Linear Wireless Mesh Network Planning

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***Abstract*—Wireless mesh networks consist of mesh routers and clients, where mesh routers compose the network backbone and serve clients. The antennas associated with the routers can be omnidirectional or directional, which have a direct influence in topology construction. With this information in hand, the objective of this work is to propose and evaluate LMP, an algorithm that, given a set of coordinates organized in sequence, decides which of them will have a mesh router installed. This decision must guarantee coverage (each coordinate must be within the coverage area of at least one mesh router) and connectivity (each mesh router must communicate with at least another one). Results obtained with real network testbeds are used to compare the required number of mesh routers, transmission rate and the average and worst signal quality with those from various techniques.**

I. Introduction

Wireless Mesh networks consist of mesh routers and mesh clients. The routers are, typically, stationary, composing the network backbone. These routers can communicate with other networks such as the Internet, LANs, etc., provided they are configured as gateways. The main advantage of this network type is robustness. Because each node can act as a potential router assisting the routing process, the higher the number of nodes, the higher the number of alternative routes.

As mentioned earlier, stationary routers compose the backbone of a wireless mesh network. Choosing the positioning of these routers is the main focus of this paper. The antenna type, which can be omnidirectional or directional, has a direct impact on this choice. Working with directional antennas raises the complexity because it is only possible to determine the coverage area if the antennas are aligned in some direction.

Among the various topologies that wireless mesh networks can assume [1], this paper focus on linear wireless mesh networks. This type of network contains a set of target points sequentially organized, where the first and the last work as gateways. Mesh routers can be installed in any of these target points. The antenna type that best fits this topology is the directional, because the communication is performed over the forward and backward directions. The connectivity of the network can be achieved by using two directional antennas, one aligned towards the backward router and the other towards the forward one. Besides these characteristics, the range of directional antennas is higher than the omnidirectional ones. The mesh router and the two directional antennas compose a mesh kit. This configuration was chosen in order to address a real problem of establishing network communication over a power transmission line. In this scenario, there are a set of towers, sequentially organized, that may host a mesh kit. There are other likely scenarios where linear wireless mesh networking can be applied, like gas or oil pipelines, highways, rivers and so on.

To solve the problem of backbone construction in linear wireless mesh networks, this paper proposes and analyses LMP (Linear Mesh network Planning) algorithm. The main goal is to reduce the number of mesh kits necessary for the network construction while considering restrictions like coverage and connectivity. Coverage means that each of the target points must be within the coverage area of at least one mesh kit. Whereas connectivity dictates that a mesh kit must communicate with at least another one. To help the development of this algorithm, the network built over the power transmission line that links the Brazilian cities of Machadinho and Campos Novos, in operation since 2008, was used for comparison purposes and to detect the problems and needs of this topology.

II. Related Work

Wireless mesh networks planning has been receiving a lot of special attention recently. Most of the works on this area focus on the development of protocols rather than network planning. Many works, that address the planning problem, are based on the use of omnidirectional antennas. The main advantage of this antenna type is the easiness of creating a graph where each edge represents a communication between two nodes. Conversely, when using directional antennas, the communication between two nodes depends on the alignment of each antenna. Considering omnidirectional antennas, the proposal in [2] specifies that each node has a circular coverage area where the radius varies according to the node's transmission power. This is the usual representation of omnidirectional antennas. The use of this approach tends to simplify the antenna's propagation model. In order to address this problem, non-uniform propagation is used in [3]. In this work, real propagation models are used together with obstacle analysis, another factor that has a direct impact in signal propagation.

There is a group of work that utilize directional antennas for network planning like GPRS [4], whose objective is planning wireless mesh networks for urban areas. But, in this case, there is no concern with the antenna alignment in order to increase the coverage area. It is defined that each node has multiple antennas and the communication with another node can be established only if Line-of-Sight exists between them. Besides the urban usage of wireless mesh networks, there are works that focus on the use of this network on rural areas, like [5]. The efficient use of directional antennas is also the main focus of [6]. The authors propose an algorithm that converts a mesh network composed by omnidirectional antennas into a network that utilizes only directional antennas. However, these proposals do not consider the linear wireless mesh network scenario.

III. Problem Formulation

The wireless mesh network planning problem can be formulated using graph theory. Using this approach, let V be a sequence of target geographic coordinates. Each coordinate has a priority associated to it. Sequence V represents the vertices of a directional graph G. Considering two vertices $u, v \in V$, there is an edge starting from u towards v only if v is the best alignment option for u. For v to be considered the best alignment option of a vertex u, the process of aligning one antenna of u in the direction of v must result in the highest number of vertices being covered, including v. An additional restriction is that, all vertices located between u and v must be covered (Figure 1). Also, vertex v must have the highest priority of the vertices being analyzed. Each vertex have a limit of two edges originating from it, one towards the forward vertex and the other towards the backward one. Another important fact that allows communication between vertices is the absence of obstacles. The solution lies in choosing a sub graph that connects the first vertex of the sequence with the last one, using the lowest number of vertices as possible. An example of a graph may be seen in Figure 2.

