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Constant Approximation for Virtual Backbone Construction with Guaranteed Routing Cost in Wireless Sensor Networks

Hongwei Du*¶, Qiang Ye*, Weili Wu†, Wonjun Lee‡, Deying Li§, Dingzhu Du† and Stephen Howard*
*Department of Computer Science and Information Technology, University of Prince Edward Island, Canada.
Emails: {qye,showard}@upei.ca, hongwei.du@ieee.org.
†Department of Computer Science, University of Texas at Dallas, USA.
Emails: {dzdu,weiliwu}@utdallas.edu.
‡Department of Computer Science and Engineering, Korea University, Seoul, Republic of Korea.
Email: wlee@korea.ac.kr.
§Key Laboratory of Data Engineering and Knowledge Engineering, MOE, Renmin University of China, China
Corresponding Author. Email: deyingli@ruc.edu.cn.
¶Department of Computer Science and Technology, HITSGS, China.

***Abstract*—In wireless sensor networks, virtual backbone construction based on connected dominating set is a competitive issue for routing efficiency and topology control. Assume that a sensor networks is defined as a connected unit disk graph (UDG). The problem is to find a minimum connected dominating set of given UDG with minimum routing cost for each node pair. We present a constant approximation scheme which produces a connected dominating set *D*, whose size $|D|$ is within a factor α from that of the minimum connected dominating set and each node pair exists a routing path with all intermediate nodes in *D* and with length at most $5 \cdot d(u, v)$, where $d(u, v)$ is the length of shortest path of this node pair. A distributed algorithm is also provided with analogical performance. Extensive simulation shows that our distributed algorithm achieves significantly than the latest solution in research direction.**

I. Introduction

Recent exploitation of wireless embedded sensor technology has captivated many researchers due to its widely range of applications such as environmental monitoring, military applications, biological systems, traffic controls and so forth. These types of mobile sensor devices with sensing and communication unit forming a wireless sensor network(WSN) are practically resource constrained since they have limited storage capacity, processing speed, communication bandwidth and typically powered by batteries. The sensor nodes usually locate in an unpredictable harsh area in which recharging battery is impossible. A radio signal generated by a sender node can communicated with other nodes within its maximum transmission range. In many applications, sensor nodes require to send inquiry to other sensors via intermediate nodes for data processing while request nodes will send data back after they successfully receive it. Therefore, routing efficiency for this type of messages exchange communication will certainly advantage the whole network transmission procedure.

Virtual backbone construction is a characteristic technique for sensor nodes' message exchange communication. Forming a connected dominating set (CDS) can serve as a virtual backbone which reduces the maintaining, searching routing time and furthermore the routing table size for data transmission. A minimum connected dominating set (MCDS) incurs less maintaining overhead. Given a graph *G*=(*V*, *E*) representing a wireless sensor network, where *V* is the set of nodes and *E* is the transmission links in the graph, a node subset $D \subseteq V$ is called a *dominating set* if every node is either in *D* or has a neighbor in *D*. A dominating set is said to be connected if it induces a connected subgraph. Fig.1 (a) demonstrates the CDS where all gray nodes construct a CDS. Due to applications

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TABLE I

UPPER BOUND FOR MAXIMAL INDEPENDENT SET IN UNIT DISK GRAPH

Approx. Algorithm	Upper Bound for maximal independent set
Wan et al.[19]	$4 \cdot opt_{MCDS} + 1$
Wu et al.[22]	$3.8 \cdot opt_{MCDS} + 1.2$
Funke et al.[7]	$3.748 \cdot opt_{MCDS} + 9$
Yao et al.[20]	$3\frac{2}{3} \cdot opt_{MCDS} + 1\frac{1}{3}$
Gao et al.[8]	$3.478 \cdot opt_{MCDS} + 4.874$
Li, Wan, Yao et al.[11]	$3.4306 \cdot opt_{MCDS} + 4.8185$

in wireless networks, the MCDS problem, i.e., computing the MCDS for a given network graph, has been extensively studied since 1998 [1], [15], [16], [17], [21].

