Node-Disjoint Path Routing in Wireless Networks: Tradeoff between Path Lifetime and Total Energy

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***Abstract*— Survivability and lifetime are two important issues related to routing in wireless ad-hoc networks. Routing using node-disjoint paths enhances both survivability and data confidentiality. An elegant polynomial time algorithm has been reported recently that can compute node-disjoint paths connecting a source node to a destination node with minimum total energy. However, the problem of computing a pair of node-disjoint paths connecting a source node to a destination node with a lifetime no smaller than a given threshold has not been studied before. In this paper, we present efficient algorithms for computing a pair of node-disjoint paths connecting a source node to a destination node which either minimizes energy under lifetime constraint or maximizes lifetime under energy consumption constraint. We study the tradeoffs between path lifetime and total energy consumption in node-disjoint path routing and their effects on network throughput and network lifetime. Our preliminary simulation results show that routing with both path lifetime and total energy consumption considerations leads to significantly better network throughput and network lifetime.**

Keywords wireless ad-hoc networks, node-disjoint path routing, minimum energy consumption, prolonged network lifetime.

I. Introduction

Wireless ad-hoc network has become a very hot research topic due to its enormous application potentials. Nodes in wireless ad-hoc network are normally powered by batteries and can only last for a short term if operating at a high power level. Therefore energy-efficient routing protocols which maximize the lifetime or improve throughput of the network are of great importance.

Robustness is also a very important issue in ad-hoc networks. Generally, nodes in a wireless ad-hoc network are very fallible. Nodes may lose functionalities at any time because of energy depletion or harsh environment factors. Malicious attacks are also a big threat to the network nodes if they are used in battlefields. Suppose the node failures happen in the middle of a packet transmission [1], then very important information may be lost. So it is very necessary to support survivability in wireless ad-hoc networks.

Lou and Fang [10] propose to use multipath routing in wireless ad-hoc networks to enhance data confidentiality. Several node-disjoint paths connecting the source node to the destination nodes are computed. The source node then partitions the data into several parts using coding theory and transmit each part along a different path. In this way, all of the paths are needed to be intercepted in order to find out what is transmitted in the process.

Efficient algorithms for computing minimum cost node-disjoint paths in networks have been known for a long time, dating back to Suurballe's famous paper in 1974 [14]. However in wireless networks, all nodes within the transmitter's range will receive transmitted data, which is referred as WMA *(Wireless Multicast Advantage)* in [15]. So Suurballe's algorithm cannot be used directly due to the WMA. In a recent paper [13], Srinivas and Modiano present an elegant *source transmit power selection* algorithm which can compute node-disjoint paths with minimum total energy. In polynomial time. However, to the best of our knowledge, the tradeoff between path lifetime and total energy consumption in node-disjoint path routing has not been addressed before. This is the subject of study of our present paper.

In this paper, we propose two polynomial time algorithms for computing node-disjoint paths under constraints. The first algorithm can construct a pair of node-disjoint paths whose total energy is minimum under the constraint that the lifetime is no small than a given threshold. This algorithm is presented for some application, especially some applications in wireless ad-hoc sensor network, in which long-time transmission may be needed to deliver the continuous information stream from a source node to a sink. It always guarantees that the qualified pair of node-disjoint paths will be found when exist. In this way, the packet rejection ratio can be decreased and network throughput can be improved. The second algorithm can compute a pair of node-disjoint paths whose lifetime is maximum under the constraint that the total energy consumption is bounded by a given threshold. The motivation for presenting this algorithm is to maximize the network lifetime by avoiding both using nodes with low residual energy as relay nodes. However, going through nodes with high residual energy may be costly as compared to the minimum energy paths. Too much total energy consumption may also decrease the network lifetime. That is the reason why giving a energy bound.

