Simulation-based Analysis of Topology Control Algorithms for Wireless Ad Hoc Networks

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Abstract. Topology control aims at optimizing throughput and energy consumption of wireless networks by adjusting transmission powers or by restricting the communication to a well-chosen subset of communication links. Over the years, a variety of topology control algorithms have been proposed. However, many of these algorithms have been mainly studied from a theoretical point of view. On the other hand, existing simulation-based studies often only compare few approaches based on rather simple simulations, e.g., abstracting from communication protocols.

In this paper, we present a thorough study of a variety of topology control algorithms based on the methodology of algorithm engineering. To analyze achievable performance improvements for communication according to the IEEE 802.11g standard we use the ns-3 network simulator. In addition to analyzing the communication throughput, we also study the effects of topology control on the energy demand in the network. Based on our simulation results, we then identify properties of the computed topologies that are essential for the achieved improvements. The gained insights are finally used to motivate an extension of the well-known XTC algorithm, which enables significant performance improvements in the considered application scenario.

Keywords: topology control, algorithms, wireless communication, wireless ad hoc network, network simulator, ns-3, IEEE 802.11g, energy consumption, throughput

1 Introduction

As the amount of data that is sent through wireless ad hoc networks increases, network structures that can serve this increased demand are needed. However, as energy is a limited resource in most ad hoc networks, this must be done while also achieving low energy consumption. The goal of topology control is to increase the network throughput, for example by reducing interference between concurrent transmissions, while simultaneously decreasing the energy consumption. To achieve this goal, nodes can adjust their transmission powers and restrict communication to a subset of their neighbors.

Although many different strategies have been proposed how the communication links that are used in the network topology should be selected, there is still no real consensus about what distinguishes good topologies from bad ones. A minimum requirement of almost all approaches is that the computed topology should be connected. Additionally, most algorithms try to compute rather sparse topologies. This strategy is motivated by the assumption that interference is minimized if every node has only few neighbors in the communication graph. However, so far there exists no real indication whether this strategy is really advantageous under realistic circumstances.

To verify the aforementioned assumption and to identify general properties of good communication topologies, we present in this work a broad comparison of various topology control algorithms. While existing simulation studies usually use rather simple simulations to compare two or three approaches with each other, in this work we use the powerful ns-3 network simulator [1] to analyze a broad variety of topology control algorithms with respect to their effect on network throughput and energy demand. We chose to use the ns-3 network simulator, which is a standard tool in the networking community, as it already implements a variety of standard communication protocols. This allows us to identify and study additional effects of topology control in connection with communication according to the IEEE 802.11g standard that are usually not modeled in simple self-implemented simulations.

We then try to interpret performance differences between the considered algorithms based on fundamental properties of the computed topologies, e.g., the average number of intermediate nodes that are necessary to enable communication between distant nodes. Based on the gained insights, we propose a simple extension of the well-known XTC algorithm. This extension simply consists in adding all links that exceed a certain link quality to the original XTC topology. According to our simulation results, this simple modification already results in significant performance improvements in comparison to the standard XTC approach. The modified algorithm, $\mathrm{XTC}_{\mathrm{RLS}}$, outperforms all other approaches in our simulations. At the same time, it preserves the advantages of XTC, i.e., it produces a connected topology based solely on local information about received signal strengths.

The rest of this paper is structured as follows: In Section 2 we define the topology control problem and introduce some basic terminology. Related work is discussed in Section 3. The topology control algorithms that are analyzed in this work are then introduced in some more detail in Section 4. The simulation setup is described in Section 5 and in Section 6 the simulation results are presented. Section 7 concludes this work.

2 Problem Definition and Terminology

Networks can naturally be modeled as graphs by mapping network nodes to graph nodes and possible communication links $l = (u, v)$ between two nodes u and v to edges between the corresponding nodes in the graph. Using this notation, the problem of topology control can be seen as a selection of edges such that some desired properties are achieved. For a graph $G = (V, E)$, a subgraph

$G' = (V, E')$ with $E' \subseteq E$ must be computed such that efficient communication, high throughput, maximal network lifetime or similar criteria are achieved. Depending on the considered application, the desired properties may differ and hence several different quality criteria are commonly considered. Typical examples for such quality criteria are connectivity, symmetry, stretch factors, sparseness, throughput, and planarity [2].