The research on constructing a CDS can be classified into two categories: general graph and UDG. In general graph, Guha and Khuller [9] showed that the MCDS has no polynomial time approximation with performance ratio $\rho \ln \delta$ for $0 < \rho < 1$ unless $NP \subseteq DTIME(n^{O(\log \log n)})$ where δ is the maximum node degree of G. They also gave a polynomial-time $(3+\ln \delta)$-approximation. Ruan *et al* [14] and Du *et al* [6] had made further improvements.

In UDG, the MCDS is still NP-hard [4]. However, Cheng *et al* [3] showed that the MCDS had polynomial-time approximation scheme (PTAS) in unit disk graphs, that is, for any $\varepsilon > 0$, there is a polynomial-time algorithm producing approximate solution with size within a factor of $1 + \varepsilon$ from optimal. The running time of PTAS depends on ε, which a polynomial of high degree even for $\varepsilon = 0.5$. Therefore, fast approximations with small performance ratio is in need. Many algorithms [2], [7], [11], [12], [13], [20] for this purpose consist of two stages. In the first stage, the network constructs a maximal independent set (MIS), which must be a dominating set and in the second stage, connect the dominating set into a CDS.

To estimate the size of solution produced by such a two-stage algorithm, it is critical to establish a upper bound for the maximal independent set. Wan *et al* [19] first showed that every maximal independent set has size at most $4 \cdot opt_{MCDS} + 1$. Later, several efforts have been made on improvement of this bound in the literature[7], [8], [11], [20], [22]. Currently, the best performance ratio is that every maximal independent set has size at most $3.4306 \cdot opt_{MCDS} + 4.8185$. A full bright view of the improvement is shown in Table I.

Mostly, the approximation ratios mention above are all considered of CDS size. While for routing efficiency, there still additional metrics to be concern with, such as minimum routing cost for node pairs in this paper. Kim *et al* [10] constructed a CDS D such that $|D| \leq \alpha \cdot opt_{MCDS}$ and the diameter of D is within a constant factor from the minimum diameter that a CDS can have. Since the diameter is the longest routing cost, the work of this paper is related to it. But the paper result achieves significantly than this previous work.

Motivated from reducing routing cost [5] and from improving road load balancing [18], Minimum Routing Cost Connected Dominating Set problem (MOC-CDS) has been recently proposed. Given a network, representing as a connected graph, the problem is to compute a connected dominating set with minimum cardinality under condition that for every pair of nodes, and there exists a shortest path between a node pair such that all intermediate nodes belong to the dominating set. In Fig.1(a), node 1 sends a packet to node 6 via node $\{2, 5, 8\}$ and the length is 4, but it sends through node $\{3\}$ which length is 2 in Fig.1(b). The routing cost of original MCDS is twice of the MOC-CDS. This novel MOC-CDS problem also motivates the traffic control. In Fig.1(a), node 1 should pass through node 2, 5, 8 to node 9 while node 4 should also path through node 2, 5, 8 to node 6. Contrary to Fig.1(a), node 1 could pass through node 3, 5, 7 to node 9 while node 4 identically as usual. The traffic in Fig.1(b) has been separated which eventually alleviated the traffic flows. Ding *et al.* [5] showed that MOC-CDS has no polynomial time approximation with performance ratio $\rho \ln \delta$ for $0 < \rho < 1$ unless $NP \subseteq DTIME(n^{O(\log \log n)})$ where δ is the maximum node degree of G. They also gave a polynomial time distributed approximation algorithm with performance ratio $H(\frac{\delta(\delta-1)}{2})$ where H is the harmonic function, i.e., $H(k) = \sum_{i=1}^{k} \frac{1}{i}$.

