Sensors & Transducers, Vol. 170, Issue 5, May 2014, pp. 122-131

Sensors & Transducers

http://www.sensorsportal.com

A Quality-Aware Relay Node Placement Algorithm to Connect Disjoint WSN Segments with Topology Reorganized

[*] Zheng Zimu, Huang Zhiwei, Li Zhicheng, Peng Xinyi
South China University of Technology, Higher Education Mega Center South, Guangzhou, Guangdong Province, 510006, China
[*] Tel.: (+86)15889941925
[*] E-mail: zeedmood@hotmail.com

Received: 27 February 2014 /Accepted: 30 April 2014 /Published: 31 May 2014

Abstract: Connecting numerous separate parts can be indispensable to simply WSNs that operate autonomously or partitions of a single segmented WSN. Linking them is subject to different intersegment quality of communication and service (QoC and QoS) while relay nodes are deployed with their exact number and positions left to define, which is the problem that we focus on. Finding the optimal number and position of relays is NP-hard and therefore heuristics and approximation are pursued. This paper presents an effective approach to deploy appropriate relays to satisfy both the QoC and QoS requirements by introducing probabilistic topology control. The key idea is to regulate a new parallel rule and cost function for segments, which eventually maximizes the utilization of deployed node and avoids the deployment of additional relays as much as possible. The optimization problem is then mapped to finding the path that fulfills the both requirements together with least overheads. The experimental result is validated that although the number of relays is slightly increased to meet extra requirements, the network connectivity can be improved by up to 289.5 % with reorganized topology. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Wireless Sensor Network, Relay node placement, Topology recovery, Probabilistic topology control, Quality-aware.

1. Introduction

After decades of research, deployment techniques of Wireless Sensor Network (WSN) now become more and more refined, heading out to various applications in real world. The network nodes are expected to form a network in order to share data and coordinate their actions when participating in the execution of tasks.

However, in these situations, the whole network may get segmented into disjoint sub-networks during establishing process or by damage. A connecting algorithm can be very critical in these fields.

Network establishing examples can be seen in smart buildings. Those who deploy sensor nodes often have a sense about where and what to detect. But the problem is, after they populate sensors on where they'd love to, the resulting networks are often segmented due to long distance between nodes, barriers in practical environments or limitation of transmitter modules. As a result, nodes fail to construct a complete network and will operate abnormally. Therefore, the key to meet their very need is to reconnect the "broken" network and even enhance it from an original one.

As for damage, it can emerge in a battle field, where parts of the deployment area may be attacked. A large set of sensor nodes in the vicinity get broken down by explosives [11] or simply because of hardware malfunction during long term utilization.

Moreover, a connecting algorithm also obliges when distinct networks momentarily need to collaborate with each other. Related applications can be to effectively search for survivors, assess damage and identify safe escape paths [2], etc.

In these situations, we face the relay node placement problem and a definition is provided below: Given a segmented wireless network G and a set of possible relay positions P, this problem is to fulfill both QoC and QoS requirements such that the node in the induced topology is connected after a certain number of relay nodes deployed.

The key to the problem lies in satisfaction of distinct per-link quality requirements, such as reachability, packet reception rate, bandwidth, etc. When connecting WSNs, there is a transitional region that can probabilistically connect a pair of nodes. Such pairs of nodes are not fully connected but reachable via the so-called lossy links. These links oblige with a higher energy efficiency and larger network capacity, which allows a transmitter to connect more nodes if a transmission succeed.

The main contributions of this paper are twofold:

- We detail the cost function with both Quality of Communication (QoC) and Quality of Service (QoS). By introducing these concepts, not only either of their features can be better researched and utilized, but also their weight ratios are able to be adjusted flexibly according to different applications. On that purpose, probabilistic topology control is used in QoC related computing.
- Based on the detailed cost function, we propose a centralized relay placement algorithm to connect segmented network considering both node number and locations. Although node number is slightly more than before due to fulfillment of QoC requirement, nodes are connected with much better fault tolerance and QoS requirements are ensured.

QoC reflects the network performance in terms of reachability, e.g. PRR, Packet Reception Rate. QoS denotes the network capacity provided by established and connected network links, e.g. bandwidth, which may be real-time dynamic changed according to the application contributed by this segment. Thus, the goal of our problem would be to associate the separate segments by establishing proper links and managing complete network topology which ultimately meets the inter-segment quality of communication and capacity requirements.

In terms of topology cognitive detecting methods, they aim to detect the quality of links in local environment. A candidate set of relay nodes can be planed and populated beforehand, in order to detect the network connectivity between nodes and disjoint sub-networks. As for topology generating methods, they satisfy desired topology, which refers to the management of every node parameters such as degree of connectivity of the network, transmission power, channel to communicate, state, or role of the nodes, etc. By managing these parameters, nodes can discover and change their link status to other ones, resulting in the total improvement of whole network topology. In this paper, what topology to establish is discussed and the consideration of concrete generating methods is left for future work, in terms of topological detection and construction.

