Single Gateway Placement in Wireless Mesh Networks

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***Abstract*—Wireless Mesh Networks (WMN) are increasingly becoming popular as low cost alternatives to wired network for providing broadband access to users (the last mile connectivity). In these multi-hop networks, data is forwarded to a gateway from the nodes or from the gateway to the nodes. This paper investigates the role of gateway placement on network throughput for realistic configurations of WMNs. We show that the position of the gateway significantly bears on network throughput. It is hence important to optimize its placement. Specifically, we propose several heuristics to optimally position a single gateway in WMN and compare their relative performance in terms of network throughput with respect to the exact solution, which is obtained through cumbersome computations.**

I. INTRODUCTION

Wireless Mesh Networks (WMN) are becoming a popular solution to extend access networks. We focus in this paper on single gateway multi-hop WMN as depicted in Figure 1. In this type of networks, the traffic goes from the nodes to the gateway or from the gateway to the nodes. We will assume that all nodes have the same capabilities in that they all use omni-directional antennas, the same transmitting power and the same modulation. In [1], it is shown that the max-min throughput of a single gateway WMN is upper bounded by $\frac{A}{N}$ (where A is the maximum data-rate available in an N-node mesh network), and that this maximum achievable throughput is independent of the placement of the gateway. However, this bound is achievable only for very high transmitter power. In general, nodes cannot use very high power since this power is limited by regulations. When the transmitting power being used is low to medium, the achievable max-min throughput is much below the above bound. We will first show for different types of networks, that the placement of the gateway has an important impact on the achievable throughput at low to medium power. However finding exactly the optimal placement requires cumbersome computations. The remainder of the paper will then focus on designing simple heuristic schemes to find the gateway placement that would maximize the throughput. By gateway placement, we mean to find the best position for the gateway among $(N + 1)$ pre-specified locations. The remaining N positions with be for the nodes. In particular, we will try to answer the following question: is there a gateway placement that is optimal for all values of the transmission power?

In what follows, we survey the related work in Section II and describe the framework used in [1] since it forms the basis for this work. In Section III we present preliminary results showing the impact of gateway placement on the performance of the network. In Section IV, we propose several heuristics to optimally position the gateway in WMN and we evaluate their performance in Section V. Finally we conclude in Section VI by summarizing our results and discussing possible extensions.

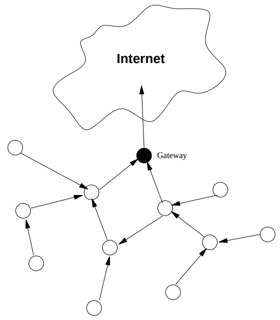


Fig. 1. Wireless Mesh Networks: An instance of a WMN with nodes arbitrarily distributed.

II. RELATED WORK

The problem of gateway placement in wireless networks is an ongoing research problem although much of the literature [4], [3], [5], [6] available, addresses the problem without a very precise physical layer model (e.g., for interference) and/or a well-defined access protocol. In [5], the authors address this problem by proposing heuristics for several wireless link models that iteratively select a new gateway position to satisfy the QoS (Quality of Service) demands of the associated nodes. In [6], the authors propose an algorithm that recursively computes the minimum weighted dominating set to determine optimal gateway placements such that the QoS requirements of the users are satisfied. Unlike these or other works ([4], [3]) available, we specifically consider the problem of optimizing single gateway placement in WMNs under a well-defined physical layer model (including a Signal to Interference Noise Ratio (SINR) based interference model) and a access protocol based on conflict-free scheduling.

A. Model Description

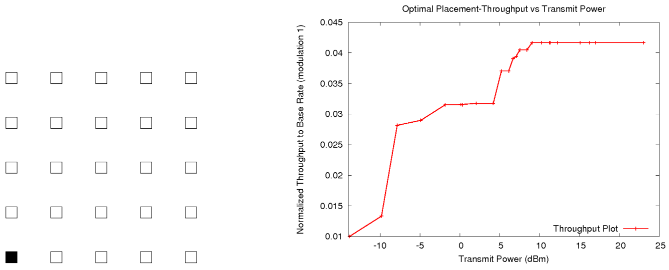
Our study is based on the model proposed and studied in [1] where we consider single-gateway **scheduled** WMNs where the term scheduled refers to the fact that these networks operate by means of precisely scheduling different subsets of non-conflicting links, rather than having individual links or nodes using random access. For example, IEEE 802.16 networks have the option to operate using this kind of scheduling. The aim of the optimization and computational framework developed in [1] is to compute the max-min throughput and the corresponding optimal configuration of a network specified in terms of its set of N node positions, the gateway position, and a set of flows given as source-destination pairs. Our objective is to maximize the minimum flow throughput that can be achieved by appropriately configuring the network in terms of the set of links to activate, their physical layer parameters, the flow routes and the link activation schedule. The following assumptions hold:

- The gateway and the nodes have only one wireless interface that operates in the same frequency band (or channel).
- The gateway and nodes all use omni-directional antennas, i.e, the antenna gain is 0 dB for all directions.
- The gateway and nodes all apply the same transmission power P_T.
- All the links are directed and a link l is characterized by three parameters
  - The transmission power P_T used by its transmitter i,
  - The distance d between its transmitter i and its receiver j, and
  - Its path loss exponent η_l.

  We omit the superscript l whenever it does not cause confusion in the context.
- The time is slotted.
- Each node uses the same modulation scheme corresponding to a normalized link rate of 1.
- A transmission from i to j is successful if the Signal to Interference Noise Ratio (SINR) is greater than or equal to a threshold β.
- The SINR for a link l in the time-slot during which i transmits to j is defined as

  $$\gamma_l = \frac{G_{ij}P_T}{N_o + \sum_{m=0,m\neq i}^{N} G_{mj}P_T\mathcal{I}(m)} \qquad i,j \in \{1\dots N\} \tag{1}$$

  where G_{ij} is the channel gain on link l, $\mathcal{I}(m)$ is the indicator function being equal to 1 if m transmits in the same time slot and N_o is the average thermal noise power in the frequency band under consideration.
- The channel gain G_{ij} is computed using a free-space propagation model: $G_{ij} = \left(\frac{d_l(i,j)}{d_o}\right)^{-\eta}$ where $d_l(i,j)$ is the Euclidean distance between nodes i and j and d_o is the crossover reference distance.



(a) 5×5 Grid (b) Throughput Curve

Fig. 2. Variation of λ^* as a function of transmit power P (dBm) for the gateway position indicated in a.

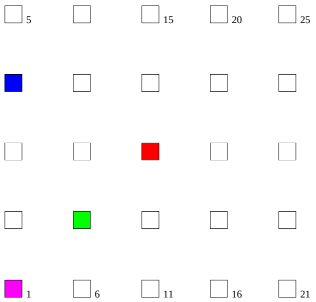
In [1], we develop a computational tool that allows us to obtain for a given network characterized by the location of its N nodes, the location of its gateway, the flow patterns (defined by source-destination pairs), the physical layer parameters, and a transmission power, the max-min throughput and the corresponding configuration. As an example, consider the 25-node grid network shown in Figure 2a with the gateway positioned at the left corner. For all the numerical results, we will assume that each node has one flow to the gateway and the cross-over distance (d_o) is normalized to 1, the path-loss exponent (η) is equal to 4, while the ambient noise N_o is equal to 1dBm, $\beta = 10$dB, and $G_{ij} = 1$ for all feasible links. The inter-node separation along the vertical and horizontal edges is 8m. Figure 2b shows the max-min throughput as a function of P_T for this network. Several comments can be made on this figure. Firstly, the larger the transmission power, the higher the throughput. For low power, the throughput is substantially lower than the maximum of $\frac{1}{N} = 0.04167$. We define P_{min} as the minimum power for which connectivity exists in the network.

B. *Gateway placement problem.*

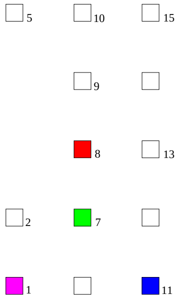
In this paper, we employ the computational tool developed in [1] to compute the exact solution to our gateway placement problem and validate our heuristics. This tool computes the maximum throughput achievable for a WMN where the gateway position and the transmit power are given. To find the exact gateway placement, we employ a “brute force” approach and use our tool to compute the throughput curves as a function of P_T for all $(N+1)$ potential gateway positions. From these $(N+1)$ positions, we create the best (respectively the worst) throughput envelope by selecting for each power P, the maximum (resp. the minimum) throughput over all $(N+1)$ positions. Clearly a good heuristic should yield a gateway placement that would produce a throughput-curve close to the best throughput envelope. The difference between the best and worst throughput envelopes is a clear indication of the importance of selecting a good gateway position from a throughput standpoint.