However, Fig.1 shows that sometimes the size of MOC-CDS may be conspicuous bigger than the size of MCDS. Thus, from perspective of obtaining the minimum routing cost, we attempt to achieve MCDS with slightly increase the size of CDS. With such consideration, we propose our concern defines as Guaranteed Routing Cost Minimum Connected Dominating Set(GOC-MCDS): Given a network $G = (V, E)$, find a CDS D in polynomial-time such that $|D| \leq \alpha \cdot opt_{MCDS}$ and for every pair of nodes u and v, there exists a path between u and v with intermediate nodes in D and length at most $\beta \cdot d(u, v)$

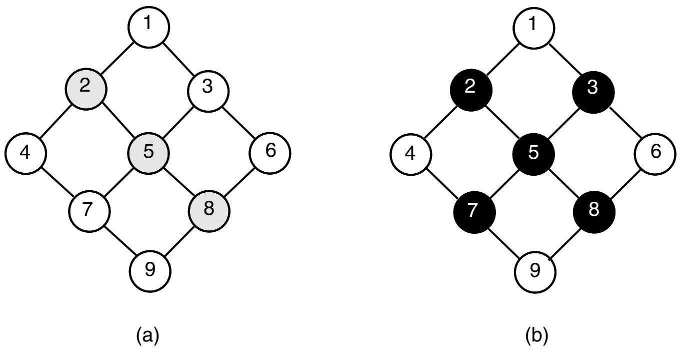

Fig. 1. (a) Original MCDS (b) MOC-CDS The gray and black nodes represent the virtual backbone.

where $d(u, v)$ is the length of the shortest path between u and v, and also α and β achieve two fixed constants.

Considering this problem, the constraint on routing cost is relaxed if ($\beta > 1$), but the CDS size is expected to be smaller. Also, we are interested in study of this problem in UDGs rather than general graphs. It is a kind of graph where nodes are homogeneous,sharing the common transmission radius. An edge exists between two nodes u and v if and only if u and v are within each other transmission range.

In this paper, we give a positive answer to this problem, that is, we present a polynomial time algorithm which produces a CDS D of size at most $\alpha \cdot opt_{MCDS}$ for some fixed constant α and with property that for every pair of nodes u and v, there is a path between u and v with intermediate nodes in D and length at most $5 \cdot d(u, v)$. We also provide a distributed version of the algorithm and computational experiments to compare our algorithm with some existing algorithms for MOC-CDS and MCDS.

The rest paper is organized as follows: In Section II, we introduce the routing cost constraints. Section III proposes the centralized algorithm for CDS virtual backbone construction. In Section IV, distributed algorithm is presented. The simulation evaluation is showed in Section V. Finally, Section VI concludes the paper.

II. Routing Cost Constraints

In this section, we cogitate the relationship between some routing cost constraints.

For a CDS *D*, let $d_D(u, v)$ denote the minimum length of a path with intermediate nodes in *D*, connecting from node *u* to node *v*.

Lemma 1: Let *G* be a connected graph and *D* a dominating set of *G*. Suppose that for any pair of nodes *u* and *v*, $d_D(u, v) \leq \alpha d(u, v)$. Then *D* is a connected dominating set.

Proof: Since *G* is connected, we have $d(u, v) < \infty$ for any two nodes *u* and *v*. Therefore, for any two nodes $u, v \in D$, $d_D(u, v) \leq \alpha d(u, v) < \infty$, that is, there is a path connecting nodes *u* and *v* within *D*. Thus, *D* induces a connected subgraph and hence *D* is a connected dominating set. ■

Lemma 2: Let *G* be a connected graph and *D* a dominating set of *G*. Then, for any pair of distinct nodes *u* and *v*,

$$d_D(u, v) - 1 \leq \alpha(d(u, v) - 1)$$

if and only if for any pair of nodes *u* and *v* with $d(u, v) = 2$

$$d_D(u, v) - 1 \leq \alpha. \tag{1}$$

Proof: It is trivial to show the "only if" part. Next, we show the "if" part. Consider a pair of distinct nodes *u* and *v*. If $d(u, v) = 1$, it is clear that $d_D(u, v) - 1 = 0 = \alpha(d(u, v) - 1)$. Next, assume that $d(u, v) \geq 2$. Consider a shortest path $(u, w_1, ..., w_k, v)$ where $k = d(u, v) - 1 \geq 1$.