The *length* of a link $l = (u, v)$ denotes the Euclidean distance d_{uv} between nodes u and v. If node u sends a signal to node v with transmission power P_{uv}, the strength of the signal usually decreases on the way from u to v with increasing distance to u. Additionally, obstacles and interference effects result in additional signal attenuation. All these effects are subsumed in the *link gain* γ_{uv}, which defines how much the signal decreases on its way from u to v. If node u sends with transmission power P_{uv}, the signal is received by v with power $\gamma_{uv} \, P_{uv}$.

In wireless networks, the maximum transmission power that a node can use is usually limited. In consequence, nodes can only communicate directly within a certain communication radius. In order to allow communication between more distant nodes, multi-hop communication has to be used in which additional nodes relay the messages. If a message is routed on a path $(n_1, n_2, \ldots, n_k)$ from node n_1 to node n_k, each direct communication between two consecutive nodes along the path is called a *hop*. Given a communication graph G, the *hop-distance* between two nodes u and v is defined as the number of edges of a shortest path from u to v in G.

3 Related Work

Topology control has been a very vivid research area in the past years. The topology control problem has been considered isolated as well as combined with other aspects of wireless communication such as scheduling, clustering or routing. For both directions, a wide variety of algorithms has been proposed. In this work, we focus on pure topology control algorithms, as this enables us to analyze the effects of topology control apart from other influences.

Early approaches to the topology control problem were often graph-based and featured well-known graph-theoretic algorithms. Examples are a local variant of the minimum spanning tree (LMST) [3], the Gabriel graph (GG) [2], or the Relative Neighborhood graph (RNG) [2]. The cone-based topology control (CBTC) method [4] and the Yao graph (YG) [5] are other approaches that are based on angular separations between nodes and signal strengths of communication links. In the COMPOW protocol [6], all nodes try to find a minimal but common transmission power while preserving network connectivity. The XTC algorithm [7] computes a topology that is similar to the RNG; however, it is capable of achieving this without knowledge about node positions but based on signal strengths. More recently, kTC [8] and Inclusive Directed RNG (IDRNG) [9] have been proposed as improvements on XTC and the Directed RNG topology control algorithms. Another approach is k-Neigh, which locally selects up to

k neighbors for each node [10]. Surveys that give a more extensive overview on existing topology control algorithms can be found in [11, 12]. In Section 4, we will give a more detailed description of those topology control algorithms that are studied in this paper.

Most topology control algorithms have been mainly analyzed on a theoretical basis, e.g., by proving upper bounds on node degrees or proving certain spanner properties. Experimental and simulation-based comparisons are only seldom given. In the rest of this section, we will give an overview on the major real-world and simulation-based studies.

In [13], Jeong *et al.* studied the throughput and the energy consumption of several variants of the k-Neigh protocol using Mica2dot nodes. They showed that dynamic determination of the transmission power can increase the throughput and decrease the energy consumption in comparison to fixed transmission powers. In [14], Duràn *et al.* apply topology control algorithms such as the Gabriel graph, Relative Neighborhood graph, Yao graph and the Delaunay triangulation to multi-hop cellular networks. Based on data from a real-world network, they found that topology control can help to achieve significantly higher signal-to-interference-plus-noise ratios (SINR). In their experiments, the RNG algorithm achieved the best link quality.

In [15], Xu *et al.* use the ns-2 network simulator to study a newly proposed topology control algorithm in comparison to the original network without topology control. In [16], Gao *et al.* propose the MaxSR topology and compare the throughput of the proposed topology with LMST, CBTC, and the original topology. The energy consumption of the LMST and the R&M protocol has been considered in [17]. The authors found that if each node sends only one packet to a sink node then the LMST topology achieves the lowest energy consumption.

The work that is most similar to our work is [18], where Blough *et al.* use the GTNetS simulator, a network simulator similar to ns-3, to study the throughput that can be achieved with topology control in IEEE 802.11 networks. They consider a minimal spanning tree topology, two variants of the k-Neigh algorithm, CBTC, a common power topology and a max-power topology. Blough *et al.* conclude from their simulations that on the one hand the common power topology does not increase the throughput and the minimum spanning tree even decreases the throughput while on the other hand topology control algorithms such as k-Neigh and CBTC can improve the throughput significantly.