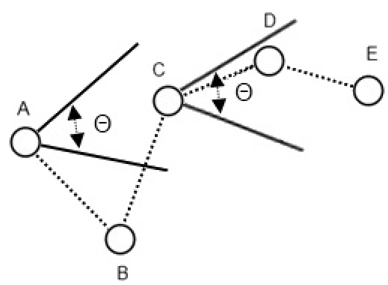


Figure 1. With a directional antenna with an opening angle θ, vertex C aligned with E covers D, however A aligned with C does not cover B.

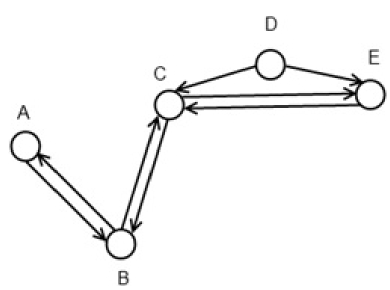


Figure 2. An example of an aligment graph. In this case, the pairs of antennas connecting A-B, B-C e C-E are aligned.

IV. Proposal

In this section, the design of LMP is discussed. Before explaining each section of the algorithm, Figure 3 shows its execution flow chart. Initially, a sequence of coordinates must be handed so the alignment graph can be built. This construction requires coverage area calculation, priority verification and obstacle analysis. With the graph in hand, a shortest path algorithm gives the coordinates that must host a mesh kit. The LMP algorithm may not find a solution to the given set of coordinates. The absence of solutions may be related to the distance between the coordinates and the presence of obstacles. After the solution is built, a group of post-processing operations improves it.

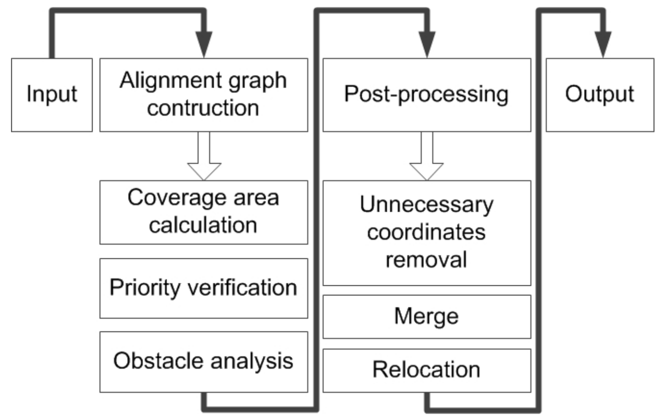


Figure 3. Flow chart of the LMP algorithm.

As an example, the solution for the alignment graph in Figure 2 is the path containing the vertices: A, B, C and E. This way, each of these vertices needs to have a mesh kit installed in order to provide connectivity and coverage to the network.

A. Coverage Area

As specified in Section III, the process of selecting the best alignment neighbor requires knowing if one or more coordinates are located within the coverage area of some antenna. The equation responsible for determining the coverage area is known as Link Budget [7]. This equation provides the received signal PRX using, basically, the sum of the output power with the gains and losses related to the antenna of both the transmitter and receiver. The equation used by the algorithm is the following:

$$PRX = PTX + GTX - LTX - LFS - LM + GRX - LRX, \quad (1)$$

where PTX and GTX represent, respectively, the output power and the antenna gain, while LTX define the loss related to cables and connectors, and LM may be used for miscellaneous losses. The LFS variable represents the result of the Free-space Path Loss equation, responsible for calculating the signal attenuation due to the distance between two antennas. LFS can be computed as:

$$LFS = 32,45 + 20 * log(FREQ) + 20 * log(DIST), \quad (2)$$

where $FREQ$ represents the frequency in Mhz and $DIST$ is the distance in kilometers. All variables mentioned to this point are related to the transmitter and the medium. GRX and LRX variables refer to the antenna gain and losses on the receiver. These two variables are used only when calculating the Link Budget equation to a candidate for best neighbor. This restriction exists because this candidate, if selected, will receive a known antenna. Link Budget equation ignores these two variables when calculating the signal received by the coordinates located between the origin and its best neighbor. However, this omission does not bring any negative consequence, because a device accessing the network has its antenna gain added to the received signal.

