –40 dBm
Hopping desirability function lower and upper limits	0, 5
Hopping duty desirability function lower and upper limits	0, 1
Altitude threshold value	1950 m
Altitude desirability function lower and upper limits	0, 1

We compute the performance of a wireless cooperative communication network consisting of n devices randomly deployed over two different terrains having hilly and mountainous characteristics, as shown in Figure 4 and Figure 5, respectively.

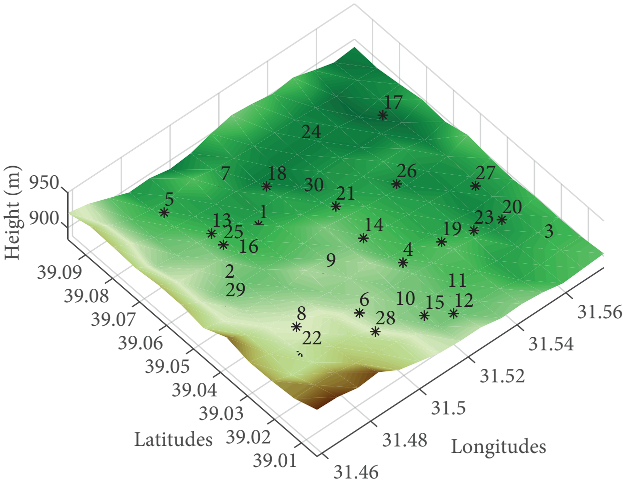

Figure 4. DTED map for a hilly terrain and a random deployment of 30 devices.

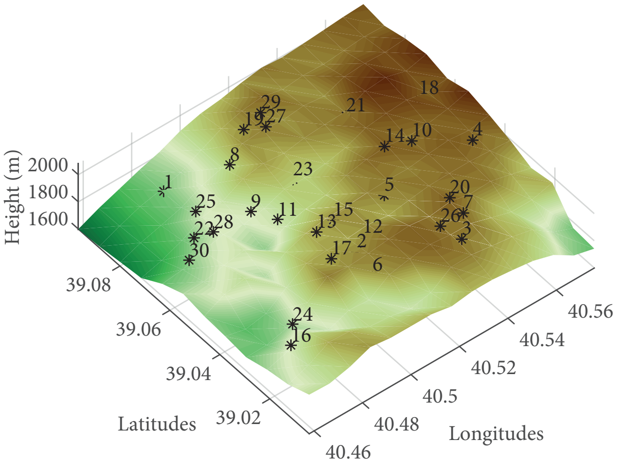

Figure 5. DTED map for a mountainous terrain and a random deployment of 30 devices.

Communication network performance is evaluated for three different connectivity requirements rates of 20%, 40%, and 100%. A DTED map has a grid structure and each grid is a 1° by 1° cell. There are basically three DTED maps, such as Level 0, 1, and 2, with different resolutions. Specifically, DTED Level 2 maps, consisting of 3601-by-3601 grids, containing one arc second grid with a dimension of approximately 30 m, have been used in this study.

Figure 6 and Figure 7 show the desirability performance scores of a network consisting of 30 devices with three different connectivity requirement rates, deployed over a hilly terrain when the ambition factor is set to 0.3 and 3 for each desirability function.

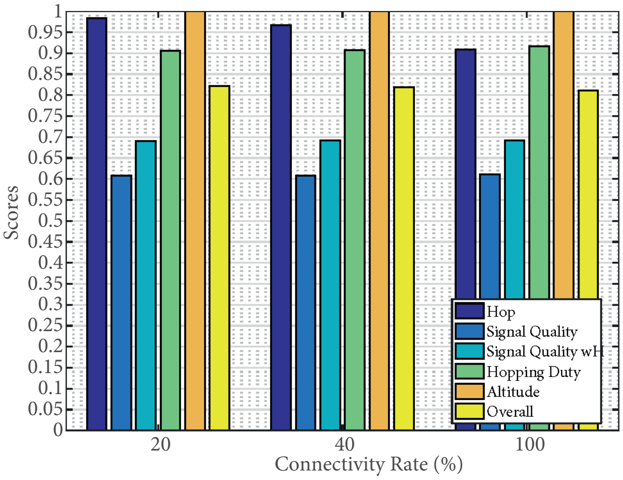

Figure 6. Performance scores for the network consisting of 30 devices deployed randomly over a hilly terrain when the desirability function's ambition factor is 0.3.