Case 1. k is odd. Note that

$$d(u, w_2) = d(w_2, w_4) = \cdots = d(w_{k-1}, v) = 2$$

By equation (1), there exist paths $(u, s_{1,1}, s_{1,2}, ..., s_{1,h_1}, w_2)$, $(w_2, s_{3,1}, s_{3,2}, ..., s_{3,h_3}, w_4)$, ..., $(w_{k-1}, s_{k,1}, s_{k,2}, ..., s_{k,h_k}, v)$ such that $1 \leq h_i \leq \alpha$ for all $i = 1, 3, ..., k$ and $s_{i,j} \in D$ for all $i = 1, 3, ..., k$ and $j = 1, 2, ..., h_i$. Now, note that $d(s_{1,h_1}, s_{3,1}) = \cdots = d(s_{k-2,h_{k-2}}, s_{k,1}) = 2$. By equation (1), there exist paths $(s_{1,h_1}, s_{2,1}, s_{2,2}, ..., s_{2,h_2}, s_{3,1})$, ..., $(s_{k-2,h_{k-2}}, s_{k-1,1}, s_{k-1,2}, ..., s_{k-1,h_{k-1}}, s_{k,1})$ such that $1 \leq h_i \leq \alpha$ for $i = 2, 4, ..., k-1$ and $s_{i,j} \in D$ for $i = 2, 4, ..., k-1$ and $j = 1, 2, ..., h_i$. Therefore, there is a path $(u, s_{1,1}, ..., s_{1,h_1}, s_{2,1}, ..., s_{k,h_k}, v)$ of length at most $\alpha k+1$ such that all intermediate nodes $s_{i,j}$, for $1 \leq i \leq k$ and $1 \leq j \leq h_i$ belong to D. Thus, $d_D(u, v) - 1 \leq \alpha \cdot d(u, v)$.

Case 2. k is even. Note that

$$d(u, w_2) = d(w_2, w_4) = \cdots = d(w_{k-2}, w_k) = 2$$

By equation (1), there exist paths $(u, s_{1,1}, s_{1,2}, ..., s_{1,h_1}, w_2)$, $(w_2, s_{3,1}, s_{3,2}, ..., s_{3,h_3}, w_4)$, ..., $(w_{k-2}, s_{k-1,1}, s_{k-1,2}, ..., s_{k-1,h_{k-1}}, w_k)$ such that $1 \leq h_i \leq \alpha$ for all $i = 1, 3, ..., k-1$ and $s_{i,j} \in D$ for all $i = 1, 3, ..., k-1$ and $j = 1, 2, ..., h_i$. Now, note that $d(s_{1,h_1}, s_{3,1}) = \cdots = d(s_{k-1,h_{k-1}}, v) = 2$. By equation (1), there exist paths $(s_{1,h_1}, s_{2,1}, s_{2,2}, ..., s_{2,h_2}, s_{3,1})$, ..., $(s_{k-1,h_{k-1}}, s_{k,1}, s_{k,2}, ..., s_{k,h_k}, v)$ such that $1 \leq h_i \leq \alpha$ for $i = 2, 4, ..., k$ and $s_{i,j} \in D$ for $i = 2, 4, ..., k$ and $j = 1, 2, ..., h_i$. Therefore, there is a path $(u, s_{1,1}, ..., s_{1,h_1}, s_{2,1}, ..., s_{k,h_k}, v)$ of length at most $\alpha k + 1$ such that all intermediate nodes $s_{i,j}$, for $1 \leq i \leq k$ and $1 \leq j \leq h_i$ belong to D. Thus, $d_D(u, v) - 1 \leq \alpha \cdot d(u, v)$. ■