Assume that sensor nodes have no mobility while RNs can be populated to link the segments. The number of relays should be cut down, if the cost and overhead during the deployment of the additional nodes are measured. However, it is already NP-hard for the placement problem addressed in this paper, which explores the minimal count of RNs connecting all segments, even without any consideration of QoC and QoS goals [3-4]. With such restrictions, we developed an optimized approach, which is multi-round threshold-based instead of computing the accurate value, as quality of communication and capacity aware relay nodes placement algorithm (CSR).

CSR pursues centralized greedy heuristics and opts to reduce the relay count required for establishing a segment-connected topology that meets the desired QoC and QoS goals. CSR models the target area as a grid of cells. The problem with this model is then mapped to spotting the cells that ought to be populated with relays, through which the total number of situated RNs is reduced and the goals are met. CSR also innovates a cost function based on both the connectivity performance and residual capacity of deployed nodes. The algorithm then endeavors to obtain path, which costs the least, between segments that meets the desired QoC and QoS meanwhile maximizing the contribution of the placed RNs. We also regulated a parallel rule to measure the connectivity of the whole network during inter-segment federation. Finally, every node can granularly applies certain topology generating method, such as increasing its transmission power, until targeted topology is assured. CSR connects the initial disjoint sub-networks, and to make desirable trade-off among coverage, connectivity and resource management of WSNs.

To our best knowledge, no prior work has investigated both QoC and QoS-aware placement problem of relays in a segmented WSN.

This paper is organized as follows: the next section describes related work in this field. Section 3 described assumption, definition and the proposed algorithm. Section 4 including a motivation example and the effectiveness of this algorithm is validated next. Finally, Section 5 concludes the paper.

2. Related Work

Two categories of approaches have been pursued in literatures for connecting segmented WSNs, both regulating deployment based on the initial one.

The first category is mobile redeployment, which proposes to vary distance of deployed nodes. The second one is called additive deployment, which manages to populate additional relay nodes to establish reachability. As a matter of fact, certain topologies are achieved according to the surrounding environment to pursue better connectivity in the both categories.

Mobility has been exploited for data delivery in sparse mobile ad hoc networks, delay tolerant networks, and partitioned sensor networks, which forms coverage holes. In the field of mobile redeployment, approaches have also been conducted to recognize these holes and reduce them by moving sensors after an initial deployment. Approaches have also been proposed in mixed sensor networks, where some nodes are mobile and others are static. Zou and Chakrabarty [5] proposed an algorithm as a sensor deployment strategy to enhance the coverage after an initial random placement of sensors. It was assumed that sensors can be moved by "virtual force", with the force's strength determined by node distance. Dirafzoon, *et al.* [6] proposed a deployment algorithm VFIPO which combines individual particle optimization (IPO) with virtual force (VF) algorithm. Wimalajeewa and Jayaweera [7] proposed a mobility protocol for mobile node navigation in a hybrid sensor network comprising both static and mobile nodes to improve the dynamic coverage. Xirong Bao, *et al.* [8] proposed a new algorithm determining new locations on not only the combination force of attractive and repulsive ones but the coverage hole.

These algorithms are all based on the fact that nodes can be mobile or at least part of them can. However, there are circumstances under which the location of nodes needs to be fixed, because of definite transmit radiuses, sensing ranges and numerous surrounding barriers, etc. Mobile redeployment approaches are not allowed in these cases.

Confronted with these two circumstances, another approach is to deploy relays to federate segments, instead of moving populated nodes. A Cell-based Optimized Relay node Placement (CORP) algorithm is proposed by Lee and Younis [9]. CORP works in rounds and does not only manage to link distinct sub-networks, but also attempt to minimize the number of relay nodes. The approach also cuts redundant relay nodes, after all segments are linked. Its further improved algorithm, which is named QRP [10], operates greedy heuristics to also deploy the least number of relay nodes in order to federate the disjoint segments. Linking these segments may be subject to different inter-segment QoS and moreover QRP is the first approach to meet QoS requirements between every pair of two segments. Recently, a more effective algorithm, which is called EQAR [11], opts to form a connected topology using the least number of relays while meeting inter-segment capacity constraints. These approaches all simply treat the link reachability as a variable in Boolean: connected (valued 1) or not (valued 0). However, in practical environments, pairs of nodes can be not fully connected but reachable lossy links [12]. In fact, these links allow a transmitter to not only connect more nodes but also produce a better topology. According our experiments, the performance of EQAR could be improved considering lossy links.

3. The Proposed Algorithm and Methods

3.1. Assumptions

In this paper, we assume that:

1. The WSN is segmented into several parts. Every one of them operates independently and needs to collaborate to perform a task.
2. All the sensors can well perform their transmit function and coverage their monitoring area.
3. The sensors in each segment have the same protocol stack and they can be inter-operated after the federation.
4. The segments are owned and operated by the same authority or different authorities and are to be connected in an ad hoc manner to perform some common task due to the lack of infrastructure based backbone that allows communication among these segments.
5. Sensor nodes have no mobility.
6. Only one representative node is defined for each segment. Representative node is defined as, for each segment i whose location denotes the position of the segment.

