# Self-Organizing Fault-Tolerant Topology Control in Large-Scale Three-Dimensional Wireless Networks

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Topology control protocol aims to efficiently adjust the network topology of wireless networks in a self-adaptive fashion to improve the performance and scalability of networks. This is especially essential to large-scale multihop wireless networks (e.g., wireless sensor networks). Fault-tolerant topology control has been studied recently. In order to achieve both sparseness (i.e., the number of links is linear with the number of nodes) and fault tolerance (i.e., can survive certain level of node/link failures), different geometric topologies were proposed and used as the underlying network topologies for wireless networks. However, most of the existing topology control algorithms can only be applied to two-dimensional (2D) networks where all nodes are distributed in a 2D plane. In practice, wireless networks may be deployed in three-dimensional (3D) space, such as under water wireless sensor networks in ocean or mobile ad hoc networks among space shuttles in space.

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This article seeks to investigate self-organizing fault-tolerant topology control protocols for large-scale 3D wireless networks. Our new protocols not only guarantee $k$-connectivity of the network, but also ensure the bounded node degree and constant power stretch factor even under $k-1$ node failures. All of our proposed protocols are localized algorithms, which only use one-hop neighbor information and constant messages with small time complexity. Thus, it is easy to update the topology efficiently and self-adaptively for large-scale dynamic networks. Our simulation confirms our theoretical proofs for all proposed 3D topologies.

Categories and Subject Descriptors: C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design—*Network topology; wireless communication*; C.2.2 [**Computer-Communication Networks**]: Network Protocols; C.4 [**Computer Systems Organization**]: Performance of Systems—*Fault tolerance*; F.2.2 [**Analysis of Algorithms and Problem Complexity**]: Nonnumerical Algorithms and Problems

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## 1. INTRODUCTION

Multihop wireless networks (especially wireless ad hoc and sensor networks) have been undergoing a revolution that promises to have a significant impact throughout society. Unlike traditional fixed infrastructure networks, there is no centralized control over multihop wireless networks, which consist of an arbitrary distribution of wireless devices in a certain geographical area. Multihop wireless networks intrigue many challenging research problems because they inherently have some special characteristics and unavoidable limitations compared with other fixed infrastructure networks. An important requirement of these networks is that they should be self-organizing, that is, transmission ranges and data paths are dynamically restructured with changing topology. Energy conservation and scalability are probably the most critical issues because in large-scale wireless networks a massive number of mobile devices are usually powered on batteries and have limited computing capability and memory.

The *topology control* technique is to let each wireless device *locally* adjust its transmission range and select certain neighbors for communication, while maintaining a structure that can support energy-efficient routing and improve the overall network performance and scalability. By enabling each device to shrink its transmission power (which is usually much smaller than its maximal transmission power) for sufficient coverage of the farthest selected neighbor, topology control can not only save energy and prolong network life, but also improve network throughput through mitigating MAC-level medium contention. Unlike traditional wired networks and cellular networks, a large number of wireless devices are often moving during the communication, which could change network topology to some extent. Hence it is more challenging to design a topology control algorithm for multihop wireless networks: The topology should be locally and self-adaptively maintained without affecting the whole network, and the communication cost during maintaining should be minimized. There exist several topology control techniques, such as localized geometrical structures [Li et al. 2002, 2001a, 2001b; Wattenhofer et al. 2001], dynamic cluster techniques [Das and Bharghavan 1997; Stojmenovic et al. 2002; Alzoubi et al. 2003, 2002; Bao and Garcia-Luna-Aceves 2003; Wang et al. 2006], and power management protocols [Schurgers et al. 2002; Cerpa and Estrin 2002; Chen et al. 2002; Li et al. 2005]. In this article, we focus on methods based on localized geometrical structures which utilize rich geometric properties of wireless networks to enable efficient self-organizing topology control.

In order to be power efficient, traditional topology control algorithms try to reduce the number of links, and thereby reduce the redundancy available for tolerating node and link failures. Thus, the topology derived from such algorithms is more vulnerable to node failures or link breakages. However, due to constrained power capacity, hostile deployment environments, and other factors, events like individual node failures are more likely to happen, which might cause network partitions and badly degrade network performance. Therefore, in order to gain a certain degree of redundancy and guarantee overall performance, fault-tolerant becomes a critical requirement for the design of wireless networks. As fault tolerance strongly depends on network connectivity, topology design for such networks needs to consider both power efficiency and fault tolerance. Some recent work [Li and Hou 2004; Zhou et al. 2005; Bahramgiri et al. 2002] extends existing topology control algorithms with fault-tolerant.

Most existing topology control algorithms based on geometrical structures [Li et al. 2002, 2001a, 2001b; Wattenhofer et al. 2001; Li and Hou 2004; Zhou et al. 2005] are designed under two-dimensional assumption, where all wireless devices are distributed in a two-dimensional plane. However, the 2D assumption may no longer be valid if the network is deployed in space, atmosphere, or ocean, where nodes of a network are distributed over a 3D space and the differences in the third dimension are too large to ignore. Actually, in practice, wireless networks are often deployed in 3D space, such as notebooks in a multifloor building and sensor nodes in an *Under-Water Sensor Network* (UWSN) [Akyildiz et al. 2005]. 3D UWSN is used to detect and observe phenomena that cannot be adequately observed by means of ocean bottom sensor nodes, that is, to perform cooperative sampling of the 3D ocean environment. Although geometric topology control protocols have been studied in 2D networks, the design of 3D topology control is surprisingly more difficult than the design in 2D. Current 2D methods cannot be directly applied in 3D networks. Wang et al. [2008a] proved that there is no embedding method mapping a 3D network into a 2D plane so that the relative scale of all edge lengths is preserved and all 2D geometric topology control protocols can still be applied for power efficiency. Thus, any simple mapping method from 3D to 2D does not work. On the other hand, many properties of 3D networks require additional computational complexity. For example, to bound the node degree, fully partitioning a 3D ball into constant number of equal-size cones is much harder than in 2D case or even impossible without any intersection. Faced with these challenges, in this article we study how to efficiently construct topology for 3D networks to maintain fault tolerance, conserve energy, and enable energy-efficient routing.

The contributions of this article can be summarized as follows.

(1) We introduce three new localized 3D geometrical structures, which can be easily constructed using constant messages.[1]
(2) We prove that all three structures can preserve the $k$-connectivity of the network, in other words, can preserve the connectivity under $k-1$ node failures.
(3) We prove that two of the new structures can provide energy-efficient routes for routing, even under $k-1$ node failures.
(4) We prove that one of the new structures can also bound the node degree.

To the best of our knowledge, there is no previous research on 3D fault-tolerant topology control. Even compared with the existing 3D topology control methods [Bahramgiri et al. 2002; Ghosh et al. 2007] for keeping 1-connectivity, our proposed structures are much easier to construct. We demonstrate this by simulation.

The rest of the article is organized as follows. Section 2 presents our network model and summarizes desirable properties of network topology. Section 3 reviews related work on fault-tolerant and 3D topology control. In Section 4, we describe our new localized fault-tolerant 3D topologies and prove their good properties. Simulation results are reported in Section 5. We then discuss how to maintain the proposed topologies in dynamic networks in Section 6 and conclude the article in Section 7.

## 2. NETWORK MODEL AND DESIRABLE TOPOLOGICAL PROPERTIES

### 2.1 Network Model

A 3D wireless network consists of a set $V$ of $n$ wireless nodes distributed in a 3D plane $\mathbb{R}^3$. Each node has the same *maximum transmission range* $R$. These wireless nodes define a *Unit Ball Graph* (UBG), or called a *unit sphere graph*, in which there is an edge $uv$ between two nodes $u$ and $v$ iff (if and only if) the Euclidean distance $\|uv\|$ between $u$ and $v$ in $\mathbb{R}^3$ is at most $R$. In other words, two nodes can always receive the signal from each other directly if the distance between them is no more than $R$. We assume that all wireless nodes have distinctive identities and each node knows its position information either through a low-power GPS receiver or some other way (such as 3D localization methods in Zhang and Cheng [2004], Zhou et al. [2007], Cheng et al. [2008]). By one-hop broadcasting, each node $u$ can gather the location information of all nodes within its transmission range. As in the most common power-attenuation model, the power to support a link $uv$ is assumed to be $\|uv\|^\beta$, where $\beta$ is a real constant between 2 and 5 depending on the wireless transmission environment.

[1]Actually, there is no message exchange needed once each node learns its 1-hop neighbors via periodic beacon messages.

We also assume that UBG is $k$-connected for some $k > 1$, that is, given any pair of wireless devices in the network, there are at least $k$ disjoint paths between them. With $k$-connectivity, the network can survive $k - 1$ node/link failures.