The rest of the paper is organized as follows. In Section II, we define the problems and some notations. Related works are

This research was supported in part by ARO grant DAAD19-00-1-0377, NSF ITR grant ANI-0312635, and a seed grant from CEINT–The Consortium Embedded and Internetworking Technologies.

discussed in Section III. Our two algorithms are presented in Section IV and Section V. We present our simulation results in Section VI. We conclude the paper in Section VII.

II. Definitions and Notations

We consider a wireless ad-hoc network consisting of n nodes $v_1, v_2, \ldots, v_n$ that have omni-directional antennas and can dynamically adjust their transmit power. We will use $w(v)$ to denote the *residual energy* at node v. All nodes have a maximum transmit power $\mathcal{T}_{max}$, while each node can transmit at any power level in the range $[0, \mathcal{T}_{max}]$. We follow a commonly used wireless propagation model from [7] where the received signal power attenuates proportional to $d^{-\alpha}$, where d is the Euclidean distance between the receiver and the transmitter and α is a constant, typically between 2 and 4, depending on the wireless medium [7].

Let $d(u,v)$ denote the Euclidean distance between nodes u and v. Let $\mathcal{P}$ be the minimum signal power required at the receiving node. Then the minimum transmit power at node u for the signal to be received at node v is $T_{min}(u,v) = \mathcal{P} \times d(u,v)^{\alpha}$. To support the *directed wireless link* (u,v), the transmit power $T(u)$ at node u must be in the range $[T_{min}(u,v), \mathcal{T}_{max}]$. Therefore the *lifetime of wireless link* (u,v) is $l(u,v) = \frac{w(u)}{T_{min}(u,v)}$ and the *lifetime of node* u is $l(u) = \min\{l(u,v) | (u,v) \text{ is a wireless link}\}$. Let $T(u)$ denote the transmit power at node u. The energy consumption rate at node u is $T(u)$ per unit time. Therefore $l(u)$ is the same as the number of time units node u can last for transmitting at a power level of $T(u)$.

Let T be any mapping from the network nodes to the interval $[0, \mathcal{T}_{max}]$, where $T(u)$ represents the transmit power at node u. Then T uniquely defines a *directed graph* G_T, where the vertices of G_T are the n network nodes and the edges of G_T are the directed wireless links: (u,v) is a directed edge of G_T if and only if $T(u) \in [T_{min}(u,v), \mathcal{T}_{max}]$. We will use $V(G_T)$ and $E(G_T)$ to denote the vertex set and edge set of G_T respectively.

A *connection request* ρ is defined by a source node $s = s(\rho)$ and a destination node $t = t(\rho)$. Routing along node-disjoint multipaths can enhance both survivability and data confidentiality([10], [13]). Very often, a connection request is given together with a lifetime threshold L or an energy consumption threshold $\mathcal{T}$. In such cases, we are interested in either computing a pair of node-disjoint paths with minimum total energy under the lifetime constraint or computing a pair of node-disjoint paths with maximum lifetime under the energy consumption constraint.

The *lifetime of a pair of node-disjoint paths* is the minimum among the lifetimes of the source nodes and the relay nodes to keep the paths alive. The *total energy consumption of a pair of node-disjoint paths* is the summation of the transmit powers over the source nodes and the relay nodes. We are interested in the following optimization problems.

Definition 1: Given a source node s and a destination node t, the **Minimum Energy node-Disjoint Path routing (MEDP)** problem seeks a mapping T such that there is a pair of node-disjoint paths from s to t in G_T and that $\sum_{i=1}^{n} T(v_i)$ is minimized. The pair of node-disjoint paths and the transmit powers at all transmitting nodes are computed when such a pair exists.

Definition 2: Given a source node s and a destination node t, together with a lifetime threshold $L > 0$, the **minimum energy Lifetime-Bounded node-Disjoint Path routing (LBDP)** problem seeks a mapping T such that $T(u) \leq \frac{w(u)}{L}$ for every node u and that there is a pair of node-disjoint paths from s to t in G_T and that $\sum_{i=1}^{n} T(v_i)$ is minimized. The pair of node-disjoint paths and the transmit powers at all transmitting nodes are computed when such a pair exists.