When working with directional antennas, the antenna gain depends on the angle between the antenna and the coordinate being analyzed, because the irradiation pattern is not homogeneous. To determine this pattern, for each horizontal and vertical angle with 1^{o} interval, the loss related to the maximum gain angle (0^{o}) must be provided.[1].

The result from the Link Budget equation is compared to a Received Signal Strength (RSS) threshold. If the result is below this threshold, then it is not possible to establish a communication; i.e., the coordinate is outside the coverage area.

B. *Obstacle Analysis*

Another necessary factor, described in the problem formulation, for establishing communication using gigahertz frequency radios is the absence of obstacles. To determine if the obstacles will allow the communication to be established or not, the Fresnel zone equation is used. The Fresnel zone is one of the concentric ellipsoids formed between two points in a radio system (Figure 4). For a radio transmission to be possible, it is required that a percentage of this ellipsoid is free of obstacles. The rule of thumb value of this percentage is 60%. The Equation 3 shows the calculation of the Fresnel zone radius. The $PERC$ parameter represents the percentage of the Fresnel zone that must be clear of obstacles and $FREQ$ is the antenna's frequency. Values $D1$ and $D2$ are, respectively, the distance from the obstacle to the first antenna and to the second antenna. Knowing the radio and the height in which each antenna is installed, it is possible to determine the maximum elevation, above sea level, that an obstacle can have in order to allow communication.

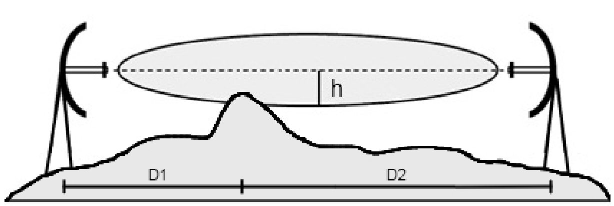


Figure 4. In the Fresnel zone, the radius h of the ellipsoid is related to the transmission frequence and distance.

[1]The irradiation pattern is typically provided by the antenna's manufacturer.

$$RADIUS = 17.31 * \sqrt{\frac{PERC * D1 * D2}{FREQ * (D1 + D2)}} \quad (3)$$

To determine the obstacles between two geographic coordinates, a database containing the geographic elevations of the region where the input coordinates are located is needed. In order to know if an obstacle will prevent the communication between two coordinates or not, all other coordinates between them, located in the database but not necessarily in the input set, are analyzed, comparing its elevation with the maximum calculated using the Fresnel zone. If the elevation value is higher than the one calculated for Fresnel zone, direct communication is not be possible.

C. *Priority Verification*

One characteristic that all coordinates must have is the priority. The priority is responsible for determining the importance of the coordinate in the input set. Four priorities were defined: never select, low, normal, always select. The first one determines that a coordinate must not be present in the solution and is useful in situations where the access to the coordinate location is difficult. The low priority determines that a coordinate is only used when a communication cannot be established using higher priority coordinates. The normal priority determines that the coordinate may be selected as if there were no priorities. The always select priority is used when a coordinate must always be present in the solution. Despite the selection priority of each coordinate, all of them continue to be treated equally by the coverage guarantee section of the heuristic.

The use of priority solves a problem detected on the network installed in the transmission line that links Machadinho to Campos Novos. As presented earlier, each coordinate selected by the algorithm is deployed with a mesh kit. To provide power to this kit, solar panels are used. This was the selected approach because it is not possible to use the 500 kV energy of the power transmission line to supply power to these devices. It was noticed that the structure of certain towers causes the incidence of shadow in the solar panels. Depending on the tower, the kit cannot be installed on the highest point for security reasons, as the devices included in the kit may fall on the wires. The towers can be grouped in two categories: those that cause the shadowing problem and the ones that do not. Unfortunately, the majority of the towers on the transmission line belongs to the first category. These towers are considered low priority, meaning that they are selected only when it is not possible to establish direct communication between two normal or always select towers.

Special caution is required when using priority as Figure 5 shows. In this situation, A can communicate directly with nodes B, C and D, where B is the node with the highest priority among them. Because of the priority, B is selected as the best neighbor of A, despite the direct communication with D. Although E is the next highest priority coordinate, no direct communication between B and E can be established, leaving

D as the best neighbor of B. This way, the communication between A and D, uses B as an unnecessary intermediate coordinate, as the communication between them can be done directly. Knowing that these situations may be present on the solution, a post-processing operation detects and removes the unnecessary coordinates.