3.2. Preliminary

Before measuring the pair-to-pair node reachability, we first introduce the corresponding concepts. Given a source node called s and a destination node called d in G, the probability that s has at least one valid data path to d in G is denoted as the two-terminal reliability $\lambda_G(s,d)$ only when s neighbours d, otherwise $\Lambda_G(s,d)$. An equivalent definition of $\Lambda_G(s,d)$ is the probability that s can deliver a packet to d by a network-wide broadcast. Given a connected network $G(\mathrm{V},E)$, its network connectivity Λ_G is the minimal of the node-pair reachability between any pair of nodes [12], i.e., $\Lambda_G = \min\{\Lambda_G(s,d), \forall s,d \in V\}$.

So far we introduce basic connectivity issues in an already-connected network. But when it comes to disjoint sub-networks, a single value model can hardly reflect different performance of partitions. With this fuzzy concept, it will be difficult to respectively measure and meet various connectivity needs for different parts. What's worse, if there are any separated parts, whichever position the next relay node is about to be populated at, the network reachability mentioned above will come out to be constantly zero. The model also still oversee any enhance of connect possibility and topology performance carried out by relay node placement. Since the influence of topology modification should be well measured during every step in connection, the "whole network" connectivity cannot be simply extended to fit in these scenes.

For these reasons we have developed a new rule to measure the connectivity of the whole network, which may contains several distinct segments.

Rule Parallelism: let n-tuple set $\{S_1, S_2, ..., S_n\}$ denotes the n disjoint sub-networks in G, and their node-pair reachability described as $\Lambda_{G_{S1}}$ to $\Lambda_{G_{Sn}}$, respectively. Then we describe the connectivity of n segmented networks as a careful-design multi-tuple concept $\Lambda_G = \{\Lambda_{G_{S1}}, \Lambda_{G_{S2}}, ..., \Lambda_{G_{Sn}}\}$ and its values is computed as the summary of its entries, i.e., $\Lambda_G = 1-(1-\Lambda_{G_{S1}})(1-\Lambda_{G_{S2}})...(1-\Lambda_{G_{Sn}}) = $
$= 1-\prod_{i=1}^{n}(1-\Lambda_{G_{Si}})$

When the n equals one, it means G is connected and the formula is degenerated as another proposed above. Details of its computing will be mentioned in other subsection.

3.3. Network Model

CSR constructs the monitoring area as a mesh, whose vertexes and edges stand for possible positions and links of nodes. Vertexes are identified by their row and column, like c_{00}, c_{01}, etc. A WSN is modelled as a directed graph $G(V, E)$ based on the mesh. V is a set of nodes which are deployed or are about to be, and E reflects the presence of links between nodes in V, in the area of interest.

In this paper, edges in the mesh existed between neighbouring vertexes are described as possibility ranged between 0 and 1, weighted with two ratios. The ratios denotes two kind of network performance, namely the quality of link reachability Λ (e.g., 0.3 / 0.6 = 0.5) and collective capacity of surrounding nodes $C(C_v)$ (e.g., 300 / 600 = 0.5) respectively. In general, the edge cost will be inversely proportional to both of them so that a least-cost and stable path selection would be achieved. Note that QoC (e.g., packet reception rate) and QoS (e.g. bandwidth) are linearly independent. Therefore the weight of each link is dynamically measured as formula (1) below. It is used for updating the graph, which will be detailed in the next subsection.

$$W(C_u, C_v) = \begin{cases} 0, \ \ if\ C(C_v) \geq QoS(P_{i,j}) \\ or\ \Lambda_{pre} \geq QoS(P_{i,j}) \\ \left(1-\dfrac{\Lambda_{pre}}{QoS(P_{i,j})}\right) \times \left(1-\dfrac{C(C_v)}{QoS(P_{i,j})}\right), \ \ otherwise \end{cases} \quad (1)$$

The factor Λ illustrates connectivity of the link, and a ratio like $\frac{\Lambda_{pre}}{QoS(P_{i,j})}$ is used to measure that to what extent the relay node will meet the need of surrounding link connectivity and topology, which will ultimately profit the network performance. When the ratio equals or is larger than one, it means the needs of links connectivity are all fully met and the formula is degenerate as another proposed as EQAR, only acquiring to maximize the capacity utilization of the deployed RNs.

3.4. Solution Overview

Firstly by broadcasting message over whole network reply, we compute the diameter and notify network. The selection of the node set that represent parts will be based on the hop counts between the two segments and the origin topology of deployed node. CSR prioritizes the handling of inter-segment paths by the stringency of path between disjoint parts in terms of the QoC and QoS. It is measured as the ratio of QoS to the capacity of a relay node and the estimate ratio of QoC to the reachability of an addictive node.

After information about candidates' placement analyzed, we use a variant of Dijkstra's algorithm to find the best path and RNs are redeployed. It is carried out not only hoping to connect detached parts with the least number of relay nodes, but meanwhile to achieve higher network performance than before. The network topology is reorganized based on monitoring practice results, from the real environment. The pseudocode of CSR is given later.