### 2.2 Preferred Topological Properties

Topology control protocols aim to maintain a structure that can preserve connectivity, optimize network throughput with power-efficient routing, conserve energy, and increase fault tolerant. In the literature, the following desirable features of the structure are well regarded and preferred in wireless networks.

(1) *Fault Tolerance:* To achieve fault tolerance (surviving $k - 1$ failures), the constructed topology needs to be $k$-connected, given the communication graph (e.g., UBG) is $k$-connected.

(2) *Bounded Node Degree:* It is also desirable that the node degree in the constructed topology is small and upper-bounded by a constant. A small node degree reduces the MAC-level contention and interference, and may help to mitigate the well-known hidden and exposed terminal problems.

(3) *Power Spanner:* A good network topology should be *energy efficient*, that is, the total power consumption of the least energy cost path between any two nodes in the final topology should not exceed a constant factor of the power consumption of the least energy cost path in the original network. Given a path $v_1 v_2 \cdots v_h$ connecting two nodes $v_1$ and $v_h$, the energy cost of this path is $\sum_{j=1}^{h-1} \|v_j v_{j+1}\|^{\beta}$. The path with the least energy cost is called the shortest path in a graph. A subgraph $H$ is called a *power spanner* of a graph $G$ if there is a positive real constant $\rho$ such that for any two nodes, the power consumption of the shortest path in $H$ is at most $\rho$ times of the power consumption of the shortest path in $G$. The constant $\rho$ is called the *power stretch factor*. A power spanner of the communication graph (e.g., UBG) is usually energy efficient for routing.

(4) *Localized Construction:* Due to limited resources and high mobility of wireless nodes, it is preferred that the topology can be constructed locally and in a self-organizing fashion. Here, a topology is *localized*, that is, can be constructed locally, if every node $u$ can decide all edges incident on itself in the topology by only using the information of nodes within a constant hops of $u$. Actually, all construction algorithms of our topologies presented here only use 1-hop neighbor information. Thus, they can be self-adaptive and self-organizing.

## 3. RELATED WORK ON TOPOLOGY CONTROL

With the objective of achieving energy efficiency and maintaining network connectivity, several geometrical structures have been proposed for topology control in 2D networks, such as *Local Minimum Spanning Tree* (LMST) [Li et al. 2004b, 2003], *Relative Neighborhood Graph* (RNG) [Bose et al. 1999; Seddigh et al. 2002], *Gabriel Graph* (GG) [Karp and Kung 2000; Bose et al. 1999], *Yao Graph* (YG) [Li et al. 2002, 2001b], *Cone-Based Topology Control* (CBTC) [Wattenhofer et al. 2001; Li et al. 2001a], and so on. By constructing such sparse topology structures, transmission powers of nodes are minimized.

As a result, the number of links in the network is reduced comparing with that of the *Unit Disk Graph* (UDG), which contains an edge between two nodes if and only if their distance is at most one. On the other side, the lack of redundancy makes the topology more susceptible to node failures or link breakages. In order to achieve routing redundancy and construct $k$-connected topology, recent work has extended existing topology control algorithms to incorporate fault tolerance.

Li and Hou [2004] proposed a fault-tolerant topology control algorithm to construct the $k$-connected topology, called Fault-tolerant Local Spanning Subgraph ($\text{FLSS}_k$). During the topology construction phase, a node builds a spanning subgraph to preserve $k$-connectivity using a simple greedy algorithm. However, for each step in the greedy algorithm, they need to check the $k$-connectivity of current local graph, which is very time consuming. Besides the $k$-connectivity, the authors also proved that $\text{FLSS}_k$ can maintain bidirectional links and reduce power consumption.

Bahramgiri et al. [2002] presented a variation of the CBTC algorithm to preserve the $k$-connectivity. The algorithm increases transmission power until it reaches the maximum value or the angle between any two consecutive neighbors of the resulted topology is at most $\frac{2\pi}{3k}$. Even though the topology is proved to be $k$-connected, it does not bound node degree.

Zhou et al. [2005] modified the RNG structure as follows to construct $k$-RNG, which is $k$-connected. In $k$-RNG, an edge exists between nodes $u$ and $v$ iff there are at most $k-1$ nodes $w$ that satisfy $\|uw\| < \|uv\|$ and $\|wv\| < \|uv\|$. Zhou et al. proved that $k$-RNG can guarantee the $k$-connectivity if the original communication graph is $k$-connected.

Li et al. [2004a] generalized the Yao structure to $YG_{p,k}$, which is defined as follows: At each node $u$, any equally separated $p$ rays originating from $u$ define $p$ cones, where $p > 6$. In each cone, $u$ chooses the $k$ closest nodes, if there are any, and add directed links from $u$ to these nodes. Li et al. proved $YG_{p,k}$ can preserve $k$-connectivity. Besides, $YG_{p,k}$ is also a length/power spanner with bounded node degree.

Recently, Wang et al. [2008b] also studied how to form fault-tolerant topology for all-to-one and one-to-all communication in static wireless networks. Their solutions include several centralized approximation algorithms.

All the algorithms and structures discussed before are designed only for 2D networks. For more details on topology control in 2D networks, please refer to Hou et al. [2005], and Wang [2008, 2007]. Until recently, little research has been done on topology control for 3D wireless networks.

Wang et al. [2008a] studied 3D topology control by extending RNG and GG to the 3D case and proposing new 3D Yao-based topologies, which can be constructed locally and efficiently. They proved several properties of these new 3D structures, for example, bounded node degree and constant power stretch factor.

Bahramgiri et al. [2002] generalized the CBTC algorithm from 2D to 3D to preserve connectivity. Basically, each node $u$ increases its transmission power until there is no empty 3D cone with angle degree $\alpha$, that is, there exists at least

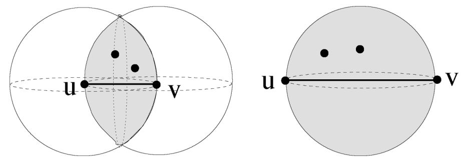


Fig. 1. 3D k-RNG (left) and 3D k-GG (right). An edge $uv$ is kept iff the shaded area has less than $k$ nodes. Here assume $k = 3$, thus $uv$ is kept.

a node in each 3D cone of degree $\alpha$ centered at $u$, if $\alpha \leqslant \frac{2\pi}{3}$. This algorithm can be extended to ensure $k$-connectivity with $\alpha \leqslant \frac{2\pi}{3k}$. Even though this approach can guarantee connectivity, the gap detection algorithm applied to check the existence of the empty 3D cone of degree $\alpha$ is very complicated. The time complexity of the gap detection algorithm at a node $u$ is $O(d^3 \log d)$, where $d$ is the node degree of $u$. Moreover, their method cannot bound node degree, as shown by Li et al. [2004a].

Similarly, Ghosh et al. [2007] also presented two CBTC-based approaches for 3D wireless networks. Though the first approach, a heuristic based on 2D orthographic projections, can provide excellent performance in practice, it cannot guarantee connectivity for sure. In the second approach, a Spherical Delaunay Triangulation (SDT) is built to determine the existence of empty 3D cones. Although the second approach can guarantee connectivity of the network, the expense to construct the SDT is very high. As a result, the second approach is not as efficient as our new proposed methods in this article (our simulation results also confirm this).

Actually, to solely achieve the connectivity of a 3D network, LMST may be the best choice, since it is very sparse and can be easily constructed even for 3D networks, and can preserve connectivity. However, LMST does not preserve the $k$-connectivity and can have a very large power stretch factor.

## 4. 3D FAULT-TOLERANT TOPOLOGY CONTROL

Most of the existing 3D topology control methods either cannot support fault tolerance [Bahramgiri et al. 2002; Wang et al. 2008a; Ghosh et al. 2007] or rely on some complex construction method [Bahramgiri et al. 2002]. In this section, we propose several simple localized topology control methods which guarantee to preserve the $k$-connectivity.

### 4.1 3D k-RNG and 3D k-GG

The first two localized structures are based on 3D RNG and 3D GG. The definitions of 3D k-RNG and 3D k-GG are as follows: An edge $uv \in RNG^k_{3D}$ iff the intersection of two balls centered at $u$ and $v$ with radius $\|uv\|$ contains less than $k$ nodes from the set $V$; an edge $uv \in GG^k_{3D}$ iff the ball with edge $uv$ as a diameter contains less than $k$ nodes of $V$. See Figure 1 for illustrations.

Based on their definitions, 3D k-RNG and 3D k-GG can be easily constructed using 1-hop neighbors' position information only. Thus, the message complexity of the topology control protocol is $O(n)$, where $n$ is the total number of nodes.