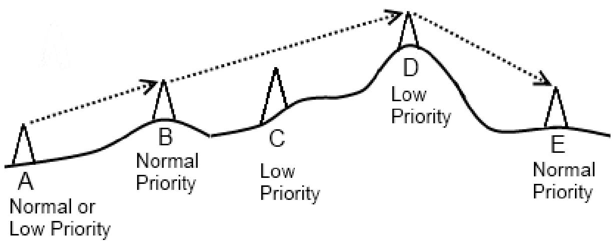


Figure 5. In this example, B is selected by the algorithm because of its priority, despite the direct communication with D.

```
LMP(V, RSSThreshold)
1: G ← Coordinates(V)
2: for each coordinate i ∈ V do
3:     SelectBestNeighbor(i, G, RSSThreshold, Forward)
4:     SelectBestNeighbor(i, G, RSSThreshold, Backward)
5: end for
6: First ← FirstCoordinate(V)
7: Last ← LastCoordinate(V)
8: R1 ← ShortestPath(G, First, Last)
9: RemoveUnnecessaryCoordinates(R1)
10: R2 ← ShortestPath(G, Last, First)
11: RemoveUnnecessaryCoordinates(R2)
12: R ← Merge(R1, R2)
13: R ← RemoveCloseCoordinates(R)
```

Figure 6. Pseudo code for the basic operation of the algorithm.

D. Building the Alignment Graph

As shown in Figure 3, the first step of the algorithm is the alignment graph construction. In order to accomplish this, it is considered that all coordinates are possible candidates for receiving a mesh kit, allowing the construction of an alignment graph like the one describe in Section III. The construction of the graph requires that each coordinate is aligned with its best neighbor. After building the graph, a shortest path algorithm provides the solution containing the minimum quantity of coordinates required in order to build the network. Depending on which coordinate (first or last) the shortest path algorithm starts its execution, two different solutions can be obtained. This occurs because v may be selected as u's best neighbor, but u may not be the best neighbor of v. Both solutions are refined by post processing operations and merged, resulting in one solution containing each other's positive aspects.

In Figure 6 the pseudo code for this procedure is presented. The set of coordinates V and the RSS threshold, used on the Link Budget equation, must be provided as input parameters. Initially, the vertices of the directional graph G are the coordinates of V (line 1). For each coordinate $i \in V$, the best alignment procedure adds an edge on G connecting i to its best neighbors (one towards the forward best neighbor and the other towards the backward one) (lines 3 and 4). After applying a shortest path algorithm on G, resulting in $R1$ and $R2$ (lines 8 and 10), both resulting sets are searched for unnecessary coordinates (lines 9 and 11), that may occur due to the use of priority, as described in Subsection IV-C. Then, $R1$ and $R2$ are merged (line 12), resulting in the R set containing the coordinates that must receive a mesh kit. Finally, the procedure for relocating close coordinates is executed (line 13), resulting in the final solution. The merge and close coordinate relocation processes are described in Section V.

The main difficulty lies in choosing the best neighbor (Section III). The pseudo code of the best neighbor selection algorithm is presented in Figure 7.

Initially, it is necessary to know in which direction the search for the best neighbor shall start. This information is given by the $Direction$ flag, which indicates if the forward or backward neighbors are analyzed. This way, the first neighbor of i can be the forward (line 2) or the backward one (line 4). With the first neighbor defined in the $Neighbor$ variable, it is now possible to determine if it is the best alignment option for i. The first step is to verify if all coordinates located between i and $Neighbor$ are being covered, which is performed by the $CoverageAnalysis$ procedure (line 9). If one of those coordinates is not being covered, then the return value is 0, which stops the best neighbor analysis (line 10). If the return value is a number different from 0, it is stored in $Counter$ (line 9) for future use. The next step is to check the best neighbor candidate's priority. If it is an always select coordinate (line 11), it must be present in the solution, but this presence must not conflict with other restrictions, like the obstacle analysis. So, if i cannot establish a direct communication with $Neighbor$, despite the always select priority, it is not selected as i's best neighbor. Also, no more coordinates are analyzed (line 20) in order to prevent the omission of the always select coordinate in the solution. This does not prevent the ignored coordinate to be part of the solution, because another one must establish a direct communication with it, or else, there is no solution for the input set.

The $ContinueAnalysis$ variable (lines 8, 13, 24 and 41) is used when an obstacle prevents direct communication with $Neighbor$ (line 40). Instead of selecting the current best neighbor, the algorithm may continue its execution. Figure 8 shows an example where $ContinueAnalysis$ is used. The coordinate A cannot establish a communication with C, leaving B as its best neighbor. However, A can also communicate with D, and D can supply the coverage for C. In order for a coordinate to be select as best neighbor when the value $ContinueAnalysis$ is set to true, it must have a direct communication with all the other coordinates. This process is performed by the $CoverageGuarantee$ procedure. That's why E cannot be selected, as its communication with C is obstructed.