Algorithm 1. Quality of Communication and Service aware relay nodes placement algorithm

Input:
V, the graph of all-populate-able nodes
, the network connectivity between nodes, ∈ populated;
, the QoS demand for nodes, ∈ populated;
P(i), the representative node of each part i;
Output:
V, the organized network graph

```
1:  For all part-pair, form their representative node-
    pair, and insert them into
2:  If and, Then
3:     Sort in the decreasing order of
4:  Else if
5:     Sort in the decreasing order of
6:  Else if
7:     Sort in the decreasing order of
8:  Else
9:     Sort in the decreasing order of,
10: End If in line 2
11: For ∀ ∈, Do
```

```
12:     Set unvisited
13:     For ∀ ∈ and >, Do
14:        If is the locational neighbour of Then
15:           Insert into, into
16:              , the possibility that  connects
17:        Else
18:           0
19:        END If in line 14
20:     End For in line 13
21:  End For in line 11
22:  While there is any  in not yet processed, Do
23:     Construct an E-size-min-heap
24:     Insert into
25:     For heap H is not empty, Do
26:           the first vertex in min heap
27:        While is visited, Do
28:           call Algorithm 3 to calculate the between,
29:           Set visited
30:           For ∈ Do
31:              Call Algorithm 2 to update weight
         between and
32:              D[] D[]+W(,)
33:              Insert into min heap H
34:           End For in line 30
35:        End While in line 27
36:     End For in line 25
37:  End While in line 22
```

When it comes to path searching, CSR does not only consider the number of relay nodes, but also recalculating the topology that may change by every RN placement, with formula (1) mentioned above.

However, when CSR processes the first inter-segment paths, there is no relay node populated between the separated segments yet in the mesh and thus our formula assigns zero to $C(C_v)$ in each edge, and the value of $\left(1-\frac{C(C_v)}{QoS(P_{i,j})}\right)$ turns out to be one. Meanwhile, $\Lambda_G(s,d)(\forall s \in N_x(d), d \in V)$ is also assumed to be one, giving the best connectivity to help the surrounding nodes, in order to recognize any beneficial modification possibility during the deployment. If the origin reachability around the placing relay node is poor and a qualify link can be set up by the new one, great chance can be seen that the topology of these area will be changed, reflecting as the suddenly improve of the Λ_X .

Algorithm 2. To update the weight.

Input:

V, the graph of all-populate-able nodes

, the network connectivity between nodes, ∈ populated;

, the QoS demand for nodes, ∈ populated;

Output:

, the weight between node and

```
1:  If not populated Then
2:     ,
3:  End If
4:     Update using formula 1
```

3.5. Detail: Reachability Calculation

To establish the final deployment, node-pair reachability computing is a must when directly connectivity is changed according to the real environment. Below we will provide some examples (in Fig. 1) and show how to compute the reachability in topologies.

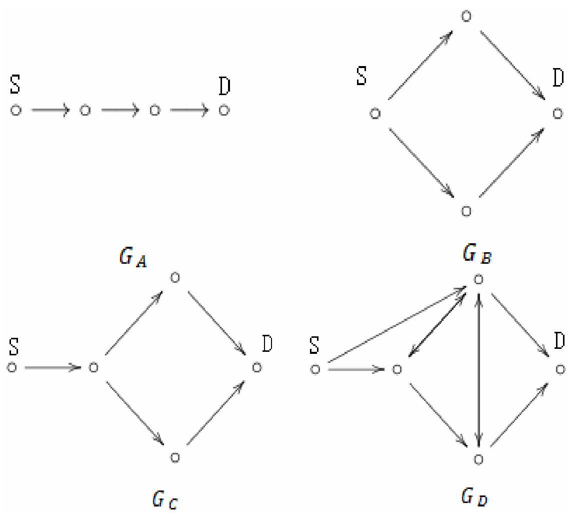

Fig. 1. Examples for transition.

There exist some particular topologies which can be computed in polynomial time. Those nodes populated all along a chain are called in series topology, e.g. Fig. 1 G_A . Then the figure $\Lambda_{G_A}(u,v)$ can be calculated- in fact all the links have the same connectivity Λ . Obviously, we have $\Lambda_{G_A}(u,v)=\lambda^3$. Parallel topology is the one with link-disjoint paths between the source and destination such as Fig. 1 G_B . These two paths both have the reachability λ^2 . By inclusion-exclusion principle in probability theory, we have $\Lambda_{G_B}(u,v)=1-(1-\lambda^2)^2$. So far, only simple assortments of series and parallel topologies can be calculated in polynomial time. These are called series-parallel topologies. For example, Fig. 1 G_C is series-parallel with $\Lambda_{G_C}(u,v)=\lambda\times(2\lambda^2-\lambda^4)$. The last topology (Fig. 1 G_D) shows a complicate one, on which the series-parallel rule cannot be directly applied. Actually, most networks are also not in series-parallel topologies and thus have to be converted into this style before further computation. Therefore, how to identify a series-parallel topology and carry out the transition is one of the key issues in the reliability theory. More recent results about reliability theory can be found in the reference [13].