Notice that all of these message exchanges are for learning the positions of 1-hop neighbors. There is no additional message exchange needed after each node learns its 1-hop neighbors via periodic beacon messages. To check whether a neighbor $w$ is inside the shaded areas, node $u$ can simply check whether $\|uw\| < \|uv\|$ and $\|wv\| < \|uv\|$ for k-RNG or $\|uw\|^2 + \|wv\|^2 < \|uv\|^2$ for k-GG. Therefore, the time complexity of the topology control protocol at each node is $O(d)$, where $d$ is the number of neighbors at that node.

Now we prove both 3D k-RNG and 3D k-GG can preserve the $k$-connectivity.

THEOREM 1. *The structures $RNG^k_{3D}$ and $GG^k_{3D}$ are k-connected if the UBG G is k-connected, that is, both $RNG^k_{3D}$ and $GG^k_{3D}$ can sustain $k-1$ node faults.*

PROOF. We first prove the theorem for 3D k-RNG. Given a set $S$ of $k-1$ nodes, $S \subset V$, due to the $k$-connectivity of $G$, we know that $G - S$ is still connected. To prove $RNG^k_{3D}$ is $k$-connected, we prove that $RNG^k_{3D} - S$ is connected by contradiction.

Assume that graph $RNG^k_{3D} - S$ is not connected, then, there must exist at least a pair of nodes such that there is no path between them. Let the nodes $u$, $v$ be the pair with the smallest distance to each other , that is, $\|uv\| \leq \|u'v'\|$ for any pair of nodes $u'$, $v'$ that are not connected. Since $uv \notin RNG^k_{3D} - S$, $uv \notin RNG^k_{3D}$. According to the definition of $RNG^k_{3D}$, there should be at least $k$ neighbors $w$ of node $u$ that satisfy the condition $\|uw\| < \|uv\|$ and $\|wv\| < \|uv\|$. Assume the removed $k-1$ nodes are neighbors of node $u$, then there is at least one neighbor $w$ left in $RNG^k_{3D} - S$ with $\|wv\| < \|uv\|$. As nodes $u$, $v$ comprise the pair with the smallest distance among those disconnected pairs in $RNG^k_{3D} - S$, nodes $w$, $v$ must be connected. Therefore, nodes $u$, $v$ are also connected via $w$, which is a contradiction to the assumption. Thus, $RNG^k_{3D} - S$ is connected, and $RNG^k_{3D}$ is $k$-connected. Note that for the case where removed nodes are not all neighbors of $u$, the proof also holds.

The previous proof using contradiction can be easily adopted for 3D k-GG. Again, assume $GG^k_{3D} - S$ is not connected. We can also find $u$, $v$, which are the disconnected node pair with the smallest distance to each other. Since $uv \notin GG^k_{3D} - S$, $uv \notin GG^k_{3D}$. As a result, there must be at least $k$ neighbors $w$ of node $u$ inside the ball with edge $uv$ as a diameter. After removing $k-1$ neighbors of node u, there must be at least one neighbor $w$ of $u$ left. Since $\|wv\| \leq \|uv\|$, $w$ and $v$ are connected. Thus, $u$ and $v$ are connected, which is a contradiction. Therefore, $GG^k_{3D} - S$ is connected, and $GG^k_{3D}$ is $k$-connected. □

Considering the power efficiency of routes in 3D networks, 3D k-RNG is not a power spanner for UBG. The counterexample given by Li et al. [2001b] for the 2D case can be a special case in 3D space. Thus, here we only prove the power efficiency for 3D k-GG.

THEOREM 2. *The structure $GG^k_{3D}$ is a power spanner of UBG with spanning ratio bounded by one.*

PROOF. According to Wang et al. [2008a], $GG^1_{3D}$ is a power spanner of UBG with the power stretch factor of one. From the construction of $GG^k_{3D}$, it is easy to know that $GG^1_{3D} \subseteq GG^k_{3D}$, with $k > 1$, as a result, $GG^k_{3D}$ is also a power spanner of UBG with spanning ratio bounded by one. □

This theorem shows that all links in the least energy cost paths are kept in 3D k-GG. In other words, 3D k-GG provides energy-efficient routes for routing algorithms.

Next, we consider the situation with at most $k-1$ node failures. Assume that the set of $k-1$ failure nodes is $S$ and UBG$(V, E)$ is the original communication graph. We use UBG* to represent the communication graph without failure nodes and links, namely, UBG* $= G(V-S, E-\{uv|u \in S \text{ and } v \in S\})$. Similarly, $GG^{k*}_{3D}$ is the graph that removes all failure nodes and links from 3D k-GG. We can prove the following theorem on the power efficiency of 3D k-GG.

THEOREM 3. *The structure $GG^{k*}_{3D}$ is a power spanner of UBG* with spanning ratio bounded by one even with $k-1$ node failures $S$.*

PROOF. Basically, we need to prove that every link on the least energy cost paths in UBG* is kept in $GG^{k*}_{3D}$. We prove this by contradiction. Consider any link $uv$ in any least energy cost path in UBG*. Assume that $uv \notin GG^{k*}_{3D}$, thus $uv \notin GG^k_{3D}$. By the definition of $GG^k_{3D}$, there must be at least $k$ neighbors of node $u$ inside the ball $B$ with edge $uv$ as a diameter. After removing $k-1$ failure nodes $S$, there must be at least one neighbor left and let us assume it as $w$. Since $w$ is inside ball $B$, $\|uw\|^2 + \|wv\|^2 < \|uv\|^2$. Remember $\beta > 2$, thus $\|uw\|^\beta + \|wv\|^\beta < \|uv\|^\beta$. In other words, the path using $uw$ and $wv$ costs less energy than the path using $uv$. This is a contradiction. It implies that the assumption is wrong, that is, that edge $uv$ remains in $GG^k_{3D}$ and $GG^{k*}_{3D}$. □

It is easy to show that both 3D k-RNG and 3D k-GG cannot bound node degree. Assume that a node $u$ has a large number of neighboring nodes on the surface of its transmission ball. In both 3D k-RNG and 3D k-GG, these neighboring nodes are all kept by $u$, thus $u$ will have a large node degree.

### 4.2 3D k-YG

Since both 3D k-RNG and 3D k-GG cannot bound node degree, we are also interested in constructing a fault-tolerant Yao graph for 3D networks.

In 2D networks, the Yao graph is defined as follows: At each node $u$, any $p$ equally separated rays originating at $u$ define $p$ cones. In each cone, only the shortest edge $uv$ among all edges emanated from $u$, if there is any, is kept. The node out-degree of the Yao graph is bounded by constant $p$. However, the Yao graph cannot be directly extended to 3D, while RNG and GG can. It is hard to define a fixed partition boundary of a Yao structure of a node in 3D. Notice that a disk in 2D can be easily divided into $p$ equal cones which do not intersect with each other, while in 3D case, it is impossible to divide a ball into $p$ equal 3D cones without intersections among each other. Therefore, here we use equal-sized 3D cones which are defined by neighbors' positions and can intersect with each other. Fortunately, we can prove that the number of such cones used in our protocol is still bounded by a constant.

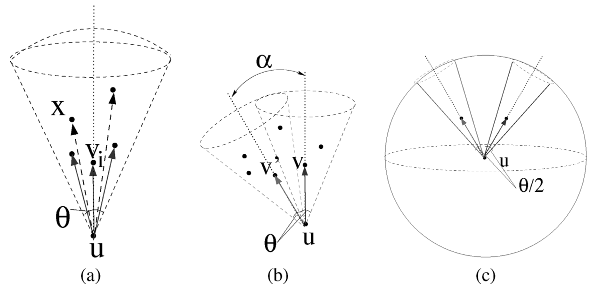


Fig. 2. Illustrations of fault-tolerant 3D Yao Graph: (a) $k$ shortest links kept in one cone; (b) and (c) bounded node degree by a volume argument.

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**Algorithm 1.** Construct Fault-Tolerant 3D Yao Structure $YG^k_{3D}$ for Node $u$.