Lemma 3: Let *G* be a connected graph and *D* a dominating set of *G*. Suppose that for any pair of nodes *u* and *v* with $d(u, v) = 2$,

$$d_D(u, v) \leq \alpha + 1.$$

Then for any pair of distinct nodes *u* and *v*

$$d_D(u, v) \leq \alpha d(u, v).$$

Proof: By Lemma 2,

$$[d_D(u, v) \leq \alpha(d(u, v) - 1) + 1 \leq \alpha d(u, v)$$

since $\alpha \geq 1$. ■

Lemma 4: Let *G* be a connected graph and *I* a maximal independent set of *G*. Suppose $D \supseteq I$ such that for any pair of nodes *u* and *v* in *I* with $d(u, v) \leq 4$,

$$d_D(u, v) \leq 4.$$

Then for any pair of distinct nodes *u* and *v*,

$$d_D(u, v) \leq 5d(u, v).$$

Proof: Consider any pair of nodes *x* and *y* with $d(x, y) = 2$. Since *I* is a maximal independent set, we can find nodes $x', y' \in I$ such that x' is adjacent to *x* and y' is adjacent to *y*. Therefore, $d(x', y') \leq 2 + d(x, y) = 4$. By assumption, we have $d_D(x', y') \leq 4$. Note that $I \subseteq D$. Thus, $x', y' \in D$. It follows that $d_D(x, y) \leq 6$.By Lemma 3, we have $d_D(u, v) \leq 5d(u, v)$ for any pair of distinct nodes *u* and *v*. ■

III. Centralized Algorithm GOC-MCDS-C

A. Algorithm Description

In this section, we introduce a simple centralized algorithm following the steps of regular MCDS algorithms.

Algorithm 1 Centralized Algorithm GOC-MCDS-C

Intially Set $D \leftarrow \emptyset$.

Step 1. Construct a maximal independent set I.

Step 2. For every pair of nodes u, v in I with $d(u, v) \leq 4$, compute a shortest path $p(u, v)$ and put all intermediate nodes of $p(u, v)$ into C.

Output $D = C \cup I$.

B. Performance Analysis

Lemma 5: Let I be a maximal independent set. Then for every $u \in I$, $|\{v \in I \mid 0 < d(u, v) \leq 4\}| \leq 80$.

Proof: For each node $v \in I$ with $d(u, v) \leq 4$, construct a disk with center v and radius 0.5. Those disks are disjoint since I is independent. Moreover, those disks are contained in a disk with center u and radius 4.5. Therefore,

$$|\{v \in I \mid d(u, v) \leq 4\}| \leq \frac{\pi 4.5^2}{\pi 0.5^2} = 81.$$

However, $\{v \in I \mid d(u, v) \leq 4\}$ contains node u. Therefore, $|\{v \in I \mid 0 < d(u, v) \leq 4\}| \leq 80$. ■

Lemma 6: In this centralized algorithm, the node subset C obtained at the second stage has size $|C| \leq 120|I|$ where I is the maximal independent set obtained in the first stage.

Proof: Construct a graph H with node set I and edge set $\{(u, v) \mid u, v, \in I, 0 < d(u, v) \leq 4\}$. By Lemma 5, the maximum node degree of H is at most 80. Therefore, H contains at most $40|I|$ edges. In the second stage of centralized algorithm for GOC-MCDS, each path $p(u, v)$ with some intermediate nodes corresponding an edge (u, v) of H, for which we add at most three nodes to set C since $d(u, v) \leq 4$. Therefore $|C| \leq 3 \cdot 40|I| = 120|I|$. ■

The following lemma was proved in [20].

Lemma 7: For any maximal independent set I, $I \leq \frac{11}{3} \cdot opt_{MCDS} + \frac{4}{3}$.

Theorem 8: The algorithm GOC-MCDS-C produces a CDS D with size $|D| \leq 443\frac{2}{3} \cdot opt_{MCDS} + 201\frac{2}{3}$ and property that for any pair of nodes u, v, $d_D(u, v) \leq 5d(u, v)$.