4 Examined Algorithms

As there exists a large variety of topology control algorithms (many of which are very similar), it is not possible to study all of them in detail. For this reason, we chose for our simulations a set of well-known algorithms that cover most of the different approaches towards topology control. In the following, we give a brief overview and short descriptions of the algorithms and topologies that are covered in our simulation study.

The first topology that we consider is the topology one gets when every sender uses the maximum transmission power and when all possible communication links are used. We call this topology *All-Links-Graph (ALG)*. Of course, all other topologies are a subset of the ALG topology. In *XTC* [7], a link between two nodes is used if there is no third node within reach that has equal or higher signal strength to both of the nodes. The *kTC* [8] algorithm searches triangles in the one-hop neighborhood of a node and discards the longest edge of such triangles if this edge is k times longer than the shortest edge in the triangle. This is similar to the approach in XTC. However, XTC discards each longest edge within such a triangle. The kTC algorithm is more robust towards errors in the perception of the received signal strength due to the parameter k and a local consensus on the signal strength. The parameter k is chosen as $1.41 \leq \sqrt{2}$, so that kTC is still a subset of the Gabriel graph and the distinction towards XTC is maximal. In the *Inclusive Directed RNG (IDRNG)* [9], communication links are selected in two steps: First the DRNG algorithm is executed, which discards communication links that do not have an empty relative neighborhood. Then each node determines the transmission power it has to use in order to reach all neighbors and adds all neighbors that can be reached using this transmission power to the topology. The *Localized Euclidean MST (LMST)* [3] is based on a local computation of Prim's algorithm in order to compute a minimum spanning tree. Each node computes the minimum spanning tree in its one-hop neighborhood and selects the communication links that are used in this tree. In the *Gabriel Graph (GG)*, a communication link from node u to node v is discarded if the circle with diameter $\mathrm{dist}(u, v)$ that has u and v on its boundary is not empty. The area that must be empty is smaller than the relative neighborhood considered in some of the previous algorithms. The *Yao Graph (YG)* [5] divides the surroundings of each node in $c = 6$ cones of equal angle and adds a communication link to the nearest neighbor in each cone. If there are two or more nearest neighbors, one neighbor is chosen arbitrarily. Bi-directionality of the constructed topology is ensured by forcing uni-directional edges to be bi-directional. The *k-Neighborhood Protocol (k-Neigh)* [10] computes a topology consisting of the k nearest neighbors of each node. k-Neigh does not necessarily yield a connected topology for lower values of k. We use $k = 8$, which should easily suffice to ensure connectivity [10]. Uni-directional edges are discarded from the topology.

4.1 XTC$_{\mathbf{RLS}}$

The algorithms discussed so far all aim at rather sparse topologies. To validate whether it is really advantageous to exclude many links from the communication, we also implemented a strategy that only excludes very weak links and keeps all links for which the received signal strength exceeds some threshold. In our simulations, the resulting topologies usually resulted in very good network performance. However, this approach has one major drawback: Depending on the considered network, it sometimes is necessary to use certain very weak links in order to guarantee connectivity of the communication topology. Thus, it sometimes happened that the computed topologies were not connected.

To deal with this problem efficiently, we propose the following extension of XTC: First, the XTC algorithm is used to create a sparse topology that is guaranteed to be connected. Afterwards, each node additionally adds all those communication links whose signal strengths exceed a given threshold. We experimentally determined -86 dBm to be a good value for the threshold and use this value in our simulations. In the following, we will refer to the described extension of XTC as XTC_{RLS}, where the RLS reminds of the restricted link strength. Note that similar to XTC, the $\mathrm{XTC}_{\mathrm{RLS}}$ topology can be easily computed in a distributed fashion based solely on local information about received signal strengths.

5 Simulation Setup

For our simulations we used version 3.13 of the network simulator ns-3 [1], which is designed for network related research and implements a wide variety of communication standards and protocols. In each simulation run, 60 nodes that are equipped with a wireless communication device according to the IEEE 802.11g standard are distributed randomly in a square-shaped deployment area. To adjust the node density, we vary the base lengths of the deployment area between 100 m and 600 m. Among the 60 nodes, 18 source-target pairs are randomly selected and each source node must transmit 5 MB of data to the corresponding target node. Note that due to the multi-hop communication this accumulates to up to 900 MB of data that must be transmitted across the network, depending on the average number of hops that are necessary for communication between distant nodes (see Section 6.1).