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(1) $u$ collects the positions of its neighbors $N_1(u)$ in UBG.
(2) Sort all neighbors $v_i \in N_1(u)$ by its length such that $\|uv_i\| \leq \|uv_{i+1}\|$, where $i = 1$ to $d$. Here $d$ is the number of neighbors.
(3) Set PROCESSED($v_i$) $= 0$ for all neighbors $v_i \in N_1(u)$.
(4) **for** $i = 1$ to $d$ **do**
(5)   **if** PROCESSED($v_i$) $= 0$ **then**
(6)     In cone $C_{uv_i}$, add $k$ shortest edges from UBG in $YG^k_{3D}$. As an example shown in Figure 2(a), with $k = 3$, $uv_i$ and the other two short edges are added in the cone $C_{uv_i}$.
(7)     Set PROCESSED($x$) $= 1$ for all neighbors $x \in C_{uv_i}$.
(8)   **end if**
(9) **end for**

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Algorithm 1 illustrates our localized algorithm for a node $u$ to build the 3D k-YG. We use identical cones with a top angle $\theta$ to partition the transmission ball at node $u$, and where to define the cones depends on the locations of its neighbors. Here $\theta$ is an adjustable parameter that could be any angle smaller than $\pi/3$. Notice that these cones are identical with the same size/shape and can intersect with each other. The algorithm first orders all links $uv_i$ in terms of their lengths. Then it processes link $uv_i$ from the shortest link and follows an ascending order. When it processes $uv_i$, it defines cone $C_{uv_i}$, adds the link $uv_i$ as well as other $k - 1$ shortest links in $C_{uv_i}$, and marks all other links in $C_{uv_i}$ as *processed*. Notice that $k$ shortest links here are the $k$ shortest directional links in UBG. The final structure of 3D K-YG is a directional graph. Figure 2(a) shows an example of the algorithm when $k = 3$.

The message complexity of Algorithm 1 is $O(n)$, since each node sends only one message in line 1 including its location information. There is zero message exchange after that, unless the underlying network topology (UBG) changes. The time complexity of the algorithm is $O(d \log d)$, since sorting in line 2 can be done in $O(d \log d)$ and the "for" loop (lines 4–9) takes $O(d)$. Significantly, this is more efficient than the method in Bahramgiri et al. [2002], whose time complexity is $O(d^3 \log d)$. Although the methods in Ghosh et al. [2007] have similar order of time complexity with our method, simulation results in Section 5 show that our method outperforms theirs in terms of running time.

Now we prove some properties of $YG_{3D}^k$ in the following three theorems.

THEOREM 4. *The structure $YG_{3D}^k$ is $k$-connected if the original UBG $G$ is $k$-connected, that is, $YG_{3D}^k$ can sustain $k-1$ node faults.*

PROOF. For simplicity, assume that all $k-1$ fault nodes $v_1, v_2, \cdots, v_{k-1}$ are neighbors of a node $u$. We show that the remaining graph of $YG_{3D}^k$ after removing the $k-1$ nodes is still connected.

Notice that $G$ is $k$-connected, thus the degree of each node is at least k. Additionally, with the $k-1$ fault nodes removed, there is still a path in $G$ to connect any pair of remaining nodes. Assume that the path uses node $u$ and has a link $uw$, we will prove by induction that there is a path in the remaining graph to connect $u$ and $w$.

If $uw$ has the smallest distance among all pairs of nodes, according to Algorithm 1 $uw$ must be in $YG_{3D}^k$. Assume the statement is true for a node pair whose distance is the $r$th shortest. Consider $uw$ with the $(r+1)$th shortest length.

If $w$ is one of the $k$ closest nodes to $u$ in some cone, the link $uw$ is kept in the remaining graph. Otherwise, for the cone in which node $w$ resides, there must be other $k$ nodes which are closer to $u$ than $w$ and they are connected with $u$ in $YG_{3D}^k$. Since we have only $k-1$ failure nodes, at least one of the links of $YG_{3D}^k$ in that cone will survive, say link $ux$. As $\angle xuw < \theta < \frac{\pi}{3}$, $xw$ in triangle $xuw$ is not the longest edge. Thus, $\|xw\| < \|uw\|$, and nodes $x$ and $w$ are connected. Then link $uw$ can be replaced by link $ux$ and a path from $x$ to $w$ by induction. This finishes the proof.

Note that for the case where the nodes removed are not all neighbors of the same node, the induction proof also holds. Induction is based on all pairs of nodes. □

THEOREM 5. *The node out-degree of $YG_{3D}^k$ is bounded by $\frac{2k}{1-cos(\frac{\theta}{4})}$.*

PROOF. After node $u$ processes $C_{uv}$, it marks all links inside $C_{uv}$ as processed and those links will never be processed again. And each processed cone adds at most $k$ outgoing links in the final structure. Therefore, we only need to prove the number of processed cones is bounded by a constant $c$, then the node out-degree will be bounded by $kc$.

It's easy to prove that for any two processed cones, the angle $\alpha$ between their axes satisfies $\alpha \geq \frac{\theta}{2}$. See Figure 2(b). Assume there exists any two processed cones $C_{uv}$ and $C_{uv'}$, the angle between their axes $\angle vuv' = \alpha < \frac{\theta}{2}$. Then, $v'$ is inside $C_{uv}$ and $v$ is inside $C_{uv'}$. One of $v$ and $v'$ will be processed first. Let us assume it is $v$. Then, after adding the $k$ shortest links in Algorithm 1, $u$ will mark all nodes in $C_{uv}$ as processed, including $v'$. Therefore, $v'$ will never be processed, which is a contradiction.

Then we show that the number of processed cones is bounded by a constant. Since $\alpha \geq \frac{\theta}{2}$, the cones with $uv$ and $uv'$ as axes and with $\frac{\theta}{2}$ as top angle cannot intersect with each other. Therefore, the total number of processed cones is

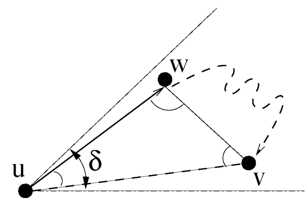



Fig. 3. Illustration of Lemma 6 for the spanner property of the Yao structure.

bounded by how many such $\frac{\theta}{2}$ cones can be put into a unit ball so that they do not intersect with each other (see Figure 2(c)). By using a volume argument, this number is bounded by $\frac{4\pi/3}{2\pi(1-cos(\theta/4))/3} = \frac{2}{1-cos(\frac{\theta}{4})}$.

Therefore, the out-degree of $YG_{3D}^{k}$ is bounded by $\frac{2k}{1-cos(\frac{\theta}{4})}$. □

Notice that $YG_{3D}^{k}$ can only bound the out-degree at each node. However, we can apply Algorithm 1 again for all incoming links in $YG_{3D}^{k}$ to bound node in-degree, same as the sparse Yao graph [Li et al. 2002] in the 2D case.

Finally, we prove a theorem which guarantees that for any pair of nodes there is at least an energy-efficient route in $YG_{3D}^{k}$. Here an energy-efficient route means the path uses at most constant time of energy than the original least energy cost path in UBG. Our proof uses the following lemma from Li et al. [2002, 2001b].

LEMMA 6. [LI ET AL. 2002, 2001b]. *The power stretch factor of the Yao-based graph is at most $\frac{1}{1-(2\sin\frac{\delta}{2})^{\beta}}$, if for every link uv that is not in the final graph, there exists a shorter link uw in the graph and $\angle vuw < \delta$, where $\delta$ is a constant smaller than $\pi/3$, as shown in Figure 3.*

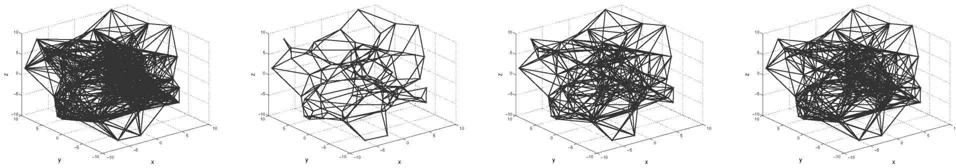
THEOREM 7. *The structure $YG_{3D}^{k}$ is a power spanner of UBG with spanning ratios bounded by a constant, $\frac{1}{1-(2sin(\frac{\theta}{2}))^{\beta}}$.*

PROOF. For a link $ux \notin YG_{3D}^{k}$, there must exist $k$ shorter links in the resulted graph. See Figure 2(a), when $k = 3$, three edges are shorter than the removed link $ux$. The angle between the removed link $ux$ and any of the $k$-shorter links is less than $\theta$. Since, $\theta < \pi/3$, by Lemma 6, the power spanning ratio of $YG_{3D}^{k}$ is $\frac{1}{1-(2sin(\frac{\theta}{2}))^{\beta}}$. □

Again, we consider the situation with at most $k-1$ node failures. Assume that $S$ is the set of failure nodes, UBG* and $YG_{3D}^{k*}$ are the communication graph without failure nodes/links and the 3D k-YG without failure nodes/links, respectively.