As for the series-parallel conversion, there are mainly two kind of fundamental approaches. The first one is called pivotal decomposition or factoring. This technique has an exponential running time in the worst case, thus it is more qualified for small-scale applications. Another method is by approximations, instead of calculating the exact pair-to-pair connectivity. It manages to find a series-parallel sub-network instead of the original network and therefore is supposed to ensure the time efficiency of our algorithm.

Note that we opt for the second solution to simplify the calculation, using an approximated algorithm which is multi-round threshold-based, instead of a simply threshold-based or χ-approximated approach. The simply threshold-based one cut down all links whose connectivity is worse than threshold, without any computation required by reachability calculation. However, when targeted area does not provide a very well network environment and most the links are not qualified enough, this implement with a still high threshold will obviously cause serious damage for network, creating numerous network segments. In order to maintain connectivity, what we can only do is to decrease the threshold, using only one poor link and eventually, suffer from long-time delay.

The χ-approximated algorithms better the reachability management in this circumstance by sending the same message from different link paths synchronously, which better utilized the lossy links. Though more bandwidth and computing resources are required, this kind of method carried out in experiments is proved to be 250 % better than the former one in terms of connectivity [12].

Nevertheless, in order to simply the calculation, these approached only carry out computation for paths that are as long as the χ –cell distance between two nodes and the factor χ is fixed according to experience, which may not suit for any cases, cannot dynamically adapt to changing environments and oversee the improvement of connectivity that χ+1 (or more)-cell-distance paths can bring. Worse still, since not all lossy links are productive, which could be noticed in motivation examples in this paper, redundant computation and routing paths are generated by simply accept all χ (or below)-cell-distance paths.

Therefore we have developed a multi-round threshold-based algorithm. In each round, possible paths with one cell-distance longer are computed and synchronously selected. Those link paths have a lower performance of connectivity than threshold are cut and others are allowed grew until the whole reachability is satisfied.

Algorithm 3. To call the connectivity calculating function.

Input:
V, the graph of all-populate-able nodes
, the network connectivity between nodes, ∈ populated;
nodes and to calculate
Output:
The connectivity between nodes and

```
1:  For ∀ ∈ not populated, Do
2:    For ∀ ∈ not populated, Do
3:      Initial an array called productF with the
        primary and secondary index u and k to store
        temporary connectivity information,
4:      from Algorithm 4, with parameters of v, w,
        product F and 1
5:    End For
6:  End For
```

Algorithm 4. To calculate the connectivity between nodes and recursively in rounds.

Input:
V, the graph of all-populate-able nodes
, the network connectivity between nodes, ∈ populated;
, an connectivity array with the primary and secondary index u and k to store temporary information;
nodes and to calculate
, previous connectivity state
Output:
, the temporary result in recent round

```
1:   1
2:   If Then
3:
4:     Output
5:   Else if
a.     Output
6:   End If in line 2
7:   For ∈ Do
8:     If, Then
9:
10:    Else
11:
12:      If, Then
13:        the recursive result from calling the
         function itself, with parameter and
14:
15:        If, Then
16:
17:          ReserveForward(v,u,w,w)
         Δ ReserveForward (start, now, end, forward) is
         an optional function to maintain a forward table.
18:        End If in line 15
```

```
19:         End If in line 12
20:      End If in line 8
21:  End For in line 7
22:  If, Then
23:
24:      ReserveForward (v,v,w,w) Δoptional.
25:  End if in line 22
26:
```

4. Examples, Experiments and Discussion

4.1. Motivation Example

In this section, a simple example is given to further illustrate the idea of CSR (Fig. 2). There are totally six nodes from two sub-networks in graph G, namely v_0, v_1, v_2 from sub-network S and v_3, v_4 from sub-network D. Dashed lines denote wireless links, labelled with the link connectivity quality, which can be measured by PRR, namely Packet Reception Rate. In this example, the representation node as data source is set as v_0, i.e., $v_{T_x} = v_0$. Candidate relay nodes can be set at solid positions r_0, r_1, r_2, r_3 in Fig. 2. Note that residual capacity provided by these relay nodes are the same.

First CSR will measure the performance of the origin networks in G. According to probability theory, there are two exclusive paths between v_0 and v_1 and the links in path $v_0 - v_2 - v_1$ are inclusive. Thus the connectivity quality of v_0 and v_1 is $\Lambda_{G(v_0,v_1)} = 1-(1-0.4)(1-0.5\cdot 0.1) = 0.43$ Similarly we have: $\Lambda_{G(v_0,v_2)} = 1-(1-0.5)(1-0.4\cdot 0.1) = 0.52$. The network reachability of sub-network S is $\Lambda_{G_s} = \min(0.43, 0.52) = 0.43$. Since D doesn't connect to v_0, its reachability is 0. Therefore, we have the whole origin network reachability $\Lambda_G = 1-(1-\Lambda_{G_s} c \Lambda_{G_D}) = 0.43$

In traditional QoC-overlook algorithms, like EQAR, r_0 and r_2 both seem to provide the shortest path ($1+\sqrt{2}$ hops) to connect S and D, which thus will be preferred and selected as final results. Moreover, the decision to select which one of them only depends on the searching order of the sorted graph, because in the view of these approaches, r_0 and r_2 that offer the same residual capacity should have no other difference. However, CSR will detect their distinction and ultimately, select neither of them. Let's start with previous solutions in QoC-overlook algorithms first.

