A Cooperative Nearest Neighbours Topology Control Algorithm for Wireless Ad Hoc Networks

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***Abstract*— In this paper, we introduce a simple distributed algorithm that assigns appropriate individual transmission powers to devices in a wireless ad hoc network. In contrast to many other proposed algorithms, it does not depend on special hardware. It requires only local neighbourhood information and therefore avoids flooding information throughout the network. Finally, the cooperative nature of the algorithm avoids that devices cause excessive interference by using unnecessarily high transmission powers. We show by means of simulation that the topologies created by this algorithm without any global knowledge are as effective as topologies resulting from a good choice of a common transmission power (which would require global knowledge) in terms of the achievable throughput.**

I. Introduction

Wireless ad hoc networks are enjoying much popularity these days: The ability to interconnect wireless devices in various scenarios is a worthwhile goal. Much effort has been spent on solving the routing challenge in such networks.

In contrast, the links of an ad hoc network are often regarded invariant. However, as opposed to wired networks, this is an unnecessary restriction in wireless networks, where the topology is (among other things) determined by the transmission powers of the participating devices. In the majority of the cases, the power level is adjustable.

Topology control can have several objectives. In this work, the goal is to avoid improper topologies that result in a poor capacity of the network: Large transmission ranges lead to increased congestion and interference on the link layer, because many devices have to share the same link. On the other hand, small ranges may result in bottlenecks that a large amount of the traffic has to pass, potentially taking a considerable detour. From this point of view, controlling the transmission powers of devices in ad hoc networks is actually mandatory for larger networks where characteristics such as node density are variable. Another possible objective of topology control is the conservation of battery power. In this context, several criteria are possible, but considerations on this issue are beyond the scope of this paper.

There are basically two categories of approaches to topology control by the adjustment of transmission powers of network nodes. The first one tries to maintain a *common power* level for all nodes in the network. In contrast, a *per node power* control scheme adjusts the transmission power of each node individually.

Assigning a common transmission power to all devices is a rather complex task, because information has to be distributed across the entire network regularly. Furthermore, density fluctuations in the network are not handled well.

Assigning per node transmission powers can be achieved by using only the stations' local neighbourhood information. An oftentimes cited argument against this approach is that it aggravates the hidden node problem. However, this problem exists just as well for common transmission powers, even when using a virtual carrier sensing mechanism (RTS/CTS), as shown in [1]. There is reason to hope that reducing the transmission powers in dense network regions while using higher powers in sparse areas to maintain connectivity actually reduces the overall interference. Addressing this topic in a theoretical manner is very complex, but our conjecture is backed by the simulation results presented below.

There exist several approaches to per node power control, and a representative selection is introduced in section II. Most of them try to guarantee a connected network. While this is a desirable characteristic, giving a hard guarantee rather than minimising the probability of network partitioning limits the use of these approaches to very specific scenarios, because additional information is necessary: The requirement that the devices provide directional information inhibits their use with today's popular off-the-shelf hardware. The need for positional information, i.e. GPS receivers, rules out indoor scenarios and small, energy-constrained devices. Other approaches require proactive routing protocols, thereby being unsuitable for scenarios where proactive routing is deemed a too high overhead. Other requirements only fulfilled in special cases are a time synchronisation of the devices or the possibility to estimate distances to other devices. On the other hand, pragmatic topology control algorithms introduced so far have some weaknesses as described later on.

The overview of existing approaches and their shortcomings in section II leads to the design of our novel, simple per node power control algorithm introduced in section III. Section IV presents simulation results showing that the presented algorithm is an effective approach to nearest neighbours topology control (defined below) and that it is able to keep the network

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capacity on a high level. In section V, we draw conclusions and outline subjects for further work.

II. Related Work

Some work concerning topology control in packet radio networks has already been done decades ago, the most prominent of which is probably [2], which deduces the optimal number of links a device should have for several MAC protocols. Generally, the theoretical work of this time shows that topology control is important for throughput optimisation. Although it does not provide an applicable method, the results suggest a straightforward strategy: The devices connect to a certain minimum number of nearest neighbours (henceforth referred to as the *nearest neighbours strategy*).

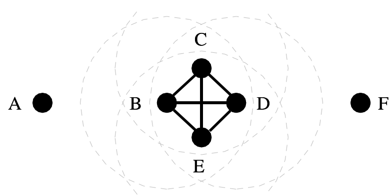


Fig. 1. The necessity of cooperation

In [3], a per node power control algorithm using the nearest neighbours strategy is presented: With the "LINT" algorithm (Local Information, No Topology), a device raises its transmission power if it has less than a predefined minimum number of links, and it lowers its transmission power if it has more than a predefined maximum number of links.