For the communication, we use end-to-end TCP connections in a CSMA/CA[1]-based network using the Open Link State Routing (OLSR) protocol. As ns-3 does not offer a standard framework to support topology control mechanisms, e.g., by restricting communication to a given subset of communication links, we adjusted the OLSR routing protocol such that it only uses the links that are selected by the considered topology control algorithm.

To model signal decay in our simulations, we use the standard log-distance path loss model as implemented in ns-3. According to the log-distance model, the path loss L in dB is given as

$$L = L_0 + 10 \cdot \alpha \cdot \log_{10}\left(\frac{d}{d_0}\right) \quad ,$$

where L_0 is the reference path loss at distance d_0, α is the path loss exponent, and d is the distance between sender and receiver. In our simulations we use $L_0 = 46.6777, d_0 = 1$, and $\alpha = 3$, which correspond to an average free space environment with some obstacles.

In each simulation run we measure the time needed to finish all transmissions and the energy that is consumed during the transmissions, as well as the time the

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[1] Carrier Sense Multiple Access with Collision Avoidance; implements collision avoidance in IEEE 802.11 wireless networks.

network devices spent in the TX, RX, IDLE and CCA_BUSY[2] states to allow the subsequent application of different energy models to our simulation results. Additionally we analyze basic properties of the computed topologies such as average node degrees, average sender-receiver distances, and the average number of hops that are necessary to allow communication between the source and target nodes. Our plots depict median values based on 50 independent simulation runs. The time limit of the simulations was set to 5000 seconds.

Energy model. While properties such as the achieved throughput or the average number of hops are rather unambiguous, the consumed energy strongly depends on assumptions about the used communication hardware. Choosing an energy model that applies for a wide variety of available wireless network devices is a difficult task. We decided to adjust the energy consumption in our simulations to the energy consumption of the Roving Networks RN-174, which has a relatively low energy demand. Table 1 states some of the relevant specifications as stated in the corresponding data sheet.

State	Idle	RX	TX (dBm)						
			0	2	4	6	8	10	12
Current (mA)	40	40	135	150	190	200	210	225	240

Table 1. Energy consumption of an RN-174, measured at 3.3 V DC [20]. The transmission and the reception states are abbreviated by TX and RX.

As we need the energy consumption for a wider range of transmission powers, we use a linear least squares fit to interpolate the current that is drawn from the battery for arbitrary transmission powers. This gives

$$\text{TxCurrent}(\text{TxPower}) = \begin{cases} 8.66 \cdot \text{TxPower} + 140.89 & \text{if TxPower} \geq -10, \\ 54.28 & \text{else,} \end{cases}$$

where TxPower is the transmission power in dBm and the function returns the current in mA. We consider the network to be active even after all transmissions are finished. Hence, we subtract the idle power consumption from the power consumption of the other states (i.e., computationally eliminate the idle power consumption). Note that due to this only transmission time and transmission power affect the energy consumption. We will see in Section 6 that this does not change the results of our analysis as the energy consumption calculated according to this measure still correlates to the time needed to finish the transmissions.

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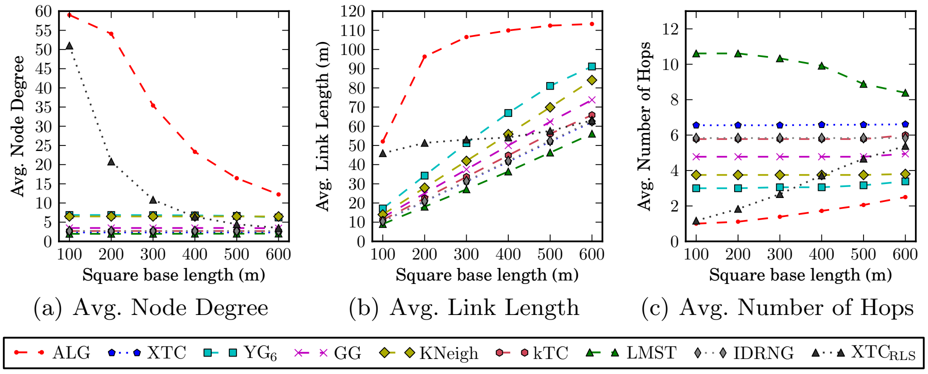
[2] We assume, according to [19], that CCA_BUSY requires the same amount of energy as the IDLE state.

