A Dynamic Topology Control Algorithm for Wireless Sensor Networks

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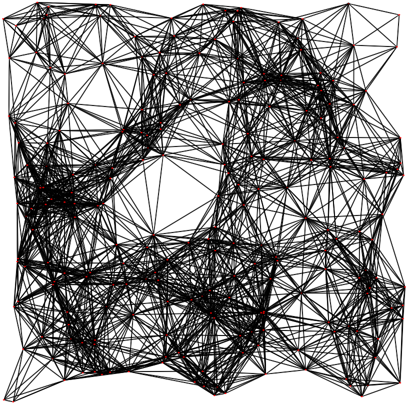
Topology Control

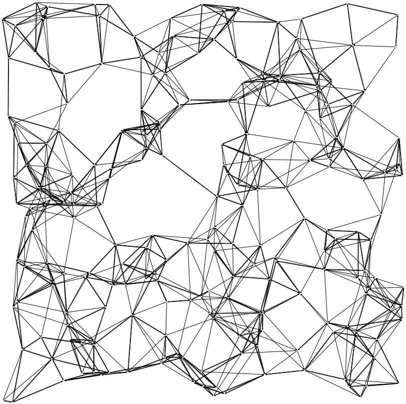
- Topology control algorithms (TCAs) for wireless sensor networks
  - dynamically form a graph representing communication network to be used by applications
  - while maintaining local and global graph properties such as
    - high link qualities
    - low node degree,
    - k-connectedness,
    - small diameter
- TCAs aim at reduced interference, less energy consumption, and increased network capacity

☛ Essence: TCAs perform a deliberate choice on each node's neighbors (physical topology is thinned out)

Topology Control



Original Topology



Controlled Topology

Topology Control Algorithms

- TCAs based on transmission power control
  - Raising transmission power
    - increases number of direct communication partners
    - reduces number of concurrent transmissions
- Many TCAs disregard
  - limited resources in WSNs
  - disregard fluctuations over time, i.e., they keep a computed topology forever

☛ Agility and stability of TCA have important influence of QoS for applications

Existing Work

	New	RETC[5]	EELTC[17]	STC[14]	CONREAP[8]	LEEP[4]	XTC[18]
Distributed	YES	YES	NO	YES	NO	YES	YES
Dynamic	YES	YES	NO	NO	NO	YES	NO
Stable	YES	NO	YES	YES	YES	NO	YES
Agile	YES	YES	NO	NO	NO	YES	NO
Memory depends on Δ	NO	YES	-	YES	-	NO	YES

Notation

- Model: Undirected graph $G(t) = (V, E(t))$
  - $E(t)$ set of edges at time t
  - $(u, v) \in E(t)$ iff u and v can communicate directly at time t
- TCA dynamically computes subgraph $G_c(t) = (V, E_c(t))$ of $G(t)$
  - $E_c(t) \subseteq E(t)$

☛ TCA aims to *smoothly* update $E_c(t)$ such that a list of criteria are maximized while avoiding oszillation

Criteria for $G_c(t)$

1. Link quality
   - $Q(e) \geq Q_{min}$ for each $e \in E_c(t)$ and any time t
2. Symmetry
   - Bidirectional communication
3. Connectivity
4. Bounded degree
   - Each node in $G_c(t)$ should have at most C_N neighbors regardless of the size of V or $E(t)$
5. k-Spanner
   - Distance between two nodes in $G_c(t)$ should be at most k-times the corresponding distance in $G(t)$
   - ☛ More practical criterion: Minimize average length of paths between any pair of nodes