A weakness of this implementation of the nearest neighbours strategy is that some devices may adjust to excessively high transmission powers, because they have too few links. However, the fact that a device has too few links is not necessarily caused by its own small coverage area: Neighbouring devices might refrain from increasing their transmission powers, because they have a sufficient number of links (cf. figure 1). Ultimately, a device located a little aside from the other devices might not have a single link, even though it uses maximum transmission power.

In [4], the idea behind LINT forms the basis of "LMA" (Local Mean Algorithm), which is extended to the "LMN" algorithm (Local Mean of Neighbours). In LMN, a station's neighbour count is replaced as control variable by the average of its own neighbour count and the neighbour count values of its neighbours. However, this alternative metric does not address the weakness previously introduced, and the motivation for its use is left unclear.

The "*k*-neigh protocol" introduced in [5] connects only mutual nearest neighbours, i.e. two stations are connected if and only if they are within each others *k* nearest neighbours, so that each station maintains maximally *k* bidirectional links. This approach is realised in a very straightforward way, which makes it necessary that devices estimate their distances to other devices. Therefore, the use of this protocol is restricted to certain scenarios.

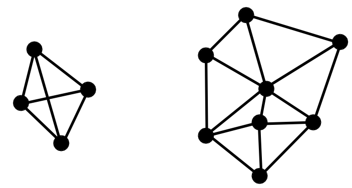


Fig. 2. Shortcoming of the nearest neighbours approach (k=3)

The "NTC" (Novel Topology Control) algorithm presented in [6] is designed to overcome a weakness of the nearest neighbours strategy: If devices are distinctly clustered, no intercluster links will be established, resulting in a disconnected network (cf. figure 2). The NTC algorithm is based on Delaunay triangulation and requires devices to know the direction of other devices. There are numerous other approaches requiring directional information which also restricts their use to specific hardware. Presenting all of them is certainly beyond the scope of this paper.

A different approach to per node power control ensuring network connectedness is taken in [7]. This publication presents two algorithms based on the idea of operating a proactive routing protocol instance on each power level. This way, the stations know which other stations are reachable if all stations operated at maximum power, but data packets can be transmitted at lower power levels. The use of this approach is restricted to scenarios where the overhead of proactive routing is tolerable. Furthermore, an implicit assumption is that the network hardware is homogeneous and it is not clear how to implement this approach in networks which consist of devices that have different capabilities of setting their power levels.

Prior to [7], the same authors have applied the idea of multiple routing agents to common power control in [8], arguing that link bidirectionality is an important goal and that asymptotically, this does not decrease throughput. In this publication, the associated overhead is considered low, but only by means of a very simplified estimation.

The idea of controlling transmission powers depending on the experienced contention is elaborated in [9]. A station increases its transmission power upon high contention and decreases its power upon low contention. The motivation behind this approach is the authors' observation that the contention falls with rising transmission range, caused by a reduced hop count that outweighs the spatial re-use. While this may be the case in their simulations involving 100 stations, we find the situation to be quite different with a higher number of participating stations in this work.

Other work (e.g. [10]) focuses on layer 1 and 2 power control: This does not allow for the control of the network topology. It may therefore be seen as an independent optimisation.

III. Distributed Per Node Power Control

This section describes our distributed topology control algorithm based on the nearest neighbours strategy. This approach only relies on local information about the availability of bidirectional links. Thus, there is no need to flood topology information through the network. Furthermore, it does not have any special hardware demands. Of course, at least some of the devices should support different power levels, but it is not necessary that all devices have the same capabilities.

The idea of nearest neighbours topology control is to assign each device a transmission power as low as possible, but large enough such that it has bidirectional links to the k nearest stations. It follows that some devices must possibly have more than k bidirectional links in order to keep some of their neighbours satisfied. Since the word "neighbour" has a rather intuitive meaning in this context, we define that a station A is the neighbour of a station B if and only if there is a bidirectional link between A and B.

With a connectionless technology like IEEE 802.11, information about local connectivity is not provided to upper layers. However, a beaconing mechanism may be used such that devices periodically broadcast "beacon" packets. When receiving such a beacon, a device knows that there is a *unidirectional* link from the beacon's sender to itself. To enable the devices to gain knowledge about link *bidirectionality*, every device adds to its own beacons a list of all devices from which it has recently received beacons.