6 Experiments

6.1 Basic topology properties

Although the main focus of our simulations lies on the effects of different topologies on the throughput and the energy consumption in wireless networks, we first want to briefly examine some basic properties of the computed topologies. This will allow us later to gain a deeper understanding of why certain topologies perform better than others.

First we take a look at the average node degree of the computed topologies, which is depicted in Figure 1(a). Apparently, all algorithms but ALG and $\mathrm{XTC}_{\mathrm{RLS}}$ produce topologies with very low node degrees. Additionally, for those algorithms the average node degree is almost independent of the node density. In contrast, for high node densities ALG and $\mathrm{XTC}_{\mathrm{RLS}}$ have rather high average node degrees. For example, for the deployment area of 100 m × 100 m almost all nodes can communicate directly in the ALG topology. Not surprisingly, for networks with low node density the average node degree of $\mathrm{XTC}_{\mathrm{RLS}}$ approaches the one of XTC.



(a) Avg. Node Degree (b) Avg. Link Length (c) Avg. Number of Hops

Fig. 1. Basic properties of the computed topologies in dependence of the deployment area.

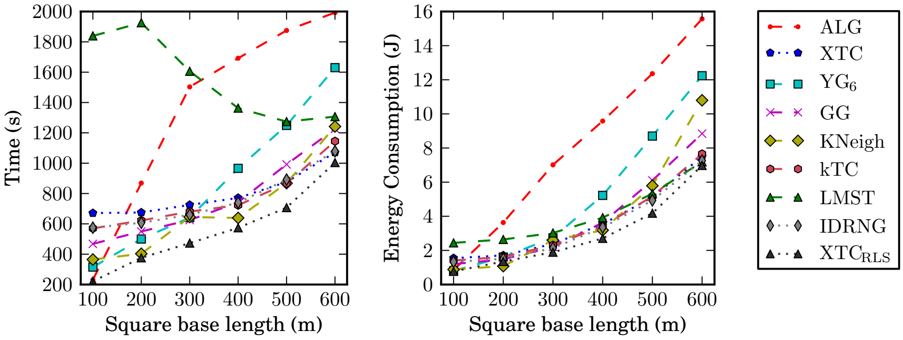
Concerning the average link length, i.e., the average distance between pairs of nodes that are allowed to communicate directly with each other, for high node densities ALG and $\mathrm{XTC}_{\mathrm{RLS}}$ result in a higher average link length than the other approaches (cf. Figure 1(b)). However, while the average link length of ALG increases up to more than 100 m for large deployment areas, the average link length of $\mathrm{XTC}_{\mathrm{RLS}}$ only approaches the one of XTC and is thus lower than the link lengths of most other approaches. The reason for this of course is that $\mathrm{XTC}_{\mathrm{RLS}}$ only adds links with relatively high link gain, which means that links that exceed about 50 m are only chosen if they are also chosen by XTC.

Figure 1(c) depicts the average number of hops that are necessary to enable communication between the randomly selected source-target pairs. For most of the topologies the number of hops is almost independent of the node density, whereas in the ALG and $\mathrm{XTC}_{\mathrm{RLS}}$ topologies the average number of hops starts close to one and rises with decreasing node density. In the following, we will see that both the required time to complete all transmissions and the consumed energy are strongly correlated with the average number of required hops. This can be explained by the fact that each message has to be sent once for each hop. Thus, the overall number of packets that are transmitted within the network also depends on the average number of hops per source-target pair.

6.2 Topology control with uniform transmission powers

In this section we study the influence of topology control when all senders use the maximum available transmission power. In this setting, performance improvements can only be achieved by avoiding weak links and by keeping the interference in the network low. As we saw in Section 6.1, most of the considered topology control algorithms try to achieve this by using only few links with very high link gain.

Communication throughput. First we examine the time that is needed to finish all transmissions, which is shown in Figure 2(a). We observe that ALG, the original topology without topology control, is only competitive for the deployment area of 100 × 100 meters. Once the nodes are deployed on an area of 200 × 200 meters or larger, almost all other topologies can finish faster, i.e., achieve higher throughput. This presents a strong motivation for the use of topology control.