Definition 3: Given a source node s and a destination node t, together with an energy threshold $\mathcal{T} > 0$, the **Maximum Lifetime energy-bounded node-Disjoint Path routing (MLDP)** problem seeks a mapping T such that $\sum_{i=1}^{n} T(v_i) \leq \mathcal{T}$ and that there is a pair of node-disjoint paths from s to t in G_T with maximum possible lifetime. The pair of node-disjoint paths and the transmit powers at all transmitting nodes are computed when such a pair exists.

III. Related Work

Many routing protocols have been proposed in the literature for the wireless ad-hoc networks [6], [12]. AODV proposed in [12] is a simple flooding-based routing scheme. [6] assumes that each node is aware of its location and presents a greedy geometric routing algorithm.

Due to the energy-constraint characteristics of nodes in wireless ad-hoc networks, energy-efficient routing for extending network lifetime or improving network throughput draw more and more attention. Chang and Tassiulas [2] formulate the lifetime maximization problem as the well studied multicommodity flow problem and propose an efficient algorithm to select the route for each packet. Moreover, their algorithm can give an optimal solution if assuming the power levels of all nodes are fixed, provided that the sequence of packets which will be delivered are given as the input of their algorithm. Since this is not very practical for highly dynamic ad-hoc networks, an on-line algorithm aiming for lifetime maximization is proposed in [7]. Their algorithm can construct a cost-bounded single path with maximal minimum residual energy for each on-line request. Li and Wan formulate several constrained shortest path problem in wireless network including max life energy-bounded path problem, max width energy-bounded path and so on. They give both centralized algorithms and distributed problems for all those algorithms. Kar *et al.* in [5] improve results from [7] in terms of both throughput and lifetime. In addition, they prove that the worst-case performance of their algorithm is bounded within a factor of $O(\log(\text{network size}))$ of the optimal solution.

The routing algorithms discussed so far can only compute a single path for each request. Recently, people begin to seek fault-tolerant routing scheme for wireless network. Generally, the disjoint paths are constructed to tolerate node/link failures. Lou and Fang [10] propose using multipath routing to enhance data confidentiality in an insecure network. Srinivas and Modiano [13] point out the differences between disjoint path problem in wireless network and that in traditional networks studied by Suurballe [14]. They propose an elegant optimal algorithms for finding both node-disjoint and link-disjoint paths in a wireless network. In this paper, we are only interested in node-disjoint paths.

Other related problems in this area include minimum energy topology control, which has been studied, among other, by Cheng *et al.* [3] and Lloyd *et al.* [9].

IV. Minimizing Total Energy under Lifetime Constraint

In this section, we present an efficient algorithm for solving **LBDP**. The algorithm is presented as Algorithm 1.

Algorithm 1 follows the idea of source transmit power selection of [13]. The difference here is that we are only interested in the wireless links whose lifetime is at least L.

In Step_1 of the algorithm, we construct a directed graph G which contains every wireless link whose lifetime is at least L. To deal with the complications due to wireless multicast advantage, Srinivas and Modiano [13] introduce the idea of source transmit power selection. Once the transmit power of the source node is fixed, the corresponding problem can be solved efficiently using Suurballe's algorithm [14]. In Step_2 of the algorithm, we compute all of the transmit power levels we need to consider at the source node. Clearly k is at most $n-1$. In Step_3 of the algorithm, we compute the minimum cost solutions for each value of the source transmit power using Suurballe's algorithm. In Step_4 of the algorithm, we output the computed solution.

The basic idea of Algorithm 1 follows that of Srinivas and Modiano [13]. However, when the goal is to minimize the total energy only, one may end up with a pair of paths whose lifetime is shorter than L. That may leads to loss of data and requires reconstruction of the path pairs, which is not a practical solution. This is where Algorithm 1 finds its applications because it guarantees to find a pair of node-disjoint paths with minimum total energy under the lifetime constraint. Fig. 1 illustrates this concept in more details.