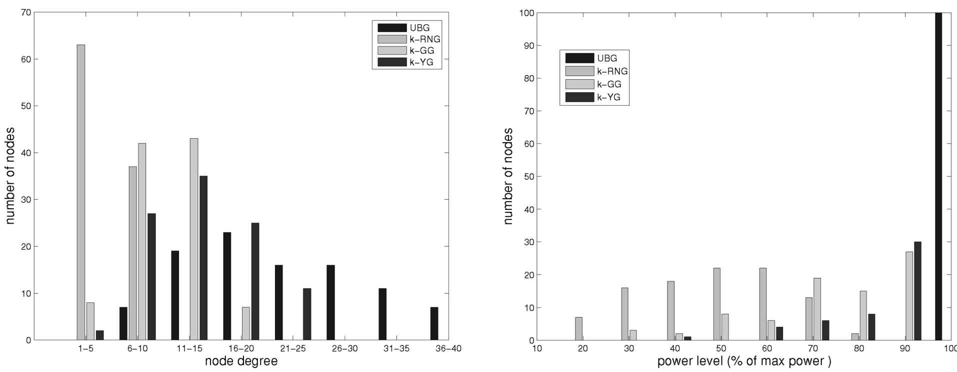
THEOREM 8. *The structure $YG_{3D}^{k*}$ is a power spanner of UBG* with spanning ratios bounded by a constant, $\frac{1}{1-(2sin(\frac{\theta}{2}))^{\beta}}$, even with $k-1$ node failures $S$.*

PROOF. For any link $ux \notin YG_{3D}^{k*}$ (also $\notin YG_{3D}^{k}$), there must exist $k$ shorter links in the resulted graph $YG_{3D}^{k}$ and $YG_{3D}^{k*}$. Thus, with at most $k-1$ node



(a) UBG (b) 3D k-RNG (b) 3D k-GG (c) 3D k-YG

Fig. 4. 3D localized topologies which are constructed from the same UBG. Here, $n = 100$, $k = 2$ and $P^{max} = R^2 = 81$.




(a) node degree (b) transmission power

Fig. 5. (a) Node degrees of the UBG and other topologies; (b) final assigned transmission power levels of nodes. Here, $n = 100$, $k = 2$ and $P^{max} = 81$.

failures, there exists at least one shorter link, say $uv$, and $\angle xuv < \pi/3$. Therefore, by Lemma 6, $YG_{3D}^{k*}$ is still a power spanner of UBG* with spanning ratios bounded by $\frac{1}{1-(2sin(\frac{\theta}{2}))^{\beta}}$. □

## 5. SIMULATIONS

In order to evaluate the performance of our 3D topology control protocols, we conduct simulations by generating random networks in 3D. In our experiments, we randomly generate a set $V$ of $n$ wireless nodes and the UBG, then test the connectivity of UBG. If it is $k$-connected, we construct different localized topologies proposed in this article, and measure the node degree as well as power efficiency of these topologies.

Figure 4 shows a set of topologies generated for a UBG with 100 wireless nodes. In the experimental results presented here, we generate $n$ random wireless nodes in a $20 \times 20 \times 20$ cube; the parameter $\theta = \pi/4$ for 3D k-YG; the fault-tolerance requirement $k = 2$; the maximum transmission range $R$ is set to 9, and the power constant $\beta = 2$, thus the maximum transmission power $P^{max} = R^2 = 81$.

For the same instance, we plotted the node degrees of different topologies in Figure 5(a). It is clear that UBG has more nodes with high node degree, while k-RNG, k-GG, and k-YG can drastically reduce node degrees. Figure 5(b)

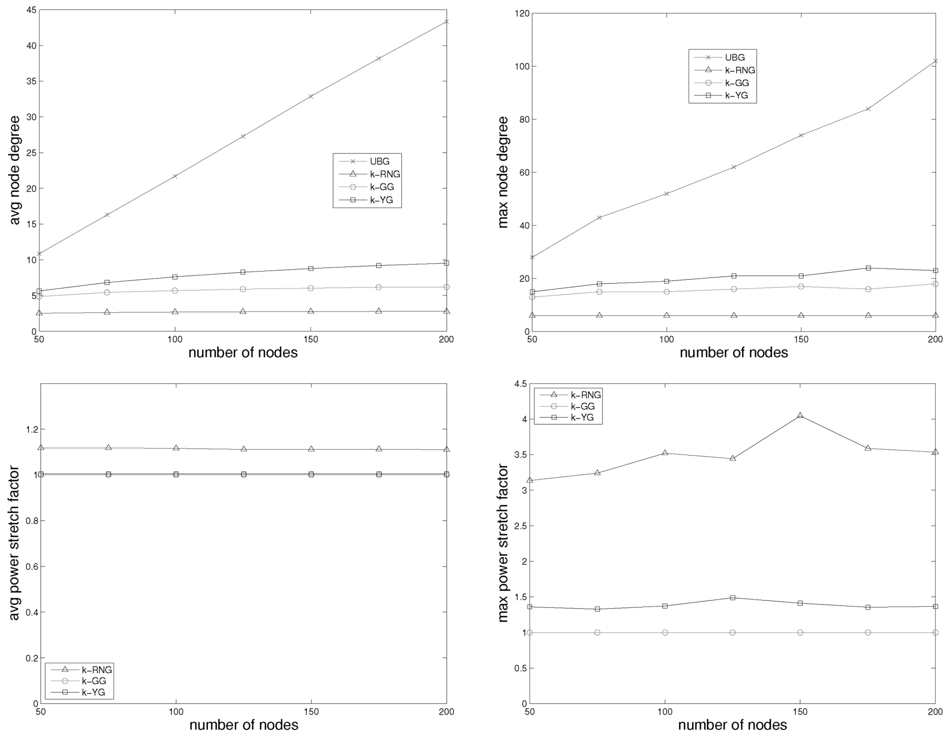



Fig. 6. Average/maximum node degree (upper row) and average/maximum power stretch factor (lower row) for $k = 1$ when the number of nodes increases.

shows the assigned minimal power levels for all the nodes. Here we assume that each node can shrink its power level to support the longest link in the generated topology. Clearly, no node needs to transmit at its maximum power level anymore in these sparse topologies. k-RNG uses the smallest power level, since it is the sparest graph. Both k-GG and k-YG can also save a lot of energy.

We then vary the number of nodes $n$ in the network from 50 to 200, where 100 vertex sets are generated for each case. The average and the maximum are computed over all these 100 vertex sets. We consider various fault tolerance requirements: $k = 1, 2, 3$. All experimental results are plotted in Figures 6 through 8 for $k = 1, 2, 3$, respectively.

The average node degree of wireless networks should not be too large to avoid interference, collision, and overhead. It should not be too small either: A low node degree usually implies that the network has a low fault tolerance and tends to increase the overall network power consumption as longer paths may have to be taken. The upper rows in Figures 6 through 8 show that all localized topologies have lower degrees compared with UBG and keep small degrees when the UBG becomes denser and denser (i.e., the number of nodes in the network increases). k-RNG is sparser than k-GG, and k-GG is sparser than k-YG. These observations can also be verified by Figure 4. Notice that k-RNG

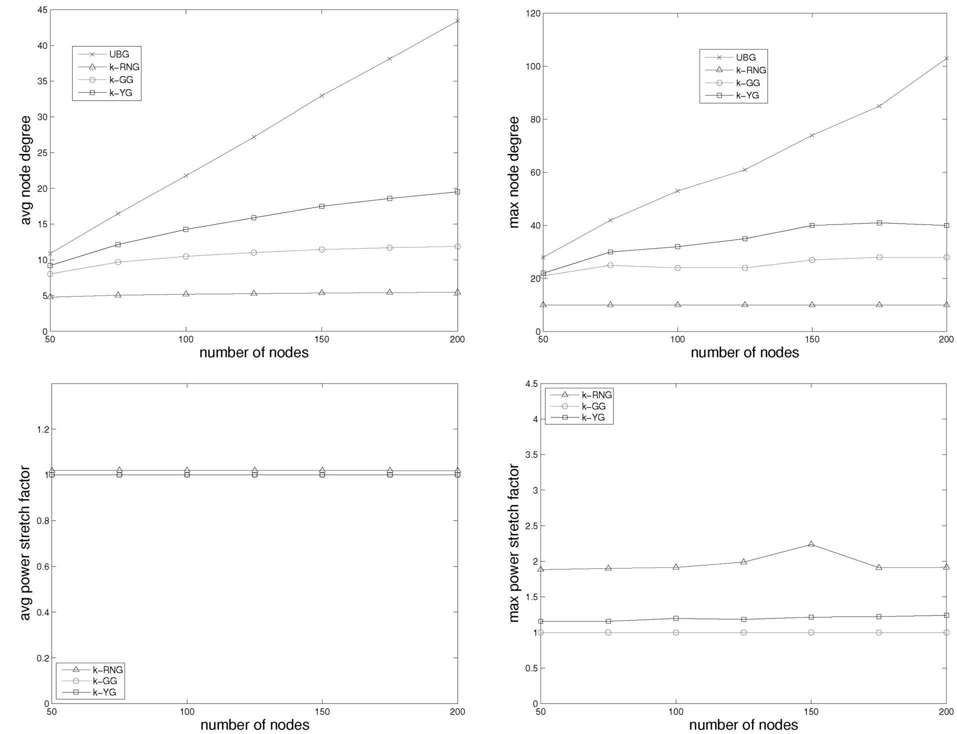



Fig. 7. Average/maximum node degree (upper row) and average/maximum power stretch factor (lower row) for $k = 2$ when the number of nodes increases.

and k-GG do not have large degrees in this experiment. The reason is that the nodes are distributed randomly in the area. In real life, the network may not be distributed randomly, and it is possible that k-RNG and k-GG have large degrees. Such examples and simulation results in 2D networks can be found in Li et al. [2002]. We also observe that a higher fault tolerance requirement $k$ will cause larger node degree in all topologies.