(a) Required Time (b) Consumed Energy

Fig. 2. Influence of topology control on the required time to finish all transmissions and on the consumed energy.

The ALG topology works well for small deployment areas as in the resulting networks most source-target pairs can communicate directly (mostly with a reasonable data rate). Since the ALG topology does not discard weak links, for larger deployment areas the OLSR routing algorithm selects more links that achieve a relatively low signal strength and hence can only communicate with low data rate and maybe even with a high packet error rate. The very poor performance of LMST can be explained in terms of bottlenecks that emerge when all communication is limited to a tree-like backbone. Surprisingly, for larger deployment areas the throughput of LMST actually improves. The reason is that the local approximation to a minimum spanning tree on average is worse and hence uses more edges on large deployment areas.

All other topologies show a similar tendency that the throughput slowly decreases with increasing deployment area. According to Figure 1(c), for most topologies this can not be explained in terms of a higher number of hops between source nodes and target nodes. Instead, this tendency is most likely caused by the fact that the average link length increases for larger deployment areas (cf. Fig. 1(b)). A higher link length also means a lower link gain, which in IEEE 802.11g networks finally causes that the achievable data rate over the link is lower.

By comparing Fig. 1(c) with Fig. 2(a), one can see that especially for small deployment areas the time that is needed to complete all transmissions is correlated to the average number of communication hops. Those topologies that require more hops usually also require more time to finish all transmissions. With increasing deployment area, however, this effect decreases as the data rate that can be achieved over the links becomes increasingly important. For networks that use a fixed data rate, the average number of hops of the topology is expected to be even more relevant for the throughput performance.

Note that our simulation results contradict the usual assumption that sparser topologies increase the throughput in the network or lower the energy consumption. Especially when comparing XTC with $\mathrm{XTC}_{\mathrm{RLS}}$, it clearly seems to pay off to include additional links as long as they provide sufficiently high link gain. However, a comparison of $\mathrm{XTC}_{\mathrm{RLS}}$ with ALG also reveals that it really helps to avoid links with low link gain.

Energy consumption. Regarding the energy consumption, which is shown in Fig. 2(b), we observe that for deployment areas above $200\,\mathrm{m} \times 200\,\mathrm{m}$ all considered topologies are more energy-efficient than the original ALG topology. At the first moment this might seem a little surprising. We did not adjust transmission powers, which implies that transmissions over long distances use the same transmission power as short-range transmissions. However, in the considered IEEE 802.11g communication protocol another factor that often is not considered comes into play: For transmissions over short distances the link gain is usually higher, which means that a higher data rate is used. This implies that short-range transmissions are finished faster and the wireless network devices spend less time in the energy-consuming TX state.

The rapid increase in energy consumption of the ALG topology for larger deployment areas can thus easily be explained by the use of long-range communication links that only allow for very low data rates. Interestingly, although the LMST topology uses only very short links, it results in the highest energy consumption of all topologies for dense networks. This observation can be explained by the high number of hops that are on average necessary to transfer data from one node to another (cf. Fig. 1(c)). Concerning XTC_{RLS}, it not only produces the topology that allows for the highest throughput in the considered scenario, but it also results in the lowest energy consumption for most of the considered node densities.

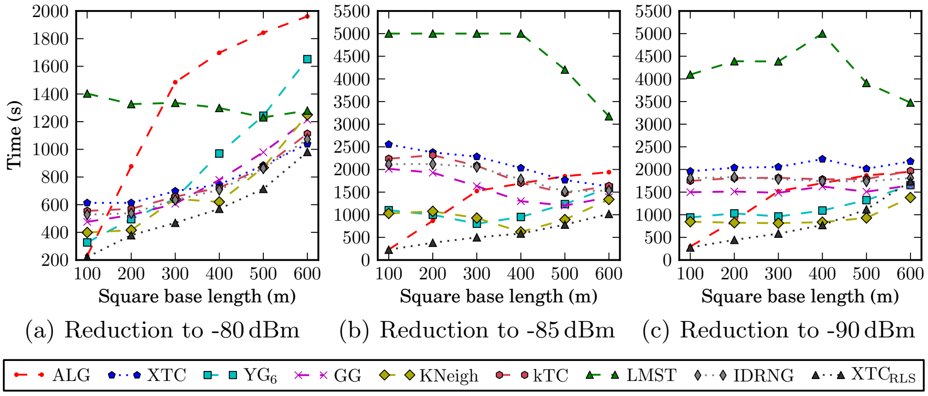
6.3 Topology control in combination with power control