Certainly, this beaconing mechanism reduces the available bandwidth by a small fraction. However, this amount is marginal in relation to the bandwidth required to distribute information across the entire network to enable the devices to agree upon a common transmission power.

An important design goal of a topology control algorithm should be to minimise the number of transmission power adjustments, since these add to the ad hoc network's instability already given by station mobility. For this reason, our algorithm does not control the neighbour count to an exact number, but rather tries to keep it within a certain range $[k_{\min}; k_{\max}]$.

This becomes important given the fact that current hardware can only switch between a few discrete power levels. The Cisco Aironet 802.11b card e.g. has six discrete power levels. With such hardware, controlling the neighbour count to an exact value would result in an oscillation between two power levels in many cases. On the other hand, since one may choose $k_{\min} = k_{\max}$, we merely handle a generalisation of the k nearest neighbours approach.

The value of $k_{\min}$ should be some neighbour count below which the resulting path lengths or the risk of a network partitioning become intolerable. The value of $k_{\max}$ should be high enough such that when a device exceeding this neighbour count reduces its power, then its neighbour count will remain above the lower bound with high probability. This means that the coarser the adjustment of the transmission power can be made, the larger this upper bound must be chosen.

We now come to the details of the algorithm, which is visualised in figure 3. Since it is a distributed algorithm, each device has to make sure by itself that its neighbour count is within a certain range. The following sections describe how a device reacts to a neighbour count that is too low (section III-A) or too high (section III-B).

A. Increasing the Neighbour Count

There are two reasons for a device A to detect that it has less than $k_{\min}$ bidirectional links:

1) The transmission power of some of the devices in A's communication range is too small. In this case, those devices (or at least some of them) need to increase their transmission power in order to establish a bidirectional link with A.
2) A's own transmission power is too small to reach more devices. In this case, A must increase its transmission power in order to reach more devices.

Additionally, either A's beacon or one of its neighbours' beacons may have been lost. In such situations, oscillations can be avoided by smoothing the neighbour count function.

Figure 1 illustrates case 1 for $k_{\min} = 3$. Since devices B, C, D, and E already have 3 bidirectional links, they have no motivation of their own to increase their transmission power. But if they do not, A will conclude that cause 2 is true and accordingly increase its own transmission power. Other devices might face the same situation, e.g. device F in figure 1. As a consequence, A and F will increase their power until they can communicate (or reach the maximum level). Whenever A and F communicate this will interfere with transmissions from devices B through E. A comparably hapless situation is that not a single device will establish a bidirectional link with A. In this case, A will not be able to communicate, but nevertheless it will switch to its highest transmission power and regularly interfere with the other devices by sending some kind of beacons, route requests, or the like.

Thus, it is necessary that devices B through E react to this situation by increasing their transmission power. This does not only lower the interference at their position, but also avoids an unnecessary decrease of the spatial re-use in the network.

To allow for this cooperation, a device must include its current status into its beacon messages, i.e. whether it has too few or enough bidirectional links. This information is encoded with a `help` flag which is set, if the device has too few bidirectional links and cleared otherwise.

Now, suppose a device B, which already has enough links, receives a beacon from a device A that has its `help` flag set. If A does not include B in its beacon list (it is outside of B's transmission range), B shall increase its transmission power in order to both help A in satisfying its link constraints and prevent A from increasing its transmission power unnecessarily.

Setting the `help` flag to establish links to other stations already within the own transmission range corresponds to case 1 above and is the first measure a station takes to increase its neighbour count. If this does not suffice and the neighbour count is below $k_{\min}$ after sending a certain number of beacons (denoted by `wait` in figure 3) with the `help` flag set, it increases its own transmission power. This corresponds to case 2 above, so the `help` flag is cleared again. Checking the two cases separately is reasonable because this prevents unnecessary transmission power adjustments. Handling them