Continuing with the priority verification, if $Neighbor$ is a never select coordinate, then it is ignored as a candidate (line

```
SelectBestNeighbor(i, G, RSSThreshold, Direction)
 1: if Direction = Forward then
 2:    Neighbor ← i + 1
 3: else
 4:    Neighbor ← i − 1
 5: end if
 6: MaxNormalPriority ← 0
 7: MaxLowPriority ← 0
 8: ContinueAnalysis ← false
 9: Counter ← CoverageAnalysis(i, Neighbor, RSSThreshold)
10: while Counter > 0 do
11:    if Priority(Neighbor) = ALWAYS SELECT then
12:       Obstacle ← CheckForObstacles(i, Neighbor)
13:       if ContinueAnalysis = true AND Obstacle = true then
14:          Obstacle ← CoverageGuarantee(i, Neighbor)
15:       end if
16:       if (Obstacle = false) then
17:          BestNeighbor ← Neighbor
18:          MaxNormalPriority ← 1 {Informing that a best neighbor
             exists}
19:       end if
20:       Finish the While Loop
21:    else
22:       if Priority(Neighbor) ≠ NEVER SELECT then
23:          Obstacle ← CheckForObstacles(i, Neighbor)
24:          if Obstacle = true AND ContinueAnalysis = true then
25:             Obstacle ← CoverageGuarantee(i, Neighbor)
26:          end if
27:          if (Obstacle = false) then
28:             if Priority(Neighbor) = NORMAL then
29:                if (Counter > MaxNormalPriority) then
30:                   MaxNormalPriority ← Counter
31:                   BestNeighbor ← Neighbor
32:                end if
33:             else
34:                {Only the low priority remains}
35:                if (Counter > MaxLowPriority) then
36:                   MaxLowPriority ← Counter
37:                   BestNeighborLow ← Neighbor
38:                end if
39:             end if
40:          else
41:             ContinueAnalysis ← true
42:          end if
43:       end if
44:    end if
45:    if Direction = Forward then
46:       Neighbor ← Neighbor + 1
47:    else
48:       Neighbor ← Neighbor − 1
49:    end if
50:    Counter ← CoverageAnalysis(i, Neighbor, RSSThreshold)
51: end while
52: if MaxNormalPriority ≠ 0 then
53:    AddEdge(G, i, BestNeighbor)
54: else
55:    AddEdge(G, i, BestNeighborLow)
56: end if
```

Figure 7. Pseudo code for the best neighbor heuristic.

22). For the two other priorities, each one has a candidate for best neighbor, one for the low priority and one for the normal priority. In order to determine the best neighbor, $Counter$ is compared with number of covered coordinates for the current best neighbor, which is $MaxNormalPriority$ (line 29) for the normal priority or $MaxLowPriority$ (line 35) for the low priority, both started with 0 (lines 6 and 7). If

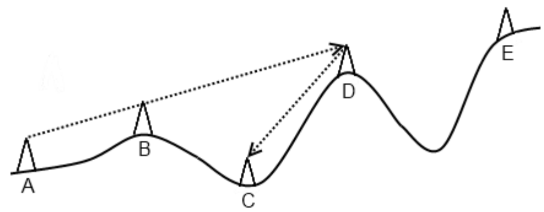


Figure 8. This example shows how D can be selected A's best neighbor, even with A not establishing a direct communication with C.

$Counter$ contains a higher value, then a new best neighbor is defined. If it is a low priority coordinate, then it is stored in $BestNeighborLow$ (line 37) or in $BestNeighbor$(line 31) if its priority is normal. The best neighbor of low priority is stored for use in situations where it is not possible to select a higher priority coordinate as the best neighbor (line 52), which would avoid building a solution.

V. Improving the Solution

After building a solution, it is possible to improve some of its characteristics. These characteristics include the number of selected coordinates and the signal distribution. The following subsections present two techniques, applied on a solution of the LMP algorithm, that detects situations where it is possible to improve the two mentioned characteristics.

A. Solving the Proximity Problem

The execution of the LMP algorithm can result in a solution that may have two coordinates located near each other. This situation is the result of the proximity of one these coordinates to an obstacle. An example of this situation can be seen in Figure 9. In this example, B was selected as best neighbor of A and, because B cannot communicate with the rest of the coordinates due to the presence of an obstacle, C was selected as B's best neighbor. Removing B is not an option because if A could communicate directly with C, C would be A's best neighbor. Upon detecting this situation, the algorithm tries to best relocate one of the two coordinates that are near.