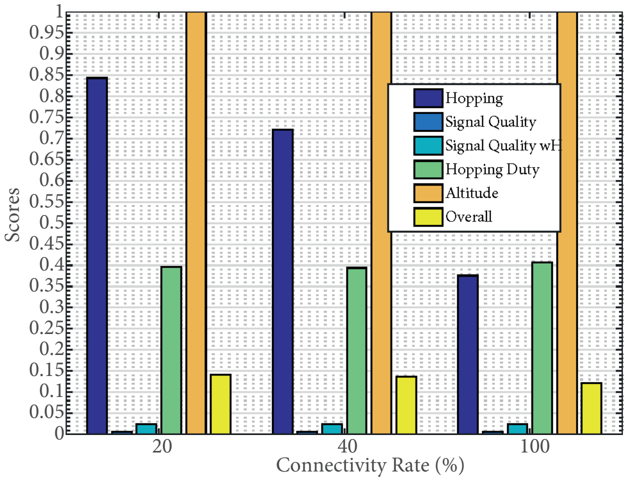

Figure 7. Performance scores for the network consisting of 30 devices deployed randomly over a hilly terrain when the desirability function's ambition factor is 3.

According to Figure 6, when the connectivity rate is increased from 20% to 40% and from 40% to 100%, the hopping score is decreased by 1.6% and 6.0%, respectively. Therefore, increasing the number of devices that need to be connected in the network increases the need for hopping. Besides, in Figure 7, the hopping scores are decreased by 14.5% and 47.9% with the increased connectivity rates. On the other hand, there is not a noticeable change in other scores. Hopping score is decreased by 14.3%, 25.5%, and 58.7% for the connectivity rates of 20%, 40%, and 100%, respectively, when the ambition factor is switched from 0.3 to 3. The altitude score has no effect on the overall performance calculation since none of the devices have been located at an altitude that is higher than the threshold.

Figures 8 and 9 and Figures 10 and 11 give the performance scores when the number of devices in a hilly terrain deployment network is 60 and 120, respectively. Hopping duty score is increased by 5.2% when the number of devices is increased from 30 to 120 at a connectivity rate of 20%, since the hopping duty is more likely to be shared by devices and the score is improved. The performance evaluation of the network deployed on a mountainous terrain is given in Figure 12 and Figure 13 for two different ambition factors of 0.3 and 3 and for three different connectivity rates.

According to the results given in Figures 6–13, changing the ambition factor from 0.3 to 3 results in a significant performance score variation due to the structure of the desirability function despite the same network being discussed. Accordingly, the simulation results simply show the impact of the ambition factor on the performance scores of the desirability functions.

To assess the effects of the terrain and the number of devices, Figures 14 and 15 are respectively given. In Figure 14, over a mountainous terrain hopping, signal quality, and hopping duty scores are decreased by

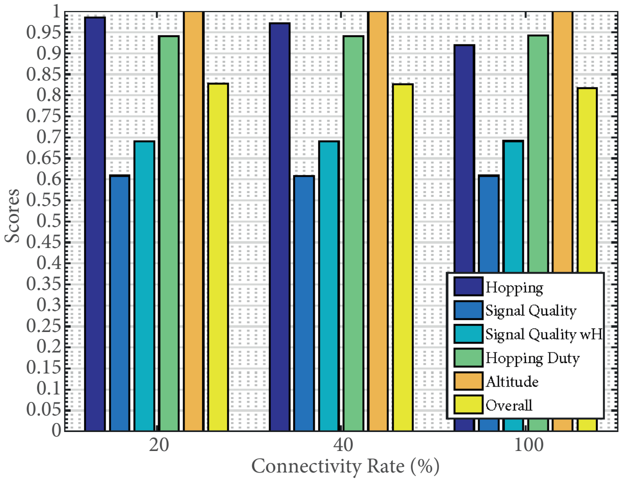

Figure 8. Performance scores for the network consisting of 60 devices deployed randomly over a hilly terrain when the desirability function's ambition factor is 0.3.

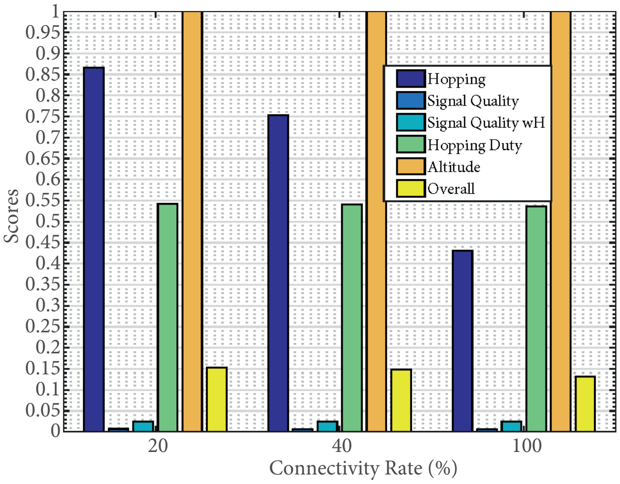

Figure 9. Performance scores for the network consisting of 60 devices deployed randomly over a hilly terrain when the desirability function's ambition factor is 3.