Theorem 1: The worst case running time of Algorithm 1 is $O(n^3)$. Whenever a pair of node-disjoint s–t path pair with lifetime at least L exists, Algorithm 1 finds such a path pair with minimum total energy.

PROOF. Step_1 takes $O(n^2)$ time. Step_2 takes $O(n)$ time. Step_3 takes $O(n^3)$ time as it needs to apply Suurballe's algorithm $O(n)$ times. Step_4 takes $O(n)$ time. Therefore the worst case running time of Algorithm 1 is $O(n^3)$.

The correctness of the algorithm lies in the fact that once the source transmit power is fixed, selecting the node-disjoint path pair and the corresponding transmit powers at relay nodes is equivalent to computing a pair of node-disjoint paths in G_i with minimum total cost.

Since Algorithm 1 only considers wireless links whose lifetime is at least L, the path pair computed must have a lifetime at least L. In addition, since the algorithm considers all wireless links whose lifetime is at least L and that the source transmit powers considered covers all possible one-hop neighbors of the source node, Algorithm 1 computes node-disjoint s–t path pair with lifetime at least L, whenever such a pair exists. □

Algorithm 1 LBDP

INPUT: The locations and residual energies of all n nodes $v_1, v_2, \ldots, v_n$; A connection request ρ with source $s(\rho)$, destination $t(\rho)$, along with a lifetime threshold $L > 0$.

OUTPUT: Either block the request or establish a pair of node-disjoint s–t paths with minimum total energy among all those whose lifetime is at least L.

step_1 Construct a directed graph G in the following way. The set of vertices V of G contains all n nodes $v_1, v_2, \ldots, v_n$ in the network. The set of directed edges E of G contains all order pairs $(u, v) \in V \times V$, (u, v) such that $w(u) \geq L \times T_{min}(u, v)$, where $w(u)$ is the residual energy at node u and $T_{min}(u, v)$ is the minimum transmit power at node u for node v to receive the signal from node u correctly.

step_2 Order the different transmit power levels at the source node s in increasing order $0 = T_0 < T_1 < T_2 < \cdots < T_k \leq \max\{\mathcal{T}_{max}, \frac{w(s)}{L}\}$ such that for any $T' \in [T_{i-1}, T_i)$, the number of wireless links incident from node s when $T(s) = T'$ is the same as that when $T(s) = T_{i-1}$ but is smaller than that when $T(s) = T_i$.

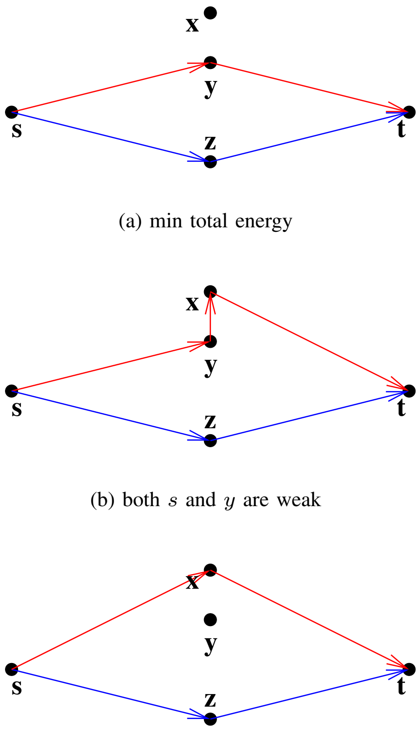
step_3 for $i := 1$ to k do
  Construct a directed graph G_i and assign edge cost in the following way: (s, v) is a directed edge
  in G_i if and only if $T_{min}(s, v) \leq T_i$. Each such directed edge (s, v) has a cost $c(s, v) = 0$. For
  any node $u \neq s$, (u, v) is a directed edge in G_i if and only if $T_{min}(u, v) \leq \frac{w(u)}{L}$. Each such
  directed edge (u, v) has a cost $c(u, v) = T_{min}(u, v)$.