III. PRELIMINARY RESULTS

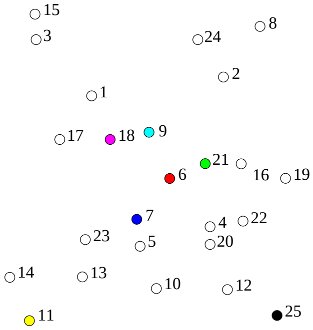
In this section, we present some preliminary results showing the impact on throughput of the gateway placement for different types networks. We work with 4 types of networks: grid networks (characterized by the distance between 2 neighboring nodes, d_{min}, see Figure 3a), regular sub-compact grids (a subset of a grid such that each node has at least one neighbor



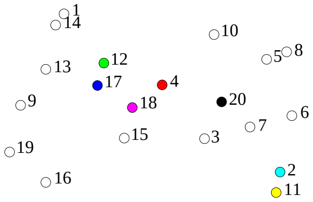
(a) Regular Grid Networks



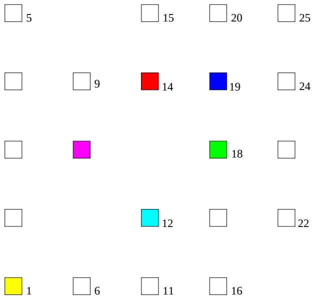
(b) A Compact Grid Network



(c) Arbitrary Network 1



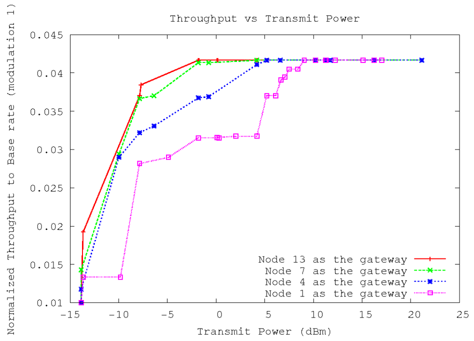
(d) Arbitrary Network 2



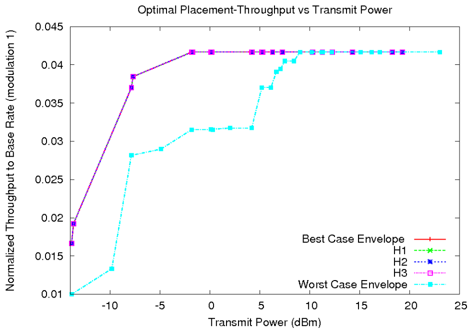
(e) Irregular Grid Network

Fig. 3. Different network topologies.

at d_{min}, see Figure 3b), arbitrary networks (see Figures 3c and d) and an irregular grid network (Figure 3e). For all numerical results for the grid and the sub-compact grid topologies, the inter-node separation d_{min} is equal to 8m.



(a)



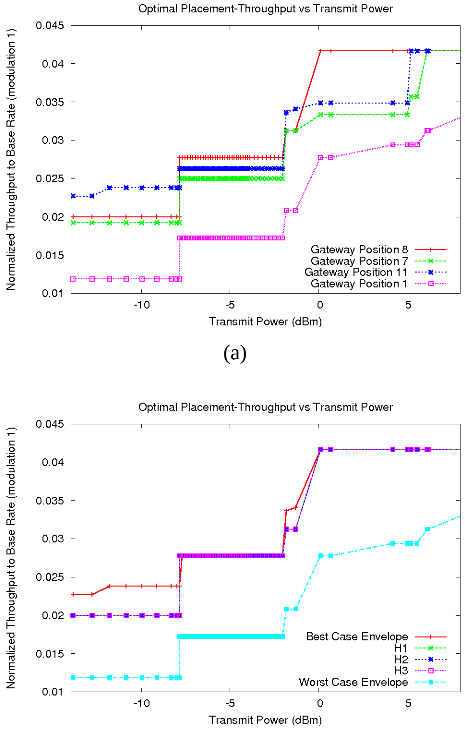
(b)

Fig. 4. a. indicates the optimal throughput curve for the grid network as a function of P_T for different gateway positions. b. indicates the envelopes and the results of our three heuristics.