Besides connectivity, the most important design metric of wireless networks is perhaps power efficiency, because it directly affects both nodes and network lifetime. The lower rows in Figures 6 through 8 show that all proposed structures have small power stretch factors even when the network is very dense. Since both k-GG and k-YG have a constant power stretch factor, their average/maximum power stretch factors remain relatively stable as the network density changes. Notice that k-RNG has much higher maximum power stretch factor than k-GG and k-YG, however, it is still smaller than 5 for all values of $k$ and quite stable when $k = 3$. The reason is again that the nodes are distributed randomly in the area and the number of nodes is not too large. The worst cases of k-RNG (like the tower structures in Li et al. [2002]) with large stretch factor are never generated by our simulator. As we expected, k-GG has a power stretch factor of one and the power stretch factor of k-YG is smaller than the theoretical bound $\frac{1}{1-(2sin(\frac{\theta}{2}))^{\beta}} = \frac{1}{1-(2sin(\frac{\pi}{8}))^{2}} \approx 2.4$. Notice that for $k = 3$,

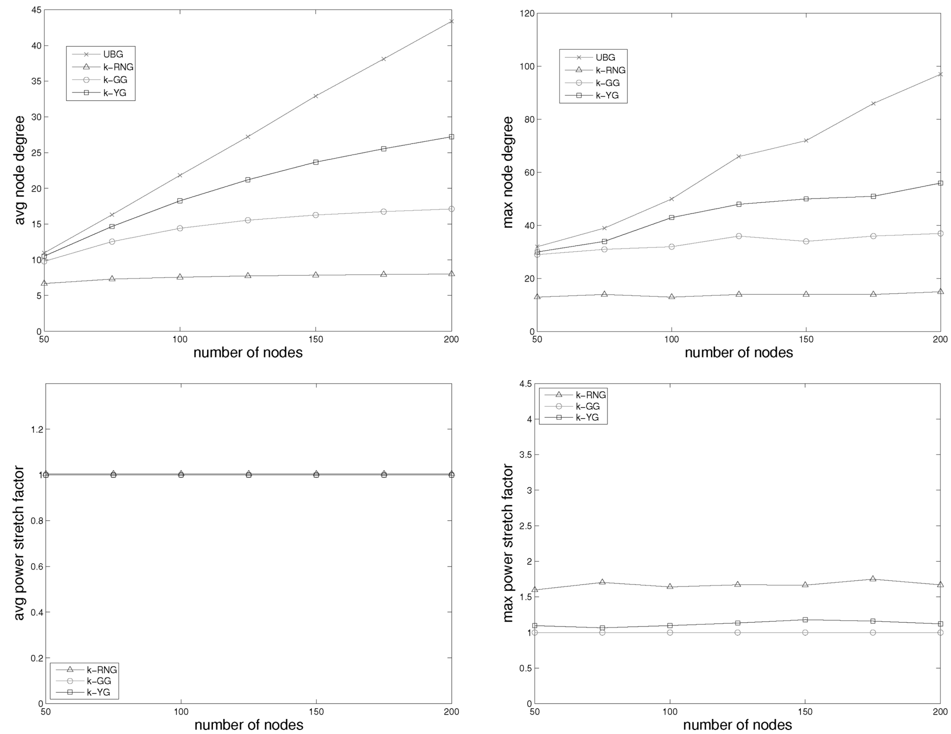



Fig. 8. Average/maximum node degree (upper row) and average/maximum power stretch factor (lower row) for $k = 3$ when the number of nodes increases.

three lines of average power stretch factors overlap. This does not indicate that the three methods tend to generate a same topology when $k$ is large. The clear differences of these topologies can still be found in plots of maximum power stretch factors and node degrees.

We also conduct simulations when the maximum transmission power $P^{max}$ is from 40 to 100. Simulation results are plotted in Figures 9 through 11. Basic conclusions from this set of simulations are coherent with previous simulation set.

Finally, we conduct simulations to compare the running time of our structures with existing 3D structures proposed in Bahramgiri et al. [2002] and Ghosh et al. [2007], even though their structures are not for fault tolerance. We construct 3D 1-RNG, 3D 1-GG, 3D 1-YG, SDT (SDT-based method in Ghosh et al. [2007]), and gap-3D$_\alpha$ (3D CBTC method in Bahramgiri et al. [2002]) for random networks with various numbers of nodes in our own simulation environment. We record the running time for each topology control method to compute its 3D structure from the original network (UBG). Figure 12(a) shows the total running time of each structure. It is clear that our structures have significant shorter running time than SDT and gap-3D$_\alpha$. In addition, all construction algorithms need more time when the network is dense. Recall that the time complexity of gap-3D$_\alpha$ at each node is $O(d^3 \log d)$, the ones of SDT

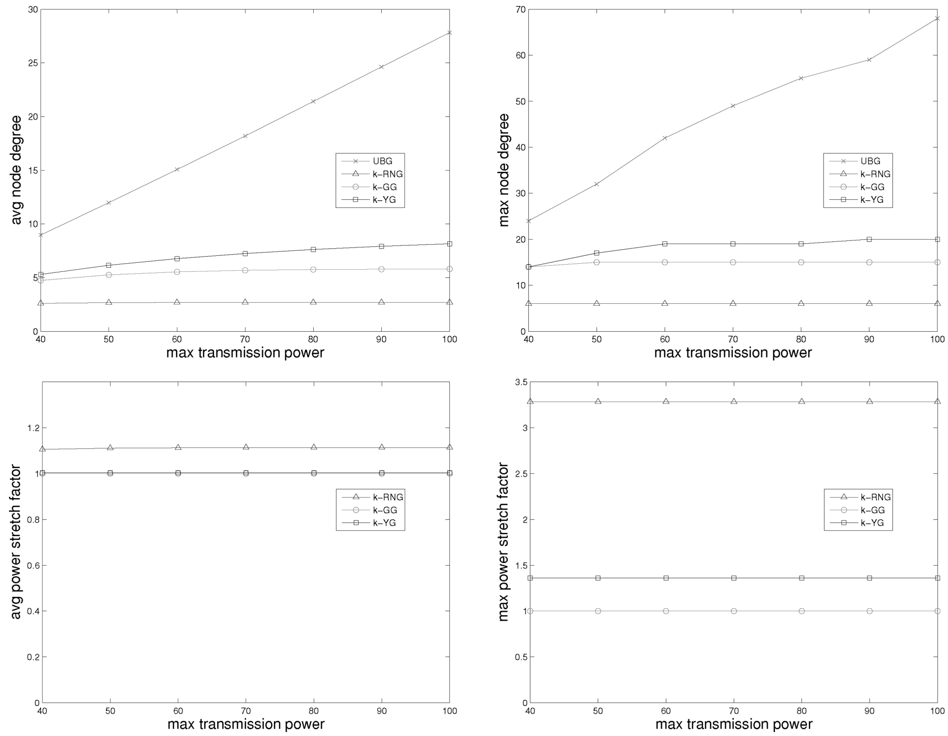



Fig. 9. Average/maximum node degree (upper row) and average/maximum power stretch factor (lower row) for $k = 1$ when the transmission power increases.

and 3D k-YG are $O(d \log d)$, while all other structures have time complexity $O(d)$. To see the difference among our three new structures, we further enlarge their running-time curves in Figure 12(b). It is also clear that 3D k-RNG and 3D k-GG cost less time than 3D k-YG, since the former do not need local ordering.