  Use Suurballe's algorithm to find a pair of node-disjoint s–t paths with minimum total energy.
  if such a pair does not exist do
    Set $c_i = \infty$;
  else
    Set c_i to the total cost of the computed path pair; Save the path pair;
  endif
endfor

step_4 if $\min\{c_i | 1 \leq i \leq k\} = \infty$ do
  Block the connection request;
else
  Let $c_{i*} = \min\{c_i | 1 \leq i \leq k\} = \infty$; for every node u do Set $T(u) := 0$ endfor ;
  Set $T(u) = T_{min}(u, v)$ for each edge (u, v) on one of the two paths such that $u \neq s$;
  Set $T(s) := T_{i*}$;
endif

Remark 1: Algorithm 1 as presented is a centralized algorithm, as is the algorithm of [13]. However, such a centralized algorithm can be easily transformed into a distributed algorithm in the following way.

The source node s can send a HELLO message with its transmit power set to $\mathcal{T}_{max}$ with its ID, location and residual



(a) min total energy

(b) both s and y are weak

(c) s is strong but y is weak

Fig. 1. Node-disjoint path pair for different objectives. If the goal is minimize total energy in the two paths, the path pair in (a) is the optimal solution. However, it may happen that the lifetime of wireless link (y, t) is shorter than the given lifetime threshold L. If both (y, x) and (x, t) are strong enough, the path pair in (b) has the total energy under lifetime constraint. If (y, x) is not strong enough either, but (s, x) is strong enough, the path pair in (c) has the total energy under lifetime constraint.

energy piggybacked in the HELLO message. Upon receiving the HELLO message from the source node, a node will reply with its ID, location and residual energy to the source node. The source node can then compute the list $T_1, T_2, \ldots, T_k$ and starts a distributed version of Suurballe's algorithm (using distributed Bellman-Ford) for each source transmit power level. This practice has been used in [8].

V. Maximizing Lifetime under Energy Constraint

In this section, we present an efficient algorithm for solving **MLDP**. The algorithm is presented as Algorithm 2.

Algorithm 2 uses Algorithm 1 as a subroutine for $O(\log n)$ times while bisecting the set of possible lifetime values that need to be considered.

In Step_1 of the algorithm, we compute the set $\mathcal{L}$. Since there are $O(n^2)$ ordered pairs of nodes, $\mathcal{L}$ has cardinality of $O(n^2)$ and can be computed in $O(n^2)$ time. In Step_2 of the algorithm, applies Algorithm 1 $O(\log n)$ times. Therefore we have proved the following theorem.

Theorem 2: The worst case running time of Algorithm 2 is $O(n^3 \log n)$. Whenever a pair of node-disjoint s–t paths with total energy at most $\mathcal{T}$ exists, Algorithm 2 finds such a path pair with maximum lifetime. $\square$

Algorithm 2 MLDP

INPUT: The locations and residual energies of all n nodes $v_1, v_2, \ldots, v_n$; A connection request ρ with source $s(\rho)$, destination $t(\rho)$, along with a energy consumption threshold $\mathcal{T} > 0$.

OUTPUT: Either block the request or establish a pair of node-disjoint s–t paths with maximum lifetime among all those whose total energy is at most $\mathcal{T}$.

step_1 Compute the set of distinct values $0 < L_1 < L_2 < \cdots < L_k$ such that for every order pair of nodes (u, v), there is some index i $(1 \le i \le k)$ such that $\frac{w(u)}{T_{min}(u,v)} = L_i$. Let $\mathcal{L} = \{L_1, L_2, \ldots, L_k\}$.

step_2 Use bisection on $\mathcal{L}$ to find the largest L_i such that the corresponding solution to **LBDP** has total energy consumption no more than $\mathcal{T}$.

if such a value cannot be found do
  Block the connection request;
else
  Output the corresponding solution;
endif

VI. Simulation Results

In this section, we evaluate the performance of our algorithms through simulations. We consider networks of 50 nodes randomly located in a 50×50 region. Every node has the maximum transmit range of 100, which means that nodes can communicate with each other directly. The energy required for transmitting a message with unit size from node u to node v is $0.00001 * d(u, v)^3$. References [5] and [7] both use similar energy consumption models.