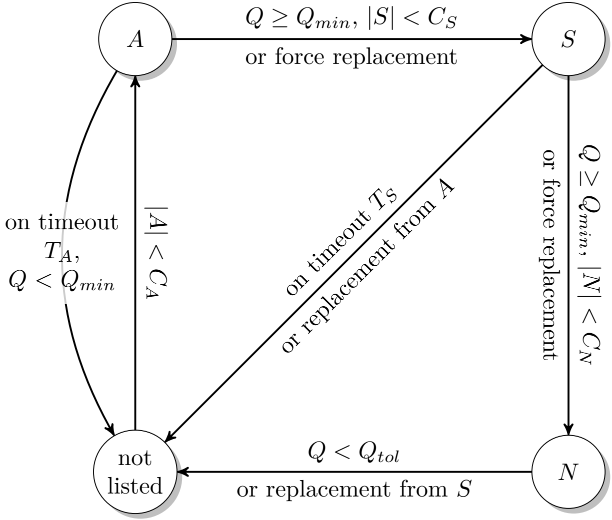
Criteria for $G_c(t)$

6. Stability
   - If $e \in E_c(t_0)$ and $Q(e) \geq Q_{min}$ at time t_0 then e should remain in $E_c(t)$ for at least $t \in [t_0, t_0 + T_N]$
   - e should remain in $E_c(t)$ for $t \geq t_0$ as long as $Q(e) \geq Q_{min}$ and other criteria are fulfilled
7. Agility
   - If $E_c(t)$ does not satisfy criteria 1 to 5 and there exists $e \in E(t) \setminus E_c(t)$ that can improve one criterion then include e into $E_c(t)$
   - If there exist $e \in E_c(t_0)$ with $Q(e) < Q_{tol}$ then e should be discarded from E_c during $[t_0, t_0 + T_N]$.

Topology Control Algorithm

- Basis of TCA: Link quality estimator (LQE)
- LQE periodically computes for each link $e = (u, v)$ a quality value $Q(e)$
  - Only links with quality above Q_{min} are considered useful
- Each node maintains three lists of fixed size
  - N: current neighborhood
  - S: standby list
  - A: assessment list
- Membership in lists depends on above defined criteria
- Promotion: From not listed ➥ A ➥ S ➥ N
- Agility and stability is supported by time-triggered transitions among lists (timers T_A and T_S)

Topology Control Algorithm



Promoting nodes from *A* to *S*

upon *expiration of timer* T_A *for* $p \in A$ **do**
  A.remove(p);
  if $p.Q \geq Q_{min}$ **then**
    if $|S| < C_S$ **then**
      S.add(p);
    else
      $q :=$ min$_Q$ S;
      if $q.Q < p.Q$ **then**
        S.remove(q);
        S.add(p);

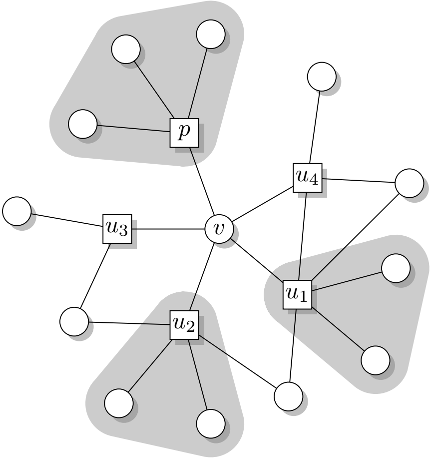
Promoting nodes from S to N

```
with Period T_N do
    for all p ∈ S in descending order do
        if p.Q ≥ Q_min then
            if |N| < C_N then
                N.add(p);
                S.remove(p);
            else
                q := replacementCandidate(N, p);
                if q ≠ null then
                    N.remove(q);
                    N.add(p);
                    S.remove(p);
```

Replacement Candidates

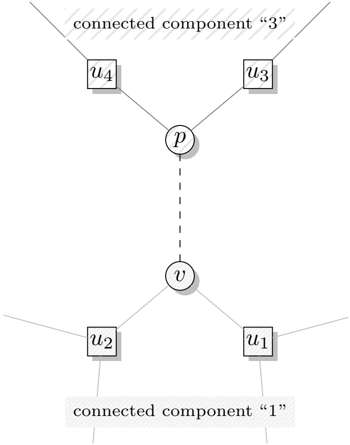
- A node $p \in S$ with $p.Q \leq Q_{min}$ replaces a node $q \in N$ if this *improves* the local topology defined by N
- Goal: Optimize criteria 1, 2, 3, and 5
- Challenge: Criteria of global nature
- Criterion 5: Minimize average path lengths
  - Each node v considers its 2-hop neighborhood C_v
  - Define $Len(X) = \sum_{w \in X} dist(v, w)$
  - Find node q such that $Len(C_v \setminus \{q\} \cup \{p\})$ is minimal
  - If $Len(C_v \setminus \{q\} \cup \{p\}) < Len(C_v)$ then replace q by p
  - Challenge: How to compute $Len(C_v \setminus \{q\} \cup \{p\})$?
    - Distributed algorithm based on weights