## 6. SELF-ADAPTIVE AND SELF-ORGANIZING UPDATES

Dynamic maintenance of the network topology is also an important issue, especially for large-scale mobile networks. Events that may cause the proposed structure to become obsolete include node moving, node joining or leaving, or node failure. Thus, dynamic update methods for these structures are needed. Fortunately, all proposed construction algorithms are localized algorithms which only use 1-hop neighbor information. Thus, the update process can be performed self-adaptively within a local area where the change occurs, that is, the topologies are easy to maintain locally when nodes move around.

Usually, there are two kinds of update methods: on-demand update or periodical update. Our algorithm can adapt and combine both these update methods at each individual node in a self-organizing fashion. If no major topology change occurs, no update will be performed until some preset timer expires.

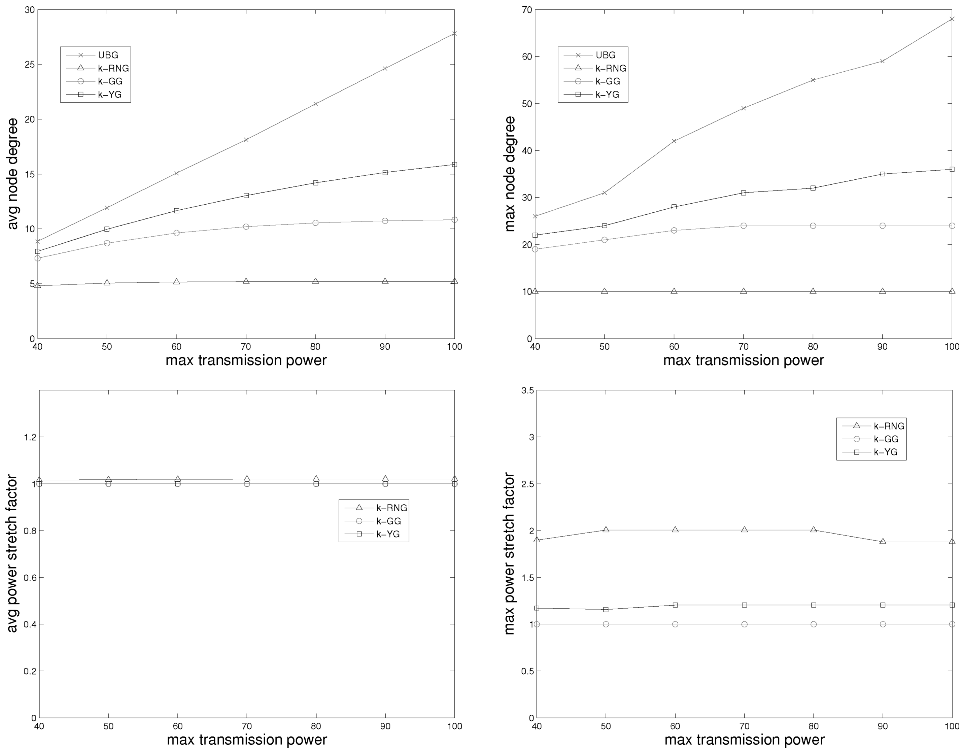



Fig. 10. Average/maximum node degree (upper row) and average/maximum power stretch factor (lower row) for $k = 2$ when the transmission power increases.

Here, nonmajor topology change means the movement of nodes does not break the geometric conditions (such as less than $k$ nodes in a ball or an intersection of two balls or a 3D cone) of the topologies. This judgment can be done in each node using only 1-hop neighbor information. For some major topology change (e.g., a high-degree node dies or a fast movement of position), an on-demand update in the local area will be performed. The nodes around the local area will adaptively update their neighbors in the constructed topology.

In summary, the proposed topologies can be: (1) self-adaptive to network environments to achieve reliable and robust performance and (2) self-organizing and scalable so that managing and maintaining costs could be minimized even in large-scale networks.

## 7. CONCLUSION

Topology control for wireless networks has been extensively studied recently and different geometric topologies were proposed to achieve the sparseness and fault tolerance. However, most of them are applied only to 2D networks. In this article, we introduce three self-organizing 3D geometric topologies (3D k-RNG, 3D k-GG, and 3D k-YG) which can be constructed locally and efficiently. We formally prove all these topologies can preserve the $k$-connectivity of the

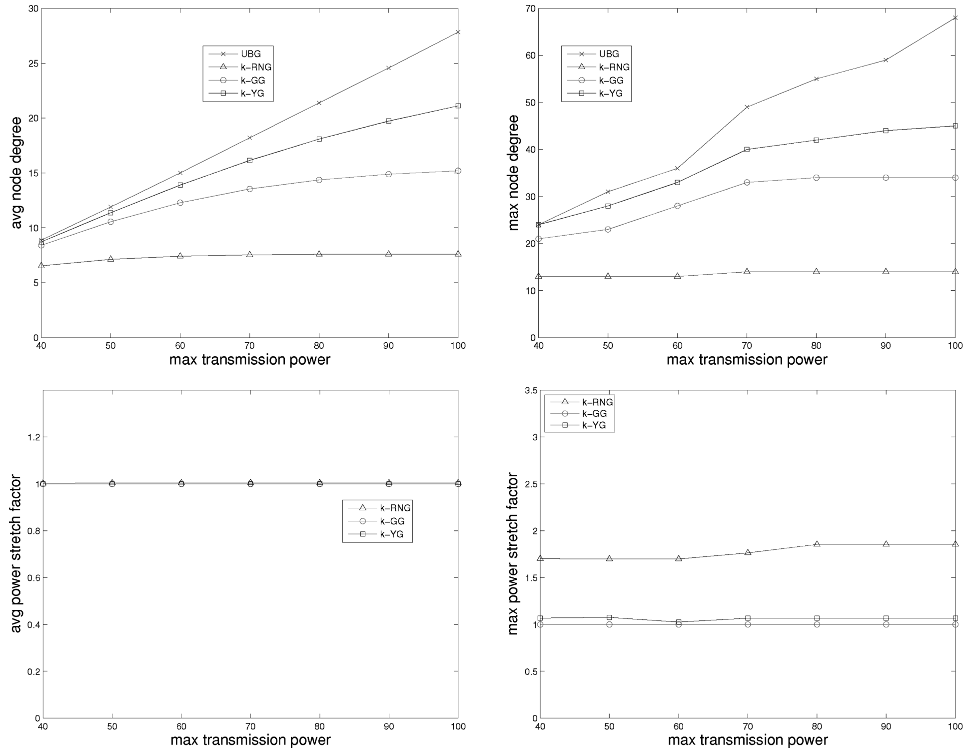
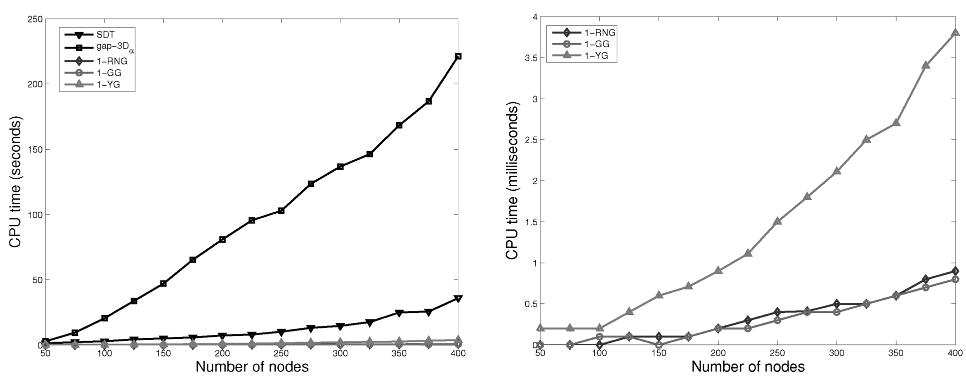



Fig. 11. Average/maximum node degree (upper row) and average/maximum power stretch factor (lower row) for $k = 3$ when the transmission power increases.




(a) (b)

Fig. 12. Running time of topology construction: (a) all 3D topologies and (b) three new topologies.

network. In addition, 3D k-GG has power stretch factor one and 3D k-YG has constant power stretch factor even with $k - 1$ node failures. Only 3D k-YG has constant bounded node out-degree. Table I summarizes the properties of all proposed and existing 3D topologies. We also conduct extensive simulations. Our results confirm the good performance of our new 3D topologies.