In the first simulation, we compare the performance of Algorithm 1 (LBDP) with the minimum energy node-disjoint path algorithm (MEDP) proposed in [13] with regard to the network throughput. Initially, 100 units energy is assigned to every node and then we inject the network with 1000 randomly generated packets. The source and destination of each packet are randomly chosen and the sizes of packets are drawn from a uniform distribution between 1 and 100 units. When a packet arrives, each algorithm will be invoked to compute two node-disjoint paths. If the algorithm can not return a solution or the lifetime of returned paths cannot satisfy the requirement imposed by the packet size, this packet will be rejected. We count the total size of successfully delivered packets and use it to represent the throughput of the network. We run simulations on 10 different randomly generated networks. Table 1 shows the simulation results.

In table I, for each algorithm, the left column shows the total size of packets that have been successfully delivered in one trial and the right columns have corresponding ratios. We can see that our algorithm outperforms the MEDP algorithm from [13] in all trials. That is because it is guaranteed that if there exists a pair of node-disjoint paths which can satisfy the lifetime requirement of one packet then our algorithm can find them. However, the MEDP algorithm from [13] can not guarantee that. So more packets will be rejected by their algorithm, especially some large packets. On average, our

TABLE I
Network Throughput

Trial	MEDP		LBDP		Inc(%)
	size	ratio(%)	size	ratio(%)	
1	42773	86.60	48196	97.58	12.68
2	36921	74.76	48158	97.51	30.43
3	39509	80.00	47587	96.35	20.44
4	33910	68.66	45359	91.84	33.76
5	47431	96.04	49082	99.38	3.48
6	43412	87.90	48553	98.31	11.84
7	40818	82.65	48174	97.54	18.02
8	34007	68.86	47635	96.45	40.07
9	43366	87.80	48500	98.20	11.85
10	37019	74.95	43437	87.95	17.34
Avg	39916.6	80.82	47468.1	96.11	18.92

algorithm improves network throughput by 18.92%.

In the second simulation, the network lifetime is used as an metric to evaluate the performance of Algorithm 2 (MLDP) and MEDP algorithm from [13]. We define the network lifetime as the time when there is one node which is drained out of energy. Every node has initial energy of 3 units. Packets with random source and destination and unit size are generated continuously and injected to the network until some node is out of energy.In addition, we set the energy-bound to be 2 times of total energy cost of minimum energy path pair. We count the total number of successfully delivered packets as the lifetime. We compare those two algorithms over 10 trials and each trial is executed on a randomly generated network.

TABLE II
Network Lifetime

Trial	MEDP	MLDP	Inc(%)
1	797	1008	26.47
2	915	1675	83.06
3	986	1618	64.10
4	569	1273	123.73
5	702	1829	160.54
6	1014	1775	75.05
7	993	1563	57.40
8	807	1527	89.22
9	864	1483	71.64
10	616	941	52.76
Avg	826.3	1469.2	77.80

Table II shows the number of successfully delivered packets by each algorithm before some node in the network goes out of energy. We find that compared with MEDP algorithm in [13], our algorithm extends the network lifetime in every trial and the network lifetime is prolonged by 77.80% on average. The total energy consumption by using our algorithm may be greater than MEDP algorithm of [13] for a particular path pair. However, our algorithm can avoid using some nodes which have relatively low energy levels to construct paths so it can achieve a more uniform distribution of residual energy. In MEDP algorithm in [13], it could be very possible that some nodes are used over and over again and depleted very quickly.