In addition to restricting the communication to a well-chosen subset of all possible links, it is also sometimes proposed that the network performance can be additionally improved by reducing the transmission power that is used for communication between nodes that are located close together. In this section, we examine the influence of such an additional optimization.

Communication throughput. As transmission power reduction can help to reduce interference effects between concurrent transmissions, it seems reasonable to assume that throughput improvements are possible if short-range transmissions use lower transmission powers. However, existing studies on this topic came to different conclusions: In [13], the authors stated that for k-Neigh on Mica2dot nodes transmission power reduction does not increase the throughput performance but at most achieves similar throughput. In contrast, the authors of [18] showed with simulations using the GTNetS simulator that an additional transmission power reduction can produce significant throughput improvements for various topology control algorithms.

To further study this topic, we conducted similar experiments as before (i.e., multi-hop communication between 18 random source-target pairs in a network of 60 nodes) but reduced the transmission powers for transmissions over short distances. Again, the time that passes until all transmissions are finished is analyzed. We consider three different reduction thresholds: the transmission power of each node is reduced such that the communication partner with the lowest received signal strength can receive the signal with $-80\,\text{dBm}$, $-85\,\text{dBm}$ and $-90\,\text{dBm}$, respectively. If the received signal strength of a communication link is already lower than this threshold, the transmission power is not reduced. The times needed to finish all transmissions are depicted for the three considered thresholds in Figure 3.

We observe that the reduction of transmission powers such that the received signal strengths do not exceed $-85\,\text{dBm}$ or $-90\,\text{dBm}$ actually results in lower throughput. This is due to the data rate management in IEEE 802.11 wireless communication, which determines the used bitrate based on the measured signal-to-interference-plus-noise ratio (SINR). The higher the SINR, the higher the possible data rate. Thus, especially links with high link gain are negatively affected by the transmission power reduction. However, if the transmission powers are



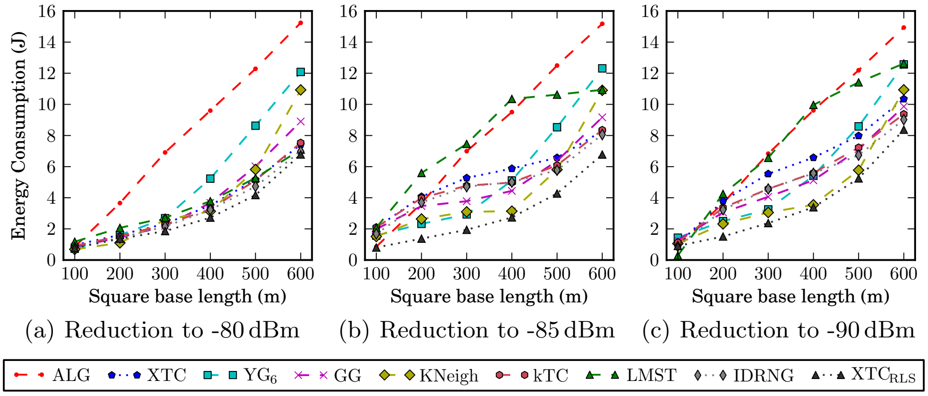
(a) Reduction to -80 dBm (b) Reduction to -85 dBm (c) Reduction to -90 dBm

Fig. 3. Time needed to finish the transmissions for different reductions of the transmission power. Note the different scales of the y-axis.

only reduced so far that the received signal strengths still equal −80 dBm, most topologies show small throughput improvements (cf. Fig. 2(a) and Fig. 3(a)). The largest improvements are achieved for the LMST topology in networks with high node density.