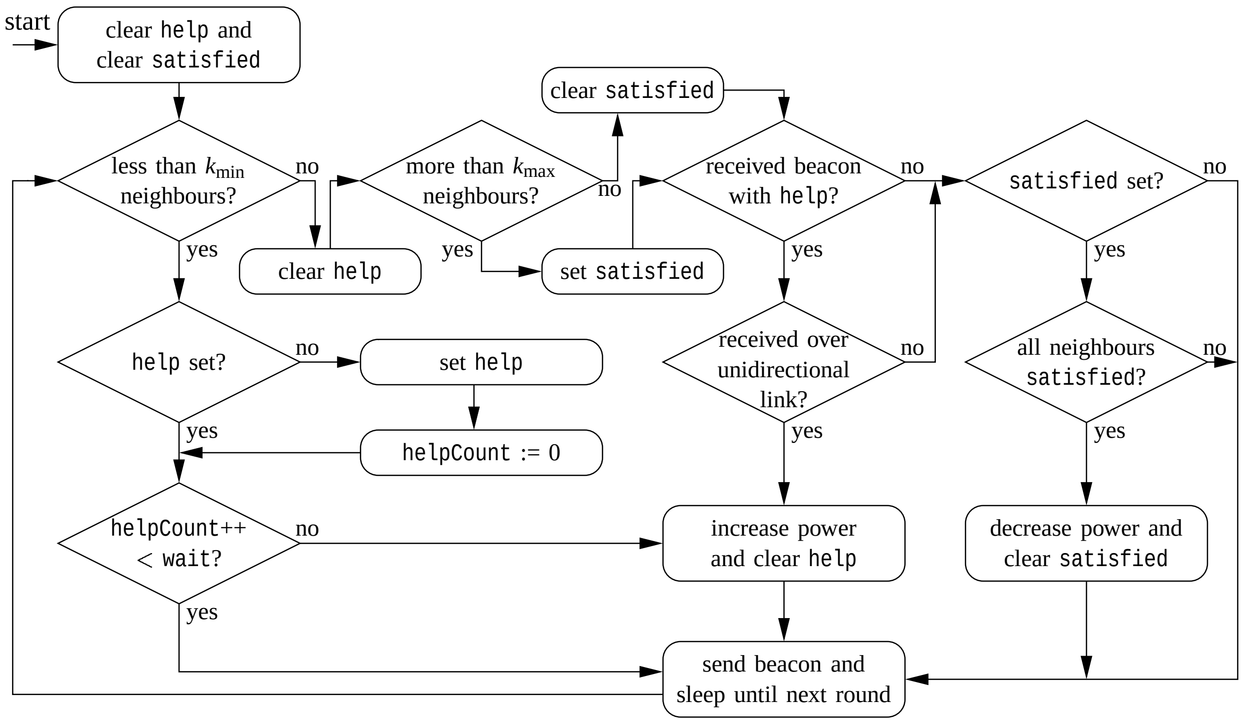


Fig. 3. Cooperative topology control algorithm

in this order should help to avoid that stations in proximity of each other use extremely different power levels.

B. Decreasing the Neighbour Count

If a device detects that it has more than k_{max} bidirectional links, it may nevertheless have to maintain its transmission power, since some neighbours may depend on these links. Reducing transmission power based solely on the own link count could cause neighbours to set their `help` flag, and consequently would again lead to an increase in transmission power.

To prevent this oscillation, a station must broadcast the information that it has more bidirectional links than needed. It does this by setting a `satisfied` flag. If a station detects that it has too many neighbours, it reduces its transmission power only if all of its neighbours have their `satisfied` flag set.

IV. Simulation Results

We have implemented our algorithm in the ns2 network simulator to evaluate two different aspects. In section IV-A, we compare transmission ranges resulting from our algorithm to minimal ranges necessary for different neighbour counts. In section IV-B, we compare the throughput in networks where all devices use a common transmission power to the throughput in networks where the devices run our topology control algorithm.

A. Comparison To Optimal Range Setting

To gain insight into the effectivity of the algorithm, we have compared the transmission ranges it assigns to the devices to the minimal transmission ranges ensuring that every device is connected to its $k = k_{min} = k_{max}$ nearest neighbours. 100 scenarios were simulated for each choice of k, each consisting of 500 nodes that were uniformly distributed on a square area with a side length of 1000 metres. The transmission range was adjusted by a constant distance of 3 metres. However, using other strategies did not change the results significantly.

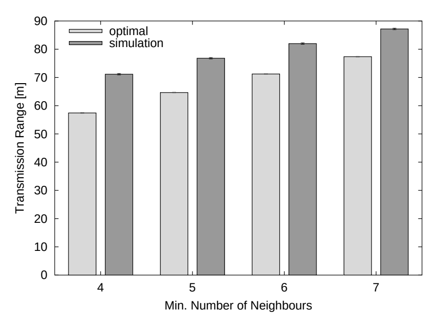


Fig. 4. Average transmission ranges in the optimal and simulated case

We observed a slightly higher average transmission range with our algorithm than optimal (cf. figure 4): The distributed approach assigns 15% to 20% larger transmission ranges on average as well as maximally. This does not come as a surprise since the devices do not have complete knowledge of the geographical positions of other stations. Thus, they may fail to find the actual nearest stations.