VII. CONCLUSIONS

In this paper, we have presented two efficient algorithms for computing a pair of node-disjoint paths in a wireless ad-hoc network, taking into consideration of both lifetime and total energy consumption. Our first algorithm can be used to find a pair of node-disjoint paths with minimum total energy subject to lifetime constraint. Our second algorithm can be applied to find a pair of node-disjoint paths with maximum lifetime subject to total energy constraint. Preliminary simulation results show that our first algorithm outperforms existing algorithm in terms of network throughput by 19% and that our second one outperforms existing algorithm in terms of network lifetime by 78%. Possible future research topics include extending these techniques to survivable multicast in wireless ad-hoc networks, along the lines of [4], [11], [16]. We also intend to report results of distributed implementations of our algorithms in a future paper.

REFERENCES

[1] J. Bang, S. Tekinay and N. Ansari, Performance analysis of cell switching management scheme in wireless packet communications; *Proceedings of IEEE Globecom'2001*, pp. 3639–3643.

[2] J.H. Chang, L. Tassiulas, Energy conserving routing in wireless ad-hoc networks; *Proceedings of IEEE Infocom'2000*, pp. 22–31.

[3] X. Cheng, B. Narahari, R. Simha, M.X. Cheng, D. Liu, Strong minimum energy topology in wireless sensor networks: NP-completeness and heuristics, *IEEE Transactions on Mobile Computing*, Vol. 2(2003), in press.

[4] A. Itai and M. Rodeh, The multi-tree approach to reliability in distributed networks, *Information and Computation*, Vol. 79(1988), pp. 43–59.

[5] K. Kar, M. Kodialam, T.V. Lakshman, L. Tassiulas, Routing for network capacity maximization in energy-constrained ad-hoc networks, *Proceedings of IEEE Infocom'2003*, pp. 673–681.

[6] B. Karp, H. T. Kung, GPSR: greedy perimeter stateless routing for wireless networks, *Proceedings of ACM Mobicom'2000*, pp. 243–254.

[7] Q. Li, J. Aslam, D. Rus, Online power-aware routing in wireless ad-hoc networks, *Proceedings of ACM Mobicom'2001*, pp. 97–107.

[8] X.Y. Li, P. J. Wan, Y. Wang, O. Frieder, Constrained shortest paths in wireless networks, *Proceedings of IEEE Milcom'2001*, pp. 884–893.

[9] E. Lloyd, R. Liu, M. Marathe, R. Ramanathan, S.S. Ravi, Algorithmic aspects of topology control problems for ad-hoc networks, *Proceedings of ACM MobiHoc'2002*, pp. 123–134.

[10] W. Lou, Y. Fang; A multipath routing approach for secured data delivery, *Proceedings of IEEE Milcom'2001*, pp. 1467–1473.

[11] M. Médard, S.G. Finn, R.A. Barry and R.G. Gallager, Redundant trees for preplanned recovery in arbitrary vertex-redundant or edge-redundant graphs, *IEEE/ACM Transactions on Networking*, Vol. 7(1999), pp. 641–652.

[12] C.E. Perkins, E.M. Royer, Ad-hoc on-demand distance vector routing, *Proceedings of IEEE WMCSA'1999*, pp. 90–100.

[13] A. Srinivas, E. Modiano, Minimum energy disjoint path routing in wireless ad-hoc network, *Proceedings of ACM Mobicom'2003*, pp. 122–133.

[14] J.W. Suurballe, Disjoint paths in a network, *Networks*, Vol. 4 (1974), pp. 125–145.

[15] J. E. Wieselthier, G. D. Nguyen and A. Ephremides, On construction of energy-efficient broadcast and multicast trees in wireless networks, *Proceedings of Infocom'2000*, pp. 585–594.

[16] G. Xue, L. Chen and K. Thulasiraman, Quality of service and quality of protection issues in preplanned recovery schemes using redundant trees, *IEEE JSAC*, Vol. 21(2003), pp. 1332–1345.