Proof: By Lemmas 6 and 7,

$$|D| \leq |C| + |I| \leq 121 \cdot |I| \leq 443\frac{2}{3} \cdot opt_{MCDS} + 201\frac{2}{3}.$$

By Lemma 4, D has the property that for any pair of nodes u, v, $d_D(u, v) \leq 5d(u, v)$. ■

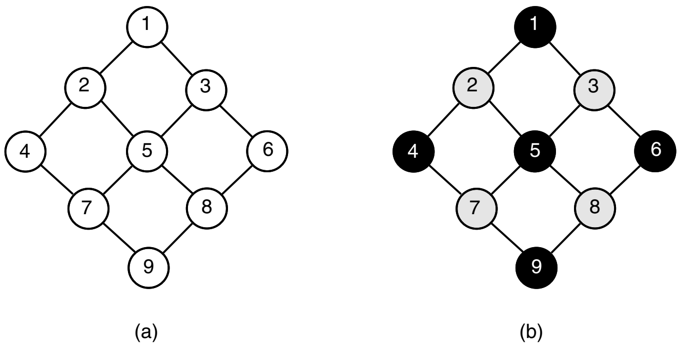

Fig. 2. Stage 1. Construct a maximal independent set (a) Initial step (b) Final step.

IV. Distributed Algorithm GOC-MCDS-D

A. Algorithm Description

Similarly, the distributed algorithm comprises of two stages. One is construct a maximal independent set as dominating set in Algorithm 2. Another is to connect this dominating set in Algorithm 3. In Fig.2(a), a initial network locate in the Euclidean plane. The black nodes represented the maximal independent set in Fig.2(b) which indicated the final step of stage 1.

Algorithm 2 Construct a MIS I (Stage 1)

1: **Initially** Every node is colored in white and is assigned with a positive integer ID; different nodes have different IDs.

2: **Step 1** Every white node send its ID to its neighbors and then compares its ID with received IDs from neighbors. If its ID is smaller than every received ID from neighbors, then it turns the color from white to black.

3: **Step 2** Every black node sends message "black" to its neighbors. If a white node receives a message "black", then it turns its color from white to grey.

4: **Step 3** Go back to Step 1 until no white node exists.

5: **Output** All black nodes form a maximal independent set I

B. Performance Analysis

This distributed algorithm has the same performance ratio as the centralized algorithm.

Theorem 9: The distributed algorithm produces a CDS D consisting of all black nodes with size $|D| \leq 443\frac{2}{3} \cdot opt_{MCDS}+$

Algorithm 3 Connect the MIS I (Stage 2)

1: **Step 1** Every black node send its ID to its neighbors.

2: **Step 2** Every node add its own ID id_2 to each received ID id_1 and then send those pairs of IDs, (id_1, id_2), to all its neighbors.

3: **Step 3** Each node do the following: Suppose its ID is id^*.

   1) For each pair of IDs id_1 and id_{1^*} received in Step 1, if $id_1 < id_{1^*}$, then send a message (id_{1^*}, id^*, id_1) to the neighbor with ID id_1.
   2) For each pair of messages (id_1, id_2) and (id_{1^*}, id_{2^*}) received at Step 2, if $id_1 < id_{1^*}$, then send a message $(id_{1^*}, id_{2^*}, id^*, id_2, id_1)$ to the neighbor with ID id_2.
   3) For each message (id_1, id_2) received at Step 2 and ID id_{1^*} received at Step 1, if $id_1 < id_{1^*}$, then send a message $(id_{1^*}, id^*, id_2, id_1)$ to the neighbor with ID id_2; otherwise, send a message $(id_1, id_2, id^*, id_{1^*})$ to the neighbor with ID id_{1^*}.

4: **Step 4** When a node with ID id_2 received a message $(id_{1^*}, id_{2^*}, id^*, id_2, id_1)$ or $(id_{1^*}, id^*, id_2, id_1)$, it sends this message to its neighbor with ID id_1.

5: **Step 5** Each black node with ID id_1 collects all messages in form (id_3, id_2, id_1) or (id_4, id_3, id_2, id_1) or $(id_5, id_4, id_3, id_2, id_1)$ received in Step 3 and Step 4. Suppose those messages form a set M. Then it perform the following computation.

while $M \neq \emptyset$ **do begin**

  choose $(id_h, ..., id_2, id_1) \in M$;

  send message $(id_h, ..., id_2, id_1)$ to

node with ID id_2;

  delete all messages starting with id_h from M;

end-while

6: **Step 6** When a node with ID id_i received a message $(..., id_{i-1}, id_i, ...)$ in previous step, it turns to black color and pass this message to node with ID id_{i-1}.