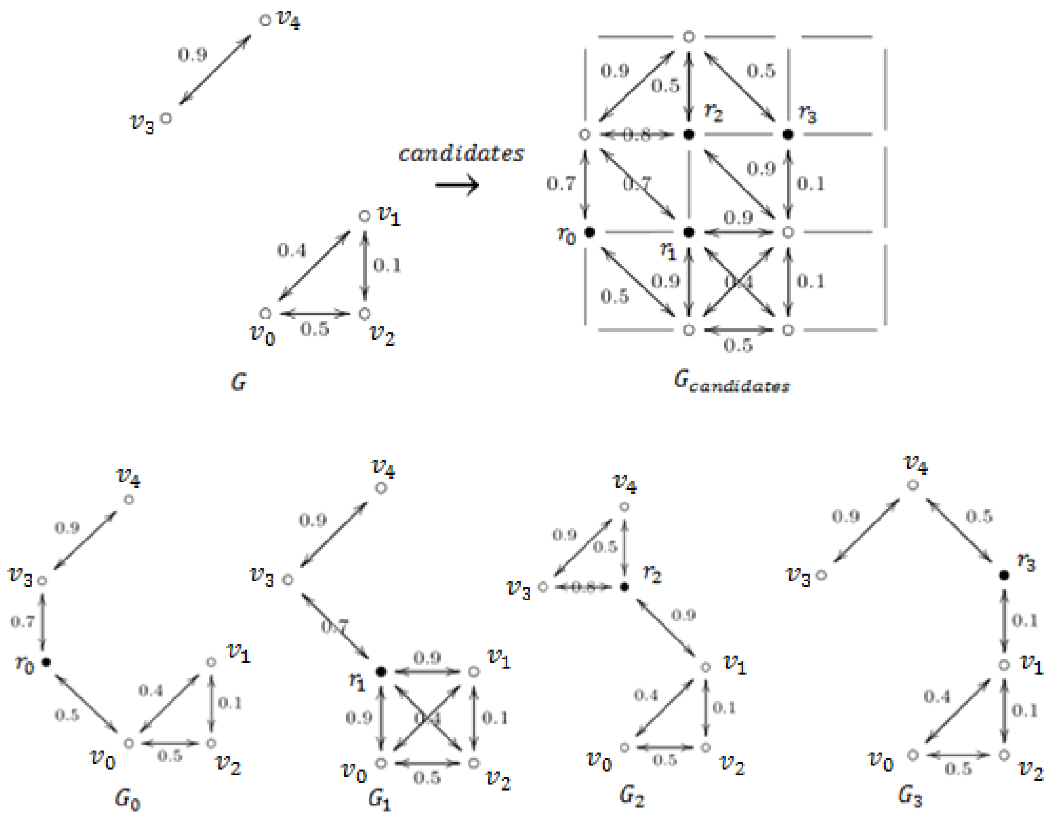

Fig. 2. An example to compare CSR with others.

For G_0, addictive relay r_0 is selected. Since it has no impact on connectivity of sub-network S, $\Lambda_{G_{0s}}$ remains the same as Λ_{G_S}, namely 0.43. Nevertheless difference emerges in sub-network D, with $G_0(v_0, v_3)$ and $G_0(v_0, v_4)$ as 0.35 and 0.315 respectively, left the final $\Lambda_{G_{0D}}$ as 0.315. Eventually its overall connectivity can be calculated as: $\Lambda_{G_0} = 1-(1-\Lambda_{G_{0s}})(1-\Lambda_{G_{0D}}) = 0.601$. The ratio of Λ_{G_0} to Λ_G, $\gamma_0 = \frac{\Lambda_{G_0}}{\Lambda_G} \times 100\% = 141.8\%$, reflects an improvement of the total network for G_0.

For G_2, the topology is marginally more complicated. Despite no impact on S (with $\Lambda_{G_{2s}}$ also 0.43), series-parallel paths are created between v_0 and nodes in D, therefore making $G_2(v_0, v_3) = G_2$

$G_2(v_0, v_1) \cdot 0.9 \cdot (1-(1-0.8) \cdot (1-0.5 \cdot 0.9)) = 0.344$, similarly $G_2(v_0, v_4) = 0.333$, $\Lambda_{G_{0D}} = 0.333$. Eventually, $\Lambda_{G_2} = 0.618$ and $\gamma_2 = 143.7\%$, both slightly better than G_0 in terms of connectivity.

As for r_1 and r_3, they also have the same number of hops ($2\sqrt{2}$) to connect the two detached sub-network, which slightly larger than the former two positions. Therefore they seem to be definitely the same and will not be chosen by QoC overlook algorithms. In fact, r_1 will serve a much better topology than r_0 and r_2, while r_3 performs much worse.

For the case of G_3, r_3 is selected. The resulted topology is shown as Fig. 2. With connectivity of sub-network remaining unchanged (0.43) and slightly improved (0.02) from that of graph, its overall network reachability is 0.441, which has a marginal improvement from G (102.65 %).

