

Power-Aware 3D Position-based Routing Algorithms for Ad Hoc Networks

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Abstract—A crucial problem in ad hoc networks is finding an efficient and correct route between a source and a destination; however for many networks, a more important problem is providing an energy efficient route because of, for example, the limited battery life of the wireless nodes. Most previous routing protocols make the routing decision without taking into account the energy budget of the nodes. In addition, when using a fixed transmission power, nodes may waste power by transmitting with more power than is needed for correct reception. In position-based routing algorithms, the nodes use the geographical position of the nodes to make the routing decisions. In this paper we present several localized power-aware 3D position-based routing algorithms that increase the life-time of the network by maximizing the life time of the nodes. These new algorithms use the idea of replacing the constant transmission power of the node with an adjusted transmission power during two stages – first a lower power while discovering the neighboring nodes, and, if needed, a second higher transmission power during the routing process. We evaluate our algorithms and compare their power savings with the current power-aware routing algorithms. The simulation results show a significant improvement in the energy saving (up to 50%).

I. INTRODUCTION

Wireless ad hoc networks are a collection of nodes that can communicate without a fixed infrastructure. Such networks are usually represented by simple graphs where the vertices have precise geometric locations and the edges are straight lines. In ad hoc networks, each node u has a maximum transmission power. For each ordered pair of nodes (u, v) , there is an associated transmission power threshold, denoted by $P(u, v)$, which indicates the transmission power needed by u so that its signal can be received by v . The transmission power threshold for a pair of nodes depends on a number of factors including the distance between the transceivers, interference, noise, environment, etc. [14]. A node transmitter can send a message directly to the nodes within its transmission range; otherwise multihop routing is used to send the packet to a node outside the node transmission range. In many applications, since wireless nodes are battery operated devices, they need to conserve energy so that node life is maximized. Transmission power management which selects the optimized power level of nodes is one of the primary means of increasing the life time of the nodes. The power consumption at each node in an ad hoc network can be divided into three phases, according to functionality [2]: (i) the power consumed for transmitting the

message; (ii) the power consumed during message reception; and (iii) the power consumed while the node is idle. In previous work [15], [18], two main metrics have been used to optimize power routing for a sequence of messages. The first metric, called the *power metric*, tries to minimize the energy consumed for each message. If the transmission range is fixed for all the nodes then the number of nodes in the route path is used as the energy required for the routing task. This metric can be optimized if the nodes can adjust their transmission range. Then the constant metric can be replaced by a power metric that depends on distances between nodes. In formal terms [7], let e_j be the energy required by the packet j to traverse a set of nodes n_1, n_2, \dots, n_k , where n_1 is the source and n_k is the destination. If $p(n_i, n_{i+1})$ is the power needed to forward j over one hop from n_i to n_{i+1} , then the aim of the power metric is $\min_{\forall j} e_j$ where $e_j = \sum_{i=1}^{k-1} p(n_i, n_{i+1})$.

A drawback of the power metric is that some nodes may be repeatedly chosen, which quickly leads to their failure. In many cases this may result in the loss of network connectivity. The second metric, called network survivability [16], [4] or *cost metric* [18], tries to maximize the life time of the nodes. We will focus on the second metric for our routing algorithms.

In position-based routing, the host forwards a message based on its position, the position of the destination, and the position of the hosts to which it can communicate directly. Recent research in this field usually addresses such routing algorithms in two dimensional space (2D) [13], [12], [17], [18]. However, in real applications, nodes may be distributed in 3D space. In this paper, we propose several 3D power aware position-based routing algorithms which try to maximize the delivery rate and, as well, maximize the network connectivity time (the number of messages that can be sent by the whole network). The new algorithms are based on the idea of replacing the constant transmission power of the node with an adjusted transmission power during two stages – while discovering the neighboring nodes and during the routing process. Our simulation experiments show that the delivery rates of the new algorithms is nearly 100% and there is significant improvement on the network life time (up to twice the life time).

After stating the network model in the following section, we present the basics of position-based and power aware routing algorithms in Sections 3 and 4. In Section 5 we give a detailed description of the new routing algorithms.

Experimental results to demonstrate the much improved performance of the proposed