7: **Step 7** When a node with ID id_i received a message $(..., id_{i-1}, id_i, ...)$ in Step 6, it goes back to beginning of Step 6.

$201\frac{2}{3}$ and property that for any pair of nodes u, v, $d_D(u,v) \leq 5d(u,v)$.

Proof: In the first stage, the distributed algorithm produces a maximal independent set I and in the second stage, the distributed algorithm connect each pair of nodes u and v with $d(u,v) \leq 4$ by a path $p(u,v)$ with length at most four. This is a little different from the centralized algorithm that connect u and v by a shortest path from u to v. Note that this difference does not change the proof of Lemma 6. Therefore, all proofs for Theorem 8 can be moved to here. ■

V. Simulation Results

In this section, we will conduct simulations to evaluate the performance of the proposed algorithms. We study two network parameters that may demonstrate the performance of the proposed algorithms: 1) virtual backbone CDS size and 2) maximum routing path length. The performance comparison of distributed algorithm GOC-MCDS-D and CDS-BD-D [10] algorithms is presented in the following.

In the simulation, we model wireless sensor network as a set of nodes randomly deploy in a 100×100 Euclidean plane. We assume that each node has an uniform transmission range. The edge between any node pairs exists when they at most the uniform transmission range. We randomly generate 100 rounds of connected graph and take the average value of size and max-min length of CDS by process each of the them in the figures. The number of nodes is varied from 10 to 100 and the common maximum transmission range is increased among 15, 20, 25 and 30.

Fig. 3 provides the comparison of GOC-MCDS-D and CDS-BD-D in terms of CDS size. As revealed in Fig. 3, the CDS size increases when the number of nodes increase. The reason is that each node has higher probability to be the intermediate node of some shortest paths when more nodes added to existing topology. From Fig 3, GOC-MCDS-D achieves bigger than CDS-BD-D while it needs more nodes added to CDS to generate shortest path in CDS for nodes' pairs outside CDS. But when the transmission range is bigger enough, the performance between both two algorithms becomes more closely.

In Fig. 4, the max-min length of CDS varies with the number of nodes. GOC-MCDS-D performs efficiently than CDS-BD-D specially when nodes density is high. The reason is that a node will have the higher probability to connect to more neighbors which does not increase the routing cost and it will remain unchanged and the CDS construction with GOC-MCDS-D with guarantee routing costing could be achieved faster than CDS-BD-D. From these simulation results, we can observe that GOC-MCDS-D generates more energy-efficiently.