Eventually, CSR may prefer G_1. Between v_0 and v_1, 5 distinct parallel paths are created in below 3 hops with the deployment of r_1 and their mutual reachability is calculated as $G_1(v_0, v_1) =$ $=1\text{-}(1\text{-}0.4)(1\text{-}0.5\cdot0.1)(1\text{-}0.9\cdot0.9)(1\text{-}0.5\cdot0.4\cdot0.9)\times$ $\times(1\text{-}0.9\cdot 0.4\cdot0.1) = 0.914$. Similarly, we have $G_1(v_0, v_2) = 0.721$, $G_1(v_0, r_1) = 0.952$ and accordingly get $\Lambda_{G_{1s}} = \min(0.914, 0.721, 0.952) =$ $= 0.721$. As for sub-network D, r_1 also enhances its performance by generating inclusive paths, boosting the reachability up to 0.6. Thus its overall connectivity is 0.884. That is to say the network is enhanced to 206.6 % from the origin figure, more effective than any other solutions mentioned above in terms of QoC and still has an improvement of 176.4 % considering average extra hops taken in G_1.

From this simple example we have the following observations. First, CSR illustrates great potentials on generating high efficiency topologies. Compared with the best of deterministic QoC-overlook ones, improves the efficiency by 32.7 %. Second, lossy links may not be actually profitable. In this example, link $\{v_1, v_2\}$ should be removed because of its poor reachability. Third, the computation of network reachability is of vital importance but may be costly in more complicated cases, thus a more simplify approach is required.

4.2. Evaluation

In this section, we compare the performance of CSR to another approach named EQAR [11]. As explained in Section 2, EQAR is a greedy algorithm for Effective QoS-Aware placement of Relay nodes, which tackles the segmented network connectivity problem that CSR addresses. However, it does not consider reachability requirements on probabilistic lossy links. Therefore, in this experiment, we additionally measure the reachability to the connected topology which EQAR creates.

Multiple configurations are simulated in these experiments, with combinations of values of N_segments and N_area. The former represents the number of segments with its value between 2 and 5. The later reflects the size of deployment area whose value varies from 200 to 1000 cells. The ratio of relay capacity and QoS requirements are applied the same in both CSR and EQAR, with values ranged randomly from 0 to 1. Note that every segment has the same number of nodes.

Generally, with sets of experiments above, we compare CSR with EQAR. In Fig. 3, the number of segments is increased and both the connectivity and number of relay are observed while the size of the target area is fixed at 300 cells. Similarly, the size of the target area grows and both the connectivity and number of relay is observed while the number of segments is fixed at 3. A larger number of segments and a larger size of deployment area obviously increase the RN count, since the connectivity and other requirements become more complicated in both algorithms. In Fig. 3 and Fig. 4, CSR both populates slightly more relays than EQAR does in order to fulfill extra QoC requirements. Meanwhile, it also better recognizes those high quality links and therefore can attain much better reachable topology.

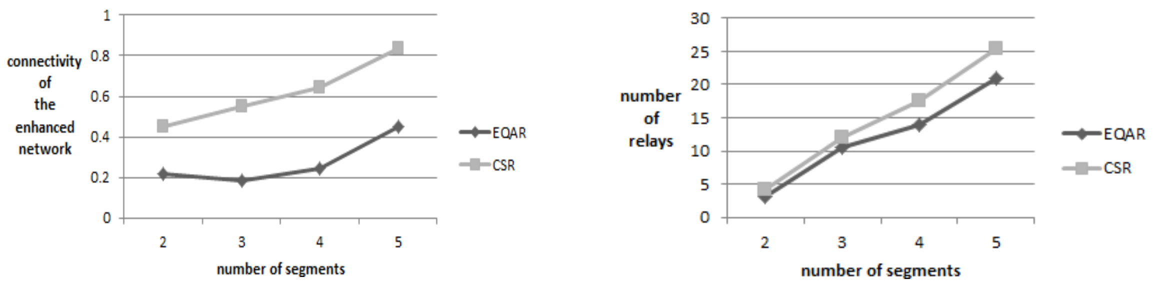

Fig. 3. Connectivity and relay number of EQAR and CSR against number of segments (size 300).

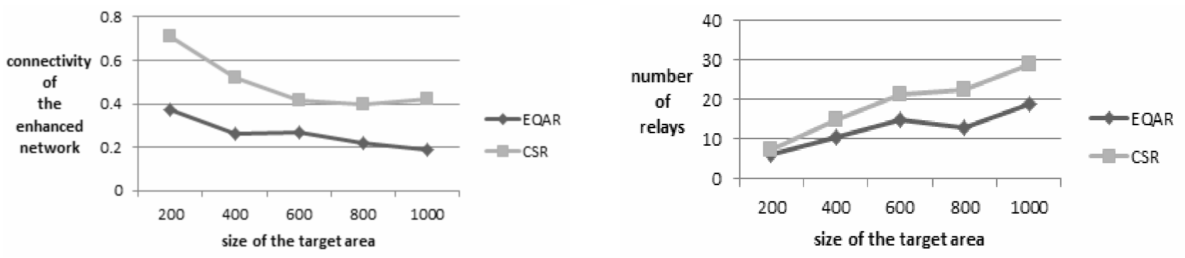

Fig. 4. Connectivity and relay number of EQAR and CSR against size of the target area (3 segments).