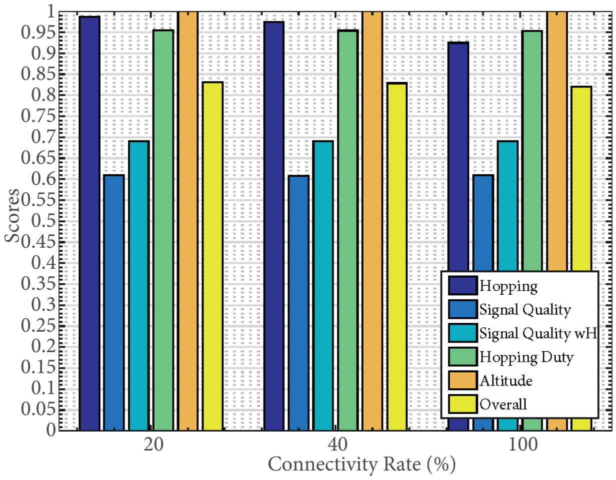

Figure 10. Performance scores for the network consisting of 120 devices deployed randomly over a hilly terrain when the desirability function's ambition factor is 0.3.

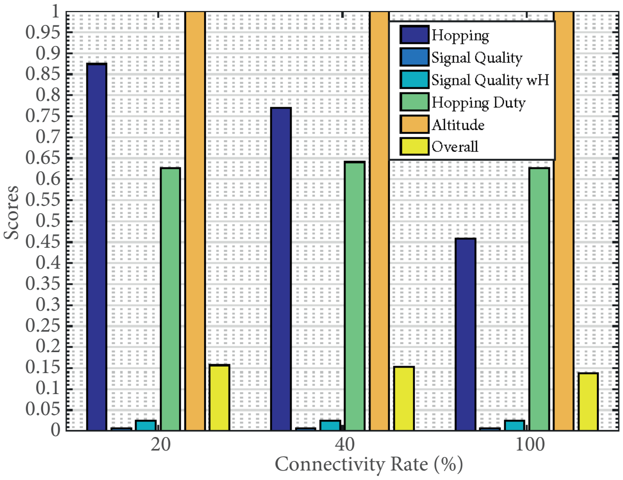

Figure 11. Performance scores for the network consisting of 120 devices deployed randomly over a hilly terrain when the desirability function's ambition factor is 3.

5.4%, 45.6%, and 3.4%, respectively, for ambition factor of 0.3 and connectivity rate of 100%.

Therefore, the mountainous terrain deployment significantly degrades the signal quality performance due to the increased roughness of the terrain. On the other hand, in Figure 15, there is a slight increase in the overall score when the number of devices is getting larger. However, scores of hopping and hopping duty are increased by 21.1% and 53.8%, respectively, when the number of devices is increased from 30 to 120.

As a result, it is observed that increasing the connectivity requirement rate does not have an adverse effect alone on the signal quality score, whereas the terrain type has the major impact on the signal quality. Furthermore, the altitude score has no effect on the overall performance score of the hilly terrain because all altitudes remain below the threshold. However, the overall score is adversely influenced by the altitude score in a mountainous terrain deployment.

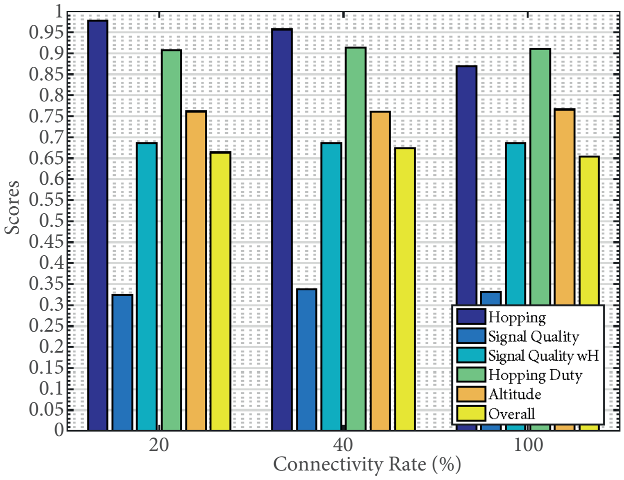

Figure 12. Performance scores for the network consisting of 60 devices deployed randomly over a mountainous terrain when the desirability function ambition factor is 0.3.