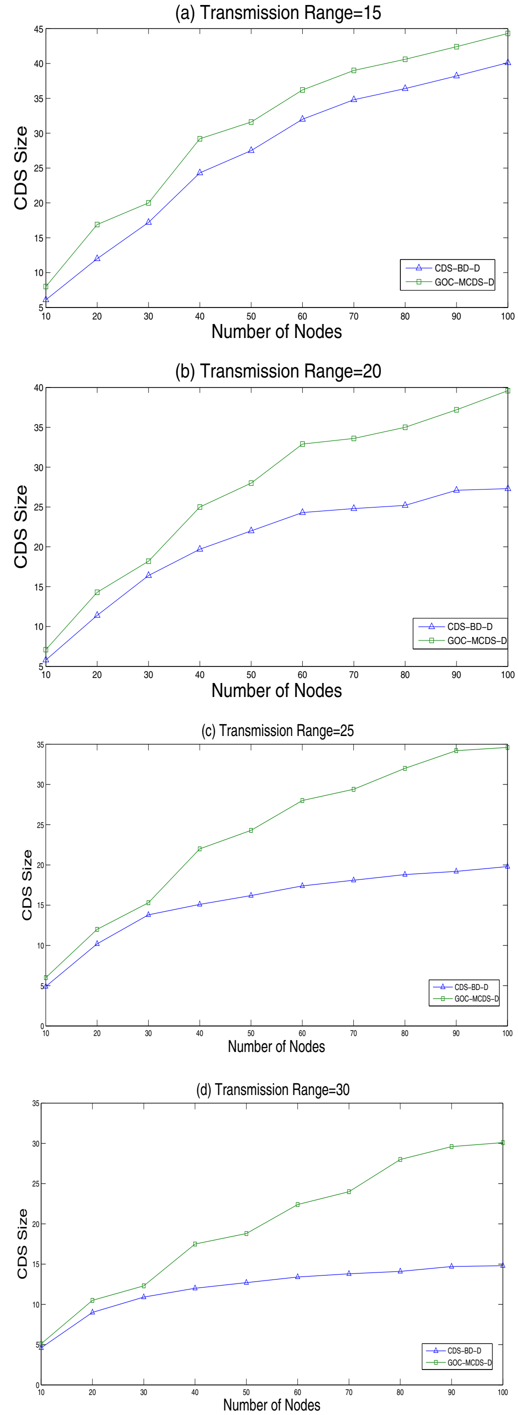

Fig. 3. Comparison of CDS Size versus number of nodes

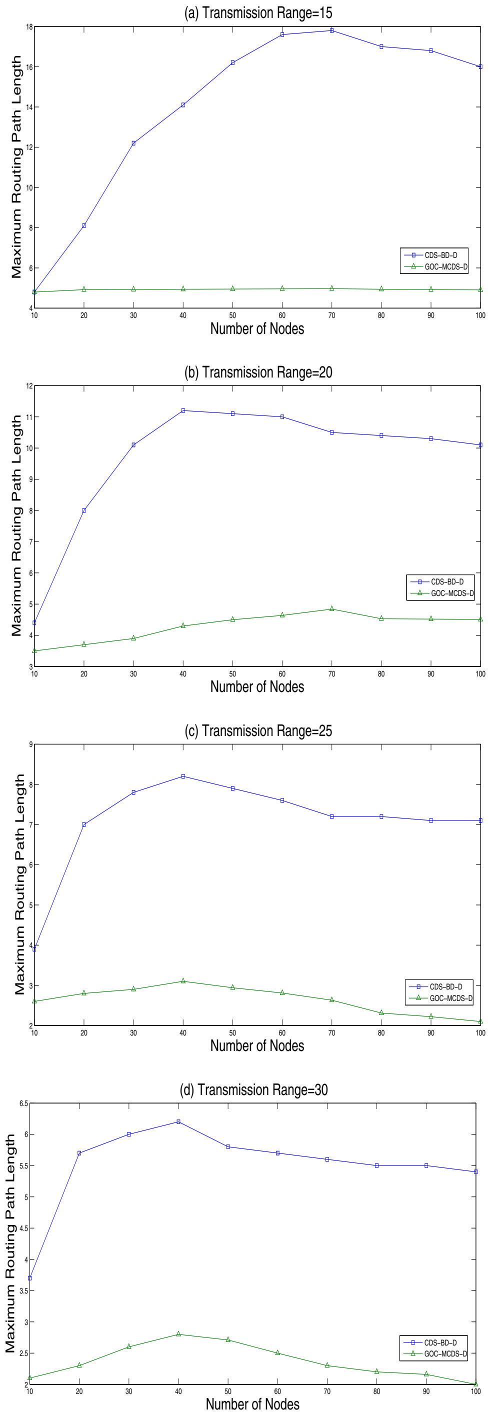

Fig. 4. Comparison of maximum routing path length versus number of nodes

Even comparing in the worth case in terms of CDS size, the increasing CDS size can be significantly improved the road load balance while distinct pair of nodes not in D will choose different shortest path to communicate. This will reduce the road load traffic flow.

VI. Conclusion

Virtual backbone construction based on MCDS is well studied in the literature. However, considering the MCDS construction with minimum routing cost for node pairs has just explored recently. In this paper, we proposed two algorithms. One centralized algorithm and another distributed algorithm. Both algorithms can achieve constant approximation performance ratio on MCDS and routing cost. In the future, some other factors such as latency, fault tolerance and so on are considered and they will be our new distributed algorithms interest for further investigation.

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