Minimizing Paths Length



p replaces u_4

Connectedness



From v's point of view u_1 resp. u_2 are as good as p

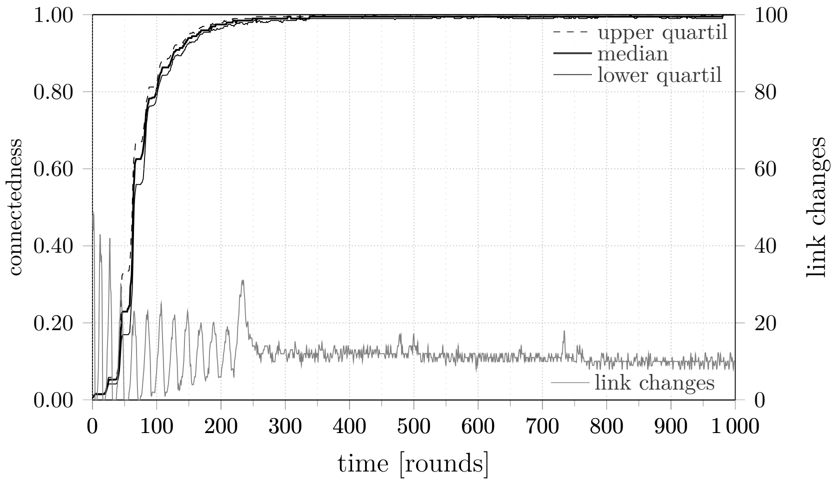
Achieving Connectedness

- Preference: A node prefers new neighbors from a different connected component
- Distributed algorithm labels nodes with the smallest identifier of node within same connected component of G_c
- Challenge:
  - Node with smallest identifier leaves component because edge is removed or failure of node
  - Solution requires knowledge of upper bound of network diameter

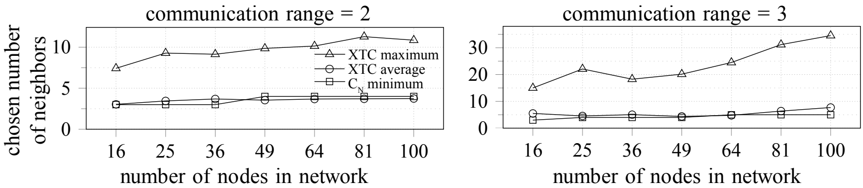
Evaluation

- Comparison with two TCAs: XTC, LEEP
- Implementation with OMNet++ and the MiXiM framework
- Regular and random node placements
- Network size and density was varied
- Used LQE: HoPS
- Node addition and removal was considered

Evaluation: Dense Setup



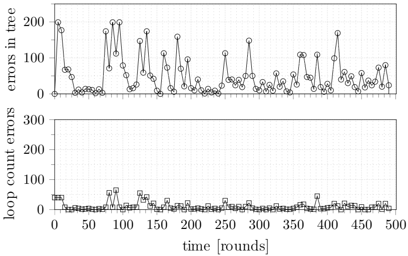
Evaluation: Comparision with XTC



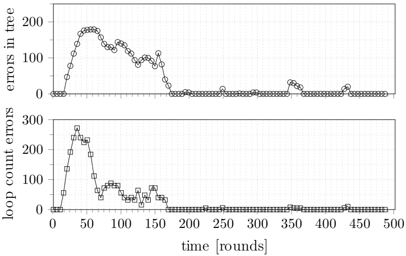
Number of required neighbors to achieve connected network

Evaluation: Comparision with LEEP

Execution of a spanning tree algorithm on top of LEEP and proposed TCA



LEEP



Proposed TCA

Summary

- Novel dynamic TCA
- Goal: Optimizing global properties of topology while keeping number of neighbors bounded
- Small footprint
- Simulations show that TCA provides a good compromise between agility and stability
- Proposed TCA is used as basis for a self-stabilizing publish subscribe system

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