Figure 4a (resp. 5a, 6a, 7a and 8a) shows the optimal throughput curves as a function of the transmission power P_T for the network shown in Figure 3a, (resp., 3b, 3c 3d and 3e) for the gateway placements indicated in color in the figure. While we have chosen to only represent the curves corresponding to some gateway placements for ease of representation, we have computed the curves for all possible gateway placements.

From those curves, we can conclude that gateway placement does matter, in that a good placement would yield a much better throughput and would achieve the upper bound $\frac{1}{N}$ at lower power as is evident from Figures 4a - 8a. In all these cases, the difference between the best gateway placement and the worst could be as high as 50% for some power levels. It is also worth noting that, in general, there is no gateway placement that is better at all powers at least for non regular networks, since for example in Figures 6a and 7a, there is no curve that dominates all the others.

The conclusion that can be drawn out of these preliminary results is that it is important to place gateways optimally from a performance standpoint. However the “brute-force” method that we have used is computationally intensive and



(a)

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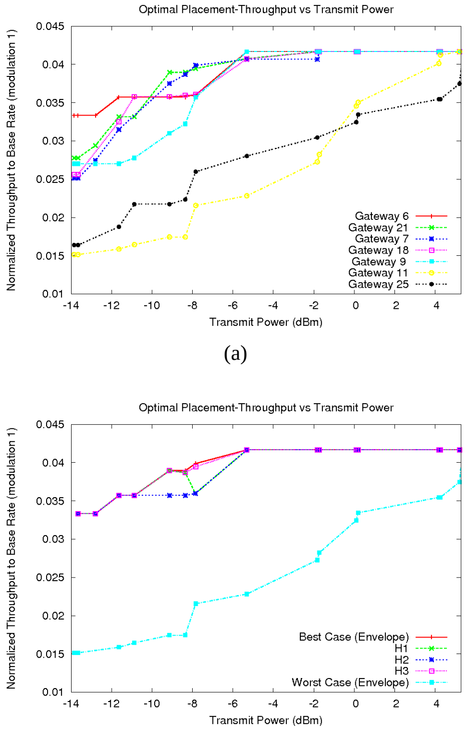
Fig. 5. a. indicates the optimal throughput curve for the compact grid network as a function of P_T for different gateway positions. b. indicates the envelopes and the results of our three heuristics.



(a)

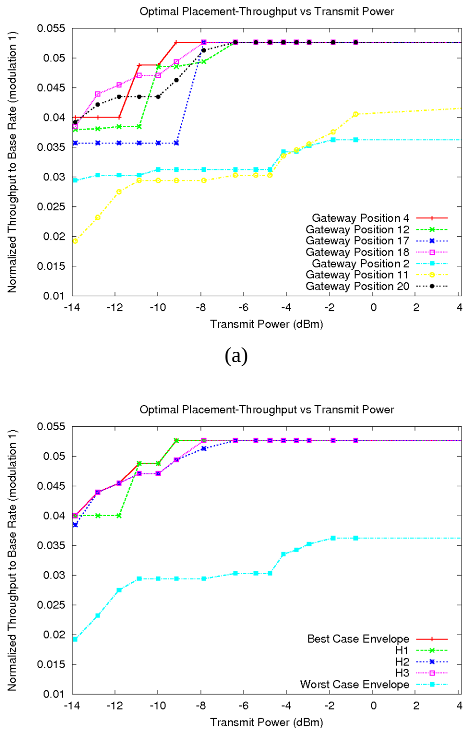
(b)

Fig. 6. a. indicates the optimal throughput curve for the arbitrary network 1 (see Figure 3c) as a function of P_T for different gateway positions. b. indicates the envelopes and the results of our three heuristics.

very cumbersome. We hence explore the design of heuristics to place single gateways in WMNs. We propose 3 heuristics that we describe in the next section. We will compare their performances in Section V.

IV. HEURISTICS

We define P_{SH} as the minimum power for which single hop transmission is possible from all the nodes to the gateway. Note that P_{min} (the minimum power to provide connectivity) does not depend on the position of the gateway while P_{SH} does. When $P_T \geq P_{SH}$, the achievable throughput is the upper bound discussed earlier. Note that this throughput can be achieved for $P < P_{SH}$ as well.