Table I. Property Summary for Proposed and Existing 3D Topologies

| 3D Structure | Connectivity | $k$-Connectivity | Out-Degree | Power Stretch Factor | Message | Time |
|---|---|---|---|---|---|---|
| *3D LMST* | yes | no | $O(1)$ | $O(n)$ | $O(n)$ | $O(d^2)$ |
| *3D SDT* | yes | no | $O(n)$ | $O(1)$ | $O(n)$ | $O(d \log d)$ |
| *gap-3D*$_\alpha$ | yes | no | $O(n)$ | $O(1)$ | $O(n)$ | $O(d^3 \log d)$ |
| *3D k-RNG* | yes | yes | $O(n)$ | $O(n)$ | $O(n)$ | $O(d)$ |
| *3D k-GG* | yes | yes | $O(n)$ | 1 | $O(n)$ | $O(d)$ |
| *3D k-YG* | yes | yes | $O(1)$ | $O(1)$ | $O(n)$ | $O(d \log d)$ |

This article is the first step towards research for 3D fault tolerant topology control, and there are still a number of challenging questions left. For example, if position information is not accurate, how do we achieve fault tolerance and power efficiency of these geometric topologies?

## REFERENCES


Akyildiz, I. F., Pompili, D., and Melodia, T. 2005. Underwater acoustic sensor networks: Research challenges. *Ad Hoc Netw. 3*, 3, 257–279.

Alzoubi, K., Li, X.-Y., Wang, Y., Wan, P.-J., and Frieder, O. 2003. Geometric spanners for wireless ad hoc networks. *IEEE Trans. Parall. Distrib. Process. 14*, 4, 408–421.

Alzoubi, K. M., Wan, P.-J., and Frieder, O. 2002. Message-optimal connected dominating sets in mobile ad hoc networks. In *Proceedings of the 3rd ACM International Symposium on Mobile Ad Hoc Networking and Computing (Mobihoc)*. ACM Press, 157–164.

Bahramgiri, M., Hajiaghayi, M. T., and Mirrokni, V. S. 2002. Fault tolerant and three-dimensional distributed topology control algorithms in wireless multi-hop networks. In *Proceedings of the 11th Annual IEEE Internation and Conference on Computer Communications and Networks (ICCCN)*, 392–397.

Bao, L. and Garcia-Luna-Aceves, J. J. 2003. Topology management in ad hoc networks. In *Proceedings of the 4th ACM International Symposium on Mobile Ad Hoc Networking & Computing (Mobihoc)*. ACM Press, 129–140.

Bose, P., Morin, P., Stojmenovic, I., and Urrutia, J. 1999. Routing with guaranteed delivery in ad hoc wireless networks. In *Proceedings of the 3rd International Workshop on Discrete Algorithms and Methods for Mobile Computing and Communications*.

Cerpa, A. and Estrin, D. 2002. ASCENT: Adaptive self-configuring sensor network topologies. *SIGCOMM Comput. Comm. Rev. 32*, 1, 62–62.

Chen, B., Jamieson, K., Balakrishnan, H., and Morris, R. 2002. SPAN: An energy-efficient coordination algorithm for topology maintenance in ad hoc wireless networks. *Wirel. Netw. 8*, 5, 481–494.

Cheng, W., Teymorian, A.Y., Ma, L., Cheng, X., Lu, X., and Lu, Z. 2008. Underwater localization in sparse 3D acoustic sensor networks. In *Proceedings of the 27th IEEE Conference on Computer Communications (InfoCom'08)*.

Das, B. and Bharghavan, V. 1997. Routing in ad hoc networks using minimum connected dominating sets. In *Proceedings of IEEE International Conference on Communications (ICC'97)*. vol. 1. 376–380.

Ghosh, A., Wang, Y., and Krishnamachari, B. 2007. Efficient distributed topology control in three-dimensional wireless networks. In *Proceedings of the 4th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks (SECON)*, 91–100.

Hou, J.C., Li, N., and Stojmenovic, I. 2005. Topology construction and maintenance in wireless sensor networks. In *Handbook of Sensor Networks: Algorithms and Architectures*, I. Stojmenovic, Ed. Wiley.

Karp, B. and Kung, H. 2000. GPSR: Greedy perimeter stateless routing for wireless networks. In *Proceedings of the ACM International Conference on Mobile Computing and Networking (MobiCom)*.

LI, Y., CHENG, M.X., AND WU, W. 2005. Optimal topology control for balanced energy consumption in ad hoc wireless networks. *J. Parall. Distrib. Comput. 65*, 2, 124–131.

LI, L., HALPERN, J. Y., BAHL, P., WANG, Y.-M., AND WATTENHOFER, R. 2001a. Analysis of a cone-based distributed topology control algorithms for wireless multi-hop networks. In *Proceedings of the ACM Symposium on Principle of Distributed Computing (PODC)*.

LI, N. AND HOU, J. C. 2004. FLSS: A fault-tolerant topology control algorithm for wireless networks. In *Proceedings of the 10th Annual International Conference on Mobile Computing and Networking (MobiCom)*. ACM Press, 275–286.

LI, N., HOU, J. C., AND SHA, L. 2003. Design and analysis of a MST-based topology control algorithm. In *Proceedings of the 22nd Annual Joint Conference of the IEEE Computer and Communications Societies (InfoCom)*.

LI, X.-Y., WAN, P.-J., AND WANG, Y. 2001b. Power efficient and sparse spanner for wireless ad hoc networks. In *Proceedings of the IEEE International Conference on Computer Communications and Networks (ICCCN'01)*. 564–567.

LI, X.-Y., WAN, P.-J., WANG, Y., AND FRIEDER, O. 2002. Sparse power efficient topology for wireless networks. In *Proceedings of the 35th IEEE Hawaii International Conference on System Sciences (HICSS)*.

LI, X.-Y., WAN, P.-J., WANG, Y., YI, C.-W., AND FRIEDER, O. 2004a. Robust deployment and fault tolerant topology control for wireless ad hoc networks. *J. Wirel. Comm. Mobile Comput. 4*, 1, 109–125.

LI, X.-Y., WANG, Y., AND SONG, W.-Z. 2004b. Applications of k-local MST for topology control and broadcasting in wireless ad hoc networks. *IEEE Trans. Parall. Distrib. Syst. 15*, 12, 1057– 1069.

SCHURGERS, C., TSIATSIS, V., AND SRIVASTAVA, M. B. 2002. STEM: Topology management for energy efficient sensor networks. In *Proceedings of the IEEE Aerospace Conference*.

SEDDIGH, M., GONZALEZ, J. S., AND STOJMENOVIC, I. 2002. RNG and internal node-based broadcasting algorithms for wireless one-to-one networks. *ACM Mobile Comput. Comm. Rev. 5*, 2, 37–44.

STOJMENOVIC, I., SEDDIGH, M., AND ZUNIC, J. 2002. Dominating sets and neighbor elimination-based broadcasting algorithms in wireless networks. *IEEE Trans. Parall. Distrib. Syst. 13*, 1, 14–25.

WANG, Y. 2007. Topology control for wireless sensor networks. In *Wireless Sensor Networks and Applications*, Y. Li et al., Eds. Springer.

WANG, Y. 2008. Fault tolerant topology design for ad hoc and sensor networks. In *Handbook of Research on Wireless Security*, Y. Zhang et al., Eds., Idea Group Reference.

WANG, Y., LI, F., AND DAHLBERG, T. 2008a. Energy-efficient topology control for three-dimensional sensor networks. *Int. J. Sensor Netw. 4*, 1-2, 68–78.

WANG, F., THAI, M.T., LI, Y., CHENG, X., AND DU, D.-Z. 2008b. Fault tolerant topology control for one-to-all and all-to-one communications in wireless networks. *IEEE Trans. Mobile Comput. 7*, 3, 322–331.

WANG, Y., WANG, W., AND LI, X.-Y. 2006. Efficient distributed low cost backbone formation for wireless networks. *IEEE Trans. Parall. Distrib. Syst. 17*, 7, 681–693.

WATTENHOFER, R., LI, L., BAHL, P., AND WANG, Y.-M. 2001. Distributed topology control for wireless multihop ad hoc networks. In *Proceedings of the 20th Annual Joint Conference of the IEEE Computer and Communications Societies (InfoCom)*.

ZHANG, Y. AND CHENG, L. 2004. A distributed protocol for multi-hop underwater robot positioning. In *Proceedings of IEEE International Conference on Robotics and Biomimetics*.

ZHOU, Z., CUI, J.-H., AND ZHOU, S. 2007. Localization for large-scale underwater sensor networks. In *Proceedings of IFIP Networking*.

ZHOU, Z., DAS, S., AND GUPTA, H. 2005. Fault tolerant connected sensor cover with variable sensing and transmission ranges. In *Proceedings of the 2nd Annual IEEE Communications Society Conference on Sensor and Ad Hoc Communications and Networks*, 594–604.

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