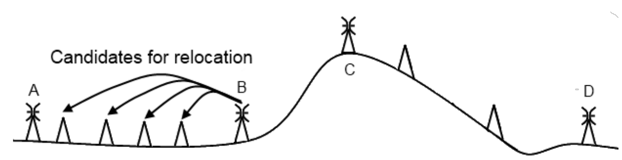


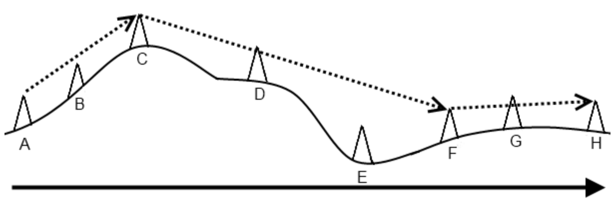
Figure 9. The B and C coordinates are located too close one from the other. Nearby coordinates may be selected for relocation.

The main problem resulting from the proximity of two coordinates is the non uniform distribution of the received signal by the neighbors coordinates, i.e., the two neighbors located one near the other have a received signal strength higher than the more distant one. This problem is also reflected to the intermediates coordinates.

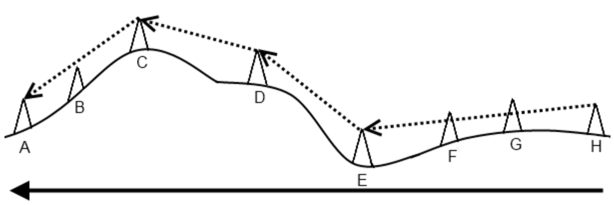
Among the candidates for relocation, the one capable of better distributing the signal received by its neighbors is selected. This distribution is calculate through the variance. Besides having the lowest variance, the restriction of coverage, connectivity and absence of obstacles must be respected. Also, the priority is considered. One coordinate is relocated only if the new one has the same or a higher priority. Always select coordinates are not relocated.

B. Merging Solutions

Before explaining how the process of merging works, it is important to demonstrate how the same set of input coordinates may result in two different solutions. An example may be seen in Figure 10. In Figure 10(a) the solution, built from the first to the last coordinate, determines that the communication between A and H uses two intermediate coordinates, which are C and F. Selecting C was necessary because of the obstacle in which it is located. Despite C not being able to establish direct communication with E, the algorithm, as shown in Figure 8, can select F as best neighbor because it can supply the coverage for E and establish a direct communication with C. With the solution built from the last to the first coordinate (Figure 10(b)), the number of intermediate coordinates used is higher. This happens because the best neighbor selected for H is E, which can only establish communication with D, which in turn requires the selection of C.



(a) In this example, two intermediate coordinates are used for A to establish communication with H.



(b) The same communication, in this example, requires the use of three other coordinates.

Figure 10. Depending on the solution's creation order, different number of coordinates may be used.

Considering the possibility of different solutions, if the coordinates selected in Figure 10(b) are part of a solution that uses fewer coordinates, in total, than the one in Figure 10(a), it is possible to decrease this number even further. This process is done by switching, in the solution with lowest number of coordinates, the pairs of communication whose number of intermediate coordinates is higher than the corresponding pair on the other solution.

VI. RESULTS

In this section, the results for two real sets of coordinates obtained with the LMP algorithm are presented. Both sets are power transmission lines provided by TBE (Transmissoras Brasilerias de Energia). The first one, which links Machadinho to Campos Novos, is composed of 85 towers totaling, approximately, an extension of 50 kilometers. Three manual solutions were built for this line by a network planning specialist. The goal of the first one was to minimize the number of installed mesh kits, where the other two added redundancy to the first one. The solution with the highest number of kits (higher redundancy) was the one selected and applied to the power transmission line. A comparison between the first manual solution and the LMP one is possible because both share the same objective. The second line links Açaílandia to Imperatriz with 128 towers in an extension of 62 kilometers. For this line, no manual solution was developed.

Regarding the parameters used by the Link Budget equation, the values are the same as the ones used in the real network. The values are: 20 dBm for the output power, 24 dBi for the directional antenna gain, 2,4 Ghz for the frequency and 5 dB loss caused by cables and connections. The miscellaneous loss parameter is not used. The horizontal and vertical irradiation patterns may be seen in Figure 11.

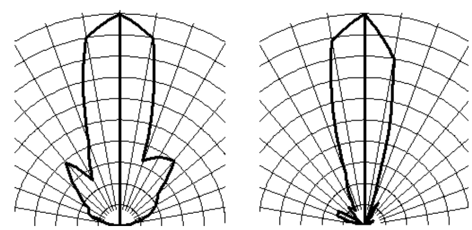


Figure 11. The horizontal (left) and vertical (right) irradiation pattern.

The elevation database, required for obstacle analysis, was obtained in the EMBRAPA's satellite monitoring site[2]. This database is encoded in a file format known as GeoTIFF, used for storing geographic information.