Particularly, in Fig. 3, every segment has the same number of nodes. Therefore the number of nodes keeps increase as the number of segments grows, and with the size of area fixed, so as the connectivity of the whole network. CSR obtained almost as twice as the connectivity of the enhanced network in EQAR. Particularly, in the case of 3 segments, the average improvement reaches 289.5 %, with average network reachability of 0.19 in EQAR and 0.55 in CSR. We can see the difference between them keeps increasing slightly as the number of segments and size enlarged.

In Fig. 4 the situation is similar. However, because the number of nodes keeps the same and the size of the target area increases, the distances between segments are increasing longer than the previous experiment and the network is more and more sparse, which requires more relay nodes to obtain the same connectivity and limits the number of possible choices for topology, which reduces the effectiveness of both algorithm. Even under such condition, CSR is still at least 30 % better than EQAR (when the size of target area reaches 600 cells). That is mainly because when it comes to select new position of relay nodes, CSR can better focus on connectivity and utilize the populated nodes.

6. Conclusions

In this paper, we have investigated the problem of providing network reachability among segments while meeting some quality goals. CSR is introduced to lessen the number of RN that meets both connectivity and quality need during RN deployment. The key idea is to regulate a new parallel rule and cost function for probabilistic topology control in terms of distinct sub-networks, which eventually strikes a better balance of QoC and QoS, maximizes the utilization of deployed node and avoids the deployment of additional relays as much as possible.

Future work can be concluded as:

1. To measure the effect and organize different methods of topology construction, like channel and transmit power modification and to save energy;
2. Considering the selection of representative node among deployed nodes;
3. To weigh the combine sequence of segments;
4. Candidate RN paths should be provided in case of bad environments, when the best placement strategy is not practical facing unexpected barriers.

References

[1]. C.-Y. Chong, S. P. Kumar, Sensor Networks: Evolution, Opportunities and Challenges, *Proceedings of the IEEE,* 91, 8, August 2003, pp. 1247-1256.

[2]. M. Younis, *et al.*, Topology management techniques for tolerating node failures in wireless sensor networks: A survey, *Comput. Netw*., 2013, Vol. 58, 2014, pp. 254–283.

[3]. G. Lin, G. Xue, Steiner Tree Problem with Minimum Number of Steiner Points and Bounded Edge-Length, *Information Processing Letters*, 69, 1999, pp. 53-57.

[4]. X. Cheng, D. Z. Du, L. Wang, B. Xu, Relay Sensor Placement in Wireless Sensor Networks, *Wireless Networks*, 14, 3, June 2008, pp. 347-355.

[5]. Zou Y., C. Krishnendu, Sensor deployment and target localization based on virtual forces, in *Proceedings of the Twenty-second Annual Joint*

Conference of the IEEE Computer and Communications Societies, 2, 2003, pp. 1293-1303.

[6]. Dirafzoon A., Virtual force based individual particle optimization for coverage in wireless sensor networks, in *Proceedings of the 2010 IEEE 23rd Canadian Conference on Electrical and Computer Engineering (CCECE'10)*, 2010, pp. 1-4.

[7]. Wimalajeewa T., S. K. Jayaweera, Distributed and collaborative node mobility management for dynamic coverage improvement in hybrid sensor networks, *Eurasip Journal on Wireless Communications and Networking*, 2011, pp. 1-17.

[8]. Xirong Bao, Ming Yang, Xuefeng Zhang, An Improved Visual Force Algorithm for Node Deployment Strategy in Wireless Sensor Network, in *Proceedings of the Control and Decision Conference (CCDC*), 2012, pp. 2216-2219.

[9]. S. Lee, M. Younis, Optimized relay placement to federate segments in wireless sensor networks, *IEEE Journal on Selected Area in Communications, Special Issue on Mission Critical Networking*, 28, 5, 2010, pp. 742-752.

[10]. S. Lee, M. Younis, QoS-aware relay node placement for connecting disjoint segments in wireless sensor networks, in *Proceedings of the Int'l Workshop on Interconnections of Wireless Sensor Networks (IWSN'10)*, Santa Barbara, California, June 2010.

[11]. Sookyoung Lee, Younis M., EQAR: Effective QoS-Aware Relay Node Placement Algorithm for Connecting Disjoint Wireless Sensor Subnetworks, *IEEE Transactions on Computers*, 60, 12, 2011, pp. 1772-1787.

[12]. Yunhuai Liu, Lionel Ni, Chuanping Hu, A Generalized Probabilistic Topology Control for Wireless Sensor Networks, *IEEE Journal on Selected Areas in Communications*, 30, 9, 2012, pp. 1780-1788.

[13]. S. Satitsatian, K. C. Kapur, An algorithm for lower reliability bounds of multistate two-teriminal networks, *IEEE Trans. Reliab.*, 55, 2, 2006, pp. 199-205.