(a)

(b)

Fig. 7. a. indicates the optimal throughput curve for the arbitrary network 2 (see Figure 3d) as a function of P_T for different gateway positions. b. indicates the envelopes and the results of our heuristics.

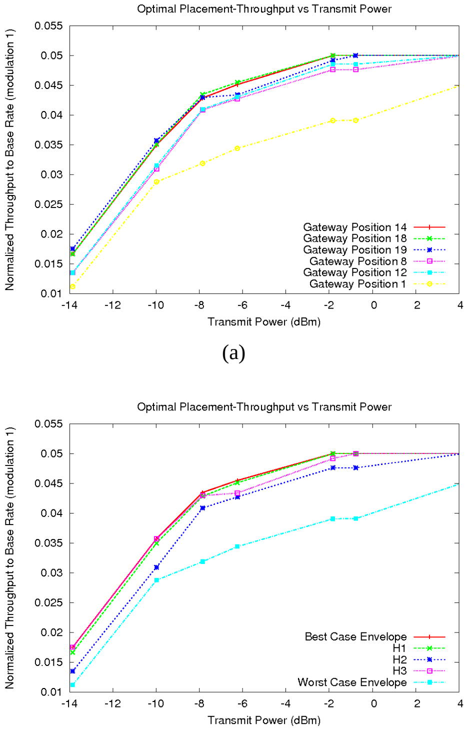
A. *Heuristics H1*

For the case of regular networks (e.g., complete grids, sub-compact grids, etc.), operating at P_{min}, it can be shown [2] that the maximum throughput is given by:

$$\lambda^* = \frac{1}{\sum_i h_{(i,j)}} \qquad i \in 1 \ldots N \tag{2}$$

where $h_{(i,j)}$ is the minimum hop count for node i to reach the gateway placed at j. Hence clearly, to maximize the network throughput at P_{min}, we need to place the gateway at the position j that is the solution of

$$min \sum_i h_{(i,j)} \qquad i,j \in 1 \ldots N, i \neq j \tag{3}$$



(a)

(b)

Fig. 8. a. indicates the optimal throughput curve for the irregular grid network (see Figure 3e) as a function of P_T for different gateway positions. b. indicates the envelopes and the results of our three heuristics.

Therefore for networks for which (2) is true, we can directly find the optimum gateway placement at P_{min}. Based on this result, we propose a heuristic (called H1 in the following) based on the minimum hop metric. More precisely, for any power $P_T \geq P_{min}$, we can compute all the feasible links, i.e., those for which the corresponding SINR assuming no interference ($\frac{G_{ij}P_T}{N_o}$) is greater than the threshold β and using these links, find the gateway placement that would be the solution of (3).

B. Heuristic H2

We also try a different heuristic, H2, based on the following reasoning. As discussed earlier, P_{SH} depends on the gateway placement. We were wondering if choosing the gateway placement that would minimize P_{SH} would be a reasonable choice. Clearly, we know that this heuristic cannot yield the best placement for all P's since it is independent on P_T and we know that in general no gateway placement is optimal for all transmission powers. H2 selects as the gateway position, the position j that ensures that the transmitter power required to satisfy

$$\forall i \quad \left(\frac{d_l(i,j)}{d_o}\right)^{-\eta} \times P \geq \beta \quad i,j \in \{1\dots N\} \quad i \neq j \tag{4}$$

is minimum. Recall that β represents the SINR threshold.

C. Heuristic 3

In an effort to incorporate some of the physical layer attributes in the heuristic used to select the gateway position, we propose the following. Let P_T be given (clearly this value impacts the set of feasible links to be considered). Let l be a feasible link from i to j. Let $\bar{\gamma}_l$ be an estimate of the SINR seen at receiver j when i transmits. Since, we are after developing a simple heuristic that does not require any knowledge on traffic or on the scheduling/routing being used, we compute $\bar{\gamma}_l$ by assuming that all other nodes (except j) transmit at the same time as i. This is clearly a very pessimistic estimate but one that we hope will capture some of the inherent attributes of the mesh network under consideration. Hence $\bar{\gamma}_l$ is computed by using (1) in which the indicator function $\mathcal{I}(m)$ is equal to 1 for all nodes, m different from i and j.