A. Metrics

In order to validate the obtained results, comparison metrics must be defined. Not always the best value for a metric means the best value for another. One example is the relation between signal strength and inter-flow interference. This interference is caused by the signal received from the other nodes' transmissions (Figure 12). The higher the number of kits added, the higher the received signal, but the inter-flow interference is also increased.

The evaluation of the LMP algorithm uses six metrics: number of kits, average signal strength, lowest received signal strength, inter-flow interference, maximum transmission rate on the weakest link and number of uncovered coordinates. The number of kits is the metric that the LMP tries to minimize respecting the provided RSS threshold. The average signal strength is obtained by adding, for each pair of directed aligned antennas, the signal strength between them and dividing this sum by the total number of pairs. The lowest received signal

[2] http://www.relevobr.cnpm.embrapa.br/download

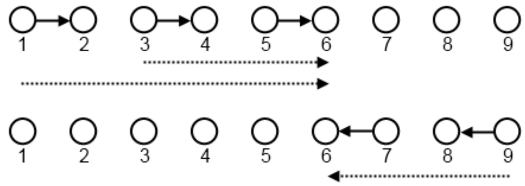


Figure 12. The communication between 5 and 6 receives interference from the pairs 1, 2 and 3, 4. When the communication occurs between 6 and 7, the interference comes from the pair 8, 9.

strength is the faintest signal value between two direct aligned antennas. The inter-flow metric is the hardest to calculate, as it is not possible to know a priori which and how many links will be formed and, also, the number of simultaneous transmissions. It is expected that a pair of directed aligned antennas will result in the formation of a link. As the goal of the algorithm is to minimize the number of kits, redundancy is not considered by LMP. This way, the incidence of redundant links is low, making it possible to consider two direct aligned antennas as a link. With this consideration, the inter-flow interference will be analyzed in two ways: through the average interference on the network and the highest interference received. With both the signal strength and interference metrics defined, it is possible to establish the signal-to-noise ratio, allowing the maximum transmission rate estimative on the weakest link, which is the one with the lowest signal-to-noise ratio. Finally, the Link Budget equation and obstacle analysis determine how many coordinates are uncovered.

As described earlier, the inter-flow interference is caused by the other nodes' transmissions. This interference is calculated using a worst case scenario, where all possible communications are active. In Figure 12 the interference received by 6, when communicating with 5, is caused by the transmissions of 1 towards 2 and 3 towards 4. When communicating with 7, the interference received by 6 is caused by the transmission of 9 towards 8. Because there are two interference values, the highest one is chosen. The described scenario is considered worst case, because, typically, not all communications happen simultaneously.

Another metric defined was the maximum transmission rate on the weakest link. Determining this rate requires the Packet Error Rate (PER) to be calculated. This value can be obtained using the method defined in [8] and is specified as the highest rate with $PER \leq 1\%$ in the link with the lowest signal-to-noise ratio.

B. Comparison between LMP and the manual solution

From the three existing manual solutions, the one with the same objective of the LMP algorithm is used on the comparison. Just like LMP, the manual solution was built respecting a minimum RSS threshold, which was -75 dBm. This is the same value used by LMP. In Table I it is possible to compare two solutions from the LMP, one using priority and the other not, with the manual one.

Table I
COMPARISON BETWEEN THE METRICS OF THE LMP SOLUTIONS AND THE MANUAL SOLUTION.

	LMP No Priority	**LMP Priority**	**Manual**
Number of Kits	14	16	16
Average Signal (dBm)	-49.95 ± 6.27	-48.92 ± 5.86	-46.84 ± 9.60
Worst Signal (dBm)	-56.66	-56.66	-58.07
Average Interference (dBm)	-68.78 ± 4.70	-69.07 ± 4.55	-69.58 ± 4.28
Strongest Interference (dBm)	-62.41	-63.31	-63.19
Maximum Transmission Rate on Weakest Link	12 Mbps	12 Mbps	12 Mbps
Number of Uncovered Coordinates	0	0	1

As it is possible to see from the results, the metric values found by the algorithm, using the input set with priority, are very similar to the one provided by the network planning specialist. Some metrics, like the worst signal and strongest interference, even presented better values. Despite the average signal being weaker in the LMP solution, it is better distributed through the line, as the standard deviation shows. The solution to the input set without priorities required a smaller number of kits, at the cost of some metrics. One interesting result is the higher value of interference from the solution with fewer kits. The reason for this is the use of directional antennas. The narrower the irradiation pattern is, the closer to a binary effect the interference assumes. If the transmitter's antenna of a communication pair is slightly aligned with the receiver of another pair, the interference is high, and if it is not, this value is low. That is what happened with the no priority solution.