Figure 5 shows a situation where this has occurred ($k = 3$). Assume that devices C, F, and G have their `satisfied` flag

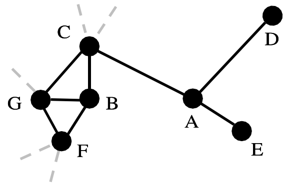


Fig. 5. Suboptimal range assignment of the implementation

set (missing devices not shown in this figure) and that links *AC* and *AD* have roughly the same cost. An optimal assignment would favour link *AB* over *AC* due to its lower cost, but the distributed algorithm might choose the suboptimal link *AC* due to the following reason. Suppose *A* starts with sharing bidirectional links solely with *B* and *E*. Consequently, *A* needs to raise its power to either reach *C* or *D*. However, since both have the same distance from *A*, it will reach both at the same time. Thus, *A* will have more than the required 3 bidirectional links and will turn its `satisfied` flag on. Now, *B* may be the first to reduce its transmission power. This results in a stable, but suboptimal range assignment.

B. Comparison To Common Transmission Ranges

To evaluate the effect of the introduced power control algorithm onto the network capacity, we have conducted another set of simulations and measured the resulting loss rate and delay of CBR traffic with and without power control. The traffic pattern consisted of 12 CBR streams with a data rate of 8 Kbit/s that were started in 3 second intervals after an initialisation phase of 15 seconds. After 55 seconds simulation time, the streams were stopped. The simulations were repeated for 30 scenarios, each again consisting of 500 stations uniformly distributed on a 1000 m $\times$ 1000 m area.

This time, we have modelled a wireless hardware with six discrete power levels. The transmission ranges were defined as 54, 92, 146, 168, 199, and 251 metres. These values conform to power levels of 1, 5, 20, 30, 50, and 100 mW (as offered by the Cisco Aironet card) for a path loss of $n = 3$ ([11]).

The AODV routing protocol implementation was modified to discard RREQs that do not arrive over bidirectional links ([12]). The simulations using topology control were carried out using $k_{\mathrm{max}} = k_{\mathrm{min}} + 6$.

The average packet delivery ratios (i.e. the fraction of packets successfully delivered, averaged over all simulations) are plotted in the first column of figure 6. We see that the choice of a common transmission range has a critical influence on the network throughput. For the node density in the simulated scenarios, a common range of 92 metres results in the highest packet delivery ratio. With a range of 54 metres, many connections cannot be established because the corresponding stations are in different network partitions. At higher ranges, the delivery ratio declines, although also the average number of hops between source and destination (plotted in the second column) decreases, showing that spatial re-use does play an important role. This is confirmed by the average node degree values (i.e. the stations' neighbour count values, averaged over all simulations) plotted in the third column: As the transmission ranges increase, extremely high numbers of devices compete for the transmission medium.

When the network topologies are actively formed with our algorithm, the choice of k_{min} within the range we have tested has a rather marginal influence on average. The resulting throughput is close to that of the optimal choice of a common range. This indicates that the aggravation of the hidden node problem is not as strong as often suspected. Actually, it seems as if it was nearly compensated by the higher spatial re-use. With higher values of k_{min}, similar effects as with the higher common transmission ranges will certainly appear.

The shortcoming of the nearest neighbours approach described in section II (cf. figure 2) arose in our simulations only for values of $k_{\mathrm{min}} < 5$. Even then, only small device clusters were separated from the rest of the connected network. The probability for two randomly chosen devices to be within the same connected component was over 0.95 in all cases. While theoretical work has proven that the minimum neighbour count necessary to achieve a connected network with high probability is unbounded with rising node count ([13]), we see that for our simulation setup, moderate values of k_{min} are sufficient to keep the partitioning probability very low.