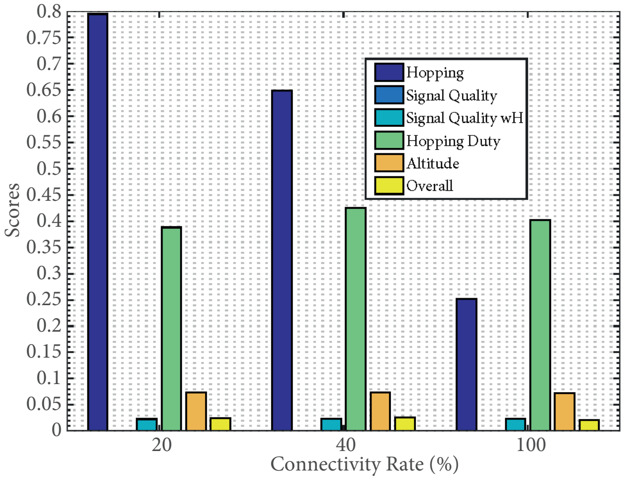

Figure 13. Performance scores for the network consisting of 60 devices deployed randomly over a mountainous terrain when the desirability functions ambition factor is 3.

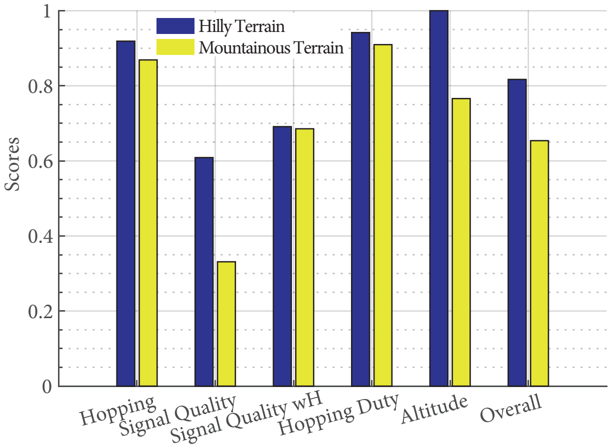

Figure 14. Performance scores for the network consisting of 60 devices with a connectivity rate of 100% deployed randomly when the desirability function ambition factor is 0.3.

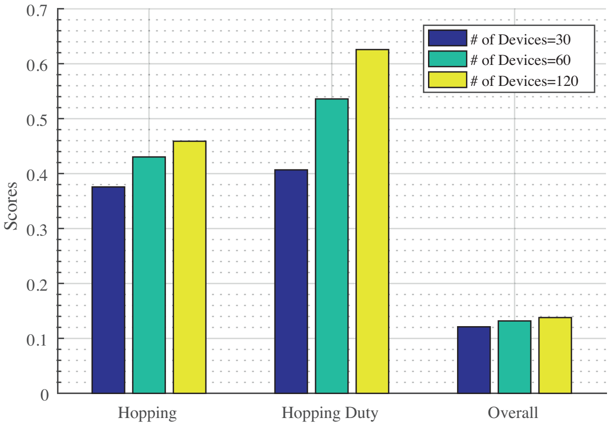

Figure 15. Performance scores for the network with a connectivity rate of 100% deployed randomly over a hilly terrain when the desirability function ambition factor is 3.

4. Conclusions

We present a desirability function-based methodology to evaluate the performance of a cooperative wireless communication network. The performance of the network is evaluated in two different terrains with three different numbers of devices and three connectivity requirement rates. Five distinct desirability functions are defined to evaluate the performance of the network in individual scores and an overall score is also obtained. Simulation results show that the ambition factor of desirability functions inherently affects the overall and particular performance scores. In addition, performance of the network depends on the terrain characteristics, number of devices in the network, and number of devices required to be connected with each other.

A remarkable result that shows the convenience of the desirability function methodology can be recognized when the scores are compared. The performance of the network according to a single metric might be pretty good, whereas the overall score might indicate a quite poor performance and vice versa. By the proposed performance evaluation approach, we integrate the individual scores into a single overall network performance score. Besides, according to the results, the desirability function-based performance evaluation methodology could support a flexible assessment approach as well as provide a settlement on the conflicting performance metrics.

This study also shows that the desirability functions can be used to develop rule-based or heuristic algorithms to improve the communication quality of a network when employing a classical multiobjective optimization algorithm is not feasible. As a future work, a rule-based algorithm will be developed to improve the performance of the network by changing device locations, which can yield higher desirability scores.

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