The maximum transmission rate on the weakest link presented the same values for all the solutions. This was caused by a similar signal-to-noise ratio, despite different signal strengths and interference values.

Another important detail is the number of uncovered coordinates from the manual solution. Because of its design, the LMP algorithm does not allow a solution to have uncovered coordinates.

C. Distance algorithm

Due to the lack of other manual solutions, the LMP algorithm will be compared with a simple technique for choosing mesh kits installation coordinates through the link's length. Knowing an approximate value of the antenna's reach, it is possible to choose the next coordinate as the one whose distance is the maximum inside the coverage area with no obstacles between. Instances of this technique were run with different values for the link's length. The power transmission line and LMP solution presented earlier were used on this comparison as well. The results may be seen on Table II.

The values presented on the table show the importance of the network planning. In order to achieve the same average

Table II
METRIC VALUES FOR THE DISTANCE ALGORITHM.

	LMP Priority	**2 Km**	**2.5 Km**	**3 Km**
Number of Kits	16	19	16	13
Average Signal (dBm)	-48.92	-48.37	-49.37	-52.14
Worst Signal (dBm)	-56.66	-50.34	-52.69	-53.57
Average Interference (dBm)	-69.07	-62.97	-66.35	-68.29
Strongest Interference (dBm)	-63.31	-57.89	-60.31	-61.76
Maximum Transmission Rate on Weakest Link	12 Mbps	12 Mbps	12 Mbps	12 Mbps
Number of Uncovered Coordinates	0	0	1	7

signal as the LMP solution, it was necessary the selection of 19 kits using 2 kilometers links and, in this case, the interference was considerably higher. Using higher distance links, without the correct planning, results in coordinates not being covered, as it is shown in the results from the 2.5 and 3 kilometers links. Also, the LMP algorithm adapts to the irradiation pattern being used, which has direct impact on the network coverage.

D. Changing the LMP RSS threshold

The second power transmission line (Açaílandia-Imperatriz) is used to show the impact of different RSS thresholds on the LMP's solutions. As mentioned previously, this threshold is related to the radio's sensitivity. So, depending on its characteristics, solutions are built accordingly. In Table III it is possible to view the different solutions for each threshold.

Table III
COMPARING THE RESULTS OBTAINED WITH DIFFERENT THRESHOLDS.

	-70 dBm	**-75 dBm**	**-80 dBm**	**-85 dBm**
Number of Kits	24	15	14	14
Average Signal (dBm)	-49.10	-53.73	-54.14	-54.14
Worst Signal (dBm)	-52.46	-56.55	-60.25	-60.25
Average Interference (dBm)	-59.01	-64.89	-65.86	-65.86
Strongest Interference (dBm)	-56.53	-62.17	-62.35	-62.35
Maximum Transmission Rate on Weakest Link	6 Mbps	6 Mbps	6 Mbps	6 Mbps

As it was expected, the lower the RSS threshold, the higher the number of mesh kits needed. However, the use of a high number of kits results in an elevated level of interference. An interesting result is the same metric values for both the -80 and -85 dBm thresholds. This was caused due to the presence of obstacles. If no obstacles were present, high sensitivity radios would allow the selection of fewer kits. But, as obstacles prevent long distance links, raising the sensitivity does not lower the number of selected kits.

The maximum transmission rates on the weakest links are worse than the ones presented on the Machadinho-Campos Novos transmission line because of its topology. This transmission line is much more linear, resulting in the binary interference effect presented on Subsection VI-B.

VII. CONCLUSIONS

In this paper, the planning of liner wireless mesh networks was discussed. The LMP algorithm was introduced as a solution for minimizing the number of mesh kits needed for a network to achieve coverage and connectivity. As the main focus of LMP is the use of directional antennas, their correct alignment is a determining factor. To determine this alignment, the best neighbor heuristic was proposed, considering, not only the coverage and connectivity needs, but also the presence of obstacles and priority. After building the solution, two post-processing techniques were employed in order to improve it.

The LMP algorithm evaluation was performed using two real power transmission lines. The manual solution for one of these lines and a simple coordinate selection technique were used for the purpose of metric comparison. Presenting similar metric values to the manual solution, and better values than the distance technique, the LMP presented itself an efficient solution to the linear wireless mesh network planning.

One additional advantage of the proposed approach is the use of real data. The coverage area is determined using the antenna's irradiation pattern and radio specifications, and not an approximation by distance. The input data for the algorithm is composed of geographic coordinates, which allows the obstacle analysis when an elevation database is provided. Given these informations, it is possible to build a solution considering real case scenarios and the restrictions of coverage and connectivity.

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