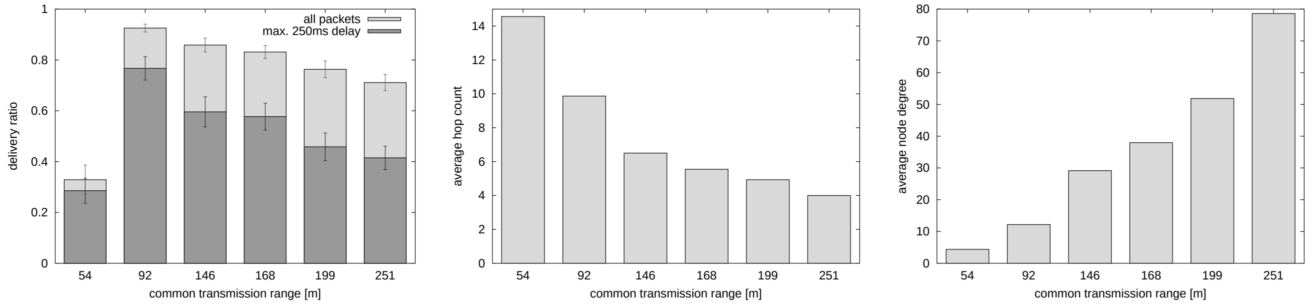
V. Conclusion & Further Work

We have presented a distributed topology control algorithm based on the nearest neighbours approach. In contrast to algorithms based on other concepts, it does not have any special requirements towards the hardware, e.g. the need for directional information. In contrast to other algorithms based on the nearest neighbours approach, its cooperative nature helps to reduce interference from stations in less dense parts or at the border of the network.

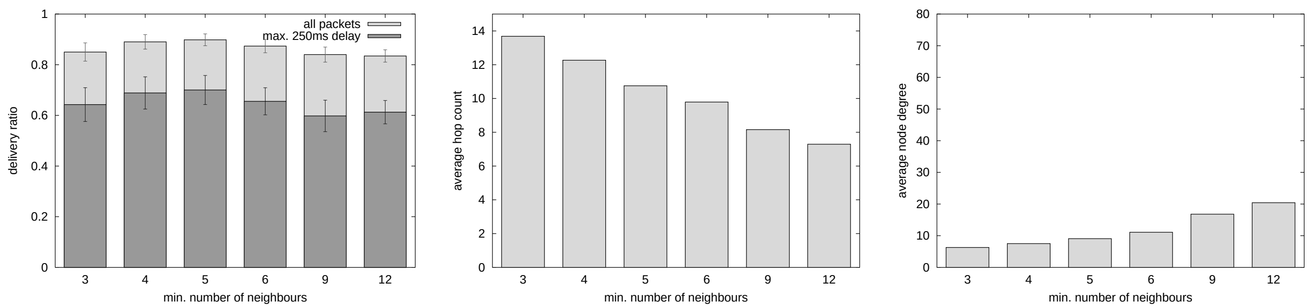
We have shown that the algorithm is capable of finding transmission powers that are quite close to the optimal values needed to maintain a certain minimum neighbour count. Also, we have shown that the throughput in networks where the transmission powers are controlled by our algorithm is close to the throughput in networks with an optimal common transmission power.

In this context, we have seen that the choice of a common power has great impact on the achievable throughput. This choice however requires global knowledge, since it is the overall node density that determines the quality of the resulting topology. With our algorithm in contrast, stations adapt to the node density in their neighbourhood, independent of the characteristics of distant parts of the network.

Consequently, the algorithm scales to arbitrary network sizes, because the load each device puts onto the network is locally bounded. This reduces the protocol overhead considerably when compared to implementations of a common transmission power scheme where local information must be spread across the network. Furthermore, the memory requirements and computational complexity are very small, both being linear in the number of neighbours.



(a) Common power levels



(b) Cooperative topology control

Fig. 6. Comparison of cooperative topology control to common power levels (average packet delivery ratios including 0.95 confidence intervals, average hop count taken by delivered packets, and average neighbour count)

Therefore, our topology control algorithm is a practical approach to keep the network capacity on a high level by dynamically adjusting transmission powers, applicable also in scenarios where the overhead associated with network-wide information exchange cannot be justified.

Further evaluation will concentrate on yet unaddressed aspects: The convergence of our algorithm in dynamic scenarios remains to be analysed. While our focus lies on maximising the network capacity, our topology control algorithm should also be evaluated in the context of energy efficiency. Furthermore, the comparison of our algorithm to the use of common transmission powers in scenarios with non-uniform node distributions could yield quite different results. The ability to adapt to local network characteristics might prove advantageous.

Finally, this work should be accompanied by theoretical work concerning the impact of nearest neighbours topology control on network characteristics.

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