Energy consumption. Especially when the power consumption of a wireless device increases with increasing transmission power, as it is assumed in this work, it seems natural that using lower transmission powers also decreases the energy consumption. It was shown, for example, in [13] that a reduction of the transmission powers yields a lower energy consumption for Mica2dot nodes. In our simulations, however, we found that this can not be stated in such a general way. Again we consider the three power control strategies that reduce the transmission powers until the received signal strength equals −80 dBm, −85 dBm, or −90 dBm. The average energy consumptions per node for the three considered setups are depicted in Figure 4. The energy consumption per node using topology control without transmission power reduction, which is shown in Figure 2(b), is very similar to the energy consumption after a reduction to received signal strengths of -80 dBm, depicted in Figure 4(a). Only for very dense instances some sparse topologies such as the LMST, XTC, kTC, IDRNG and the Gabriel graph achieve a small improvement in the energy demand. This is probably due to the significant reduction of the transmission power they achieve.

For the scenarios where the transmission powers are reduced until the received signal strengths equal -85 dBm or -90 dBm, however, the consumed energy increases significantly for most topologies. Again, this can be explained with an adaption of the data rate to the measured SINR. As the data rate is reduced, the wireless devices require more time to transmit each single packet, which leads to a higher energy consumption.



(a) Reduction to -80 dBm (b) Reduction to -85 dBm (c) Reduction to -90 dBm

Fig. 4. Energy consumption for transmissions using topology control with transmission power reduction. The transmission powers are reduced until the received signal strengths correspond to the stated values.

6.4 Performance comparison

To conclude this section, we present a brief comparison of the different topologies based on the achieved throughput and the energy consumption. Since the relative order of the topologies is similar for topology control with and without additional power control, we will focus on the results without power control, which are depicted in Figure 2.

For small deployment areas the ranking according to the throughput is strongly related to the average number of hops for communication between distant nodes, where XTC_{RLS} and ALG perform best, followed by the Yao graph, k-Neigh, the Gabriel graph, IDRNG, kTC, XTC, and finally LMST. We can see that all topologies except ALG and LMST achieve somewhat comparable throughput. For larger deployment areas the performance of ALG decreases rapidly while XTC_{RLS} still achieves the highest throughput, followed by IDRNG, XTC, kTC, the Gabriel graph, k-Neigh and LMST, which are all relatively close together. The lowest throughput is achieved by the Yao graph and ALG.

Regarding the energy consumption, most topologies achieve a similar performance. The ALG topology has the highest energy demand for most instances since links with weak signal strength are not discarded. Those links usually achieve a poor performance considering both the throughput and the energy efficiency. The LMST is worse than the other topologies (except partially ALG) for relatively dense instances, while the Yao graph and k-Neigh consume more energy than the other topologies for sparse instances. The proposed extension of XTC, XTC_{RLS}, achieves the best results for almost all instances. However, it is closely followed by most other topologies: IDRNG, Gabriel graph, kTC, XTC, k-Neigh, Yao graph and LMST. Only for the deployment area of 200×200 meters, k-Neigh achieves an energy consumption lower than that of XTC_{RLS}.

7 Conclusion

In this paper, we studied throughput and energy consumption of a variety of topology control algorithms. Especially in networks with rather low node density, all algorithms were able to improve the network throughput and the energy demand considerably. Our broad comparison made it then possible to relate the achieved performance improvements to basic properties of the computed topologies. Contrary to what is usually assumed, producing sparse topologies turned out to be not beneficial. In topologies with low average node degree usually more hops were necessary to allow communication between distant nodes. As each additional hop also means that the packets have to be relayed an additional time, sparse networks resulted in lower throughput and higher energy consumption.

Concerning power control, we showed that—contrary to what one might expect—reducing transmission powers does not necessarily result in power savings. The reason is that standard communication protocols usually adjust the data rate according to the measured SINR. Thus, lower transmission powers can result in longer transmissions and consequently in higher energy consumption. This effect is currently ignored in most studies of scheduling and routing protocols, even in those that particularly focus on energy consumption.

Motivated by the observation that denser topologies often allow for better performance and lower energy consumption, we proposed $\mathrm{XTC}_{\mathrm{RLS}}$, an extension of XTC that achieves connectivity by computing the XTC topology and that afterwards simply adds all links which provide a sufficiently high received signal strength. In our simulations, the $\mathrm{XTC}_{\mathrm{RLS}}$ algorithm outperformed all other approaches regarding both data throughput and energy efficiency.

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