Two remarks will then help us understand how we selected our metric:

- A link with a high SINR will be less prone to errors than a link with a lower SINR.
- A low SINR (or a high $\frac{1}{SINR}$) can be seen as an indicator of the likelihood of a transmission failure and hence it is reasonable to avoid path for which the product of the SINR is low (we treat $\frac{1}{SINR}$ as a multiplicative metric).

Hence we select the following link metric: $w_l = log_{10}(\frac{1}{\bar{\gamma}_l})$ and our heuristic H3 uses a shortest path algorithm on the network under consideration to compute the minimum weight path from any node n to the gateway positioned in m. We then select the gateway position m that would minimize the sum of the weights of all the shortest paths from all the nodes to m.

V. NUMERICAL RESULTS

A. Grid network

Consider the case of the regular 5×5 grid shown in Figure 3a. Clearly, as seen in Figure 4a, the throughput obtained when the gateway is at position 13 dominates the throughput obtained when the gateway is at other positions. Figure 4b, illustrates the results obtained via using the 3 heuristics as compared with the best-case (resp. the worst-case) envelope obtained by finding for a given value of P_T the best throughput (resp. the worst) over all the possible gateway positions. Clearly, all heuristics perform optimally.

B. Compact grids

Consider the case of the sub-compact grid shown in Figure 3b. Clearly, as seen in Figure 5a, there is no gateway placement that dominates all the others for all powers but position 8 is good. Figure 5b, illustrates the result of using the 3 heuristics on the compact grid as compared with the 2 envelopes. All 3 heuristics do well and are within 20% of the upper-bound.

C. Arbitrary networks

Consider the case of the networks shown in Figures 3c and 3d. Clearly, as seen in Figures 6a and 7a, no gateway position dominates for all powers.

Power (in dBm)	Gateway Position						
	Arbitrary Network I				Arbitrary Network II		
	H1	H2	H3		H1	H2	H3
-13.85	6	6	6		4	4	18
-12.80	6		6		4		
-11.82	6		6		4		
-10.82	6		6		4		
-9.98	21		21		$4, 15$		
-9.13	21		21		4		
-8.32	6		6		15		
-7.85	6		6		$4, 20$		
-6.81	6		6		$4, 18$		
-5.43	21		21		$4, 18$		
-1.83	$6, 7, 18, 21$		21		$4, 12, 17$		
0.19	$6, 7, 18, 21$		21		$4, 1217$		

TABLE I
Arbitrary Network Results: Optimal gateway position varies

Figures 6b and 7b, illustrate the results of using the 3 heuristics on these arbitrary networks. In Table I we have illustrated the results of the 3 Heuristics. Clearly, at each discrete power P_T, the "optimal" gateway position varies. H2 performs sub-optimally (refer to Figures 6b and 7b) for both the arbitrary networks. H1 and H3 however do well and are always within 18% of the upper-bound.

D. Irregular Grid Networks

For the case of the irregular grid network shown in Figure 3e, Figure 8a shows that gateway positions 14 and 18 dominate other gateway positions. The results of the 3 heuristics are shown in Figure 8b. Heuristic H1 outperforms H2 and H3. However, heuristics H2 and H3 are within 20% of the upper-bound as well.

VI. Conclusions

In this paper, we have explained the need for optimally placing a single gateway for efficient wireless mesh network operation. Clearly, as indicated in Figures 4a - 7a, the placement of gateways has a significant influence on network throughput, since in all the studied cases, the difference between the best gateway placement and the worst could be as high as 50% for some power levels. In order to determine the "optimal" placement of the gateway, we have proposed several heuristics. The minimum power heuristic H2 is sub-optimal since it designates the same position irrespective of the transmitting powers. Quite clearly, as indicated in Figures 6a, and 7a, the single node position designated by this heuristic is sub-optimal when compared to the other heuristics. The performance of heuristics H1 and H3 is very good. However, H1 often selects multiple gateway positions and hence the use of this algorithm is problematic. In fact in our evaluation, we have considered only the "best" of the selections made for each power by H1, but we could only do that because we had access to the results for all powers and all gateway positions. Heuristic H3 on the other hand selects a single gateway position and hence forms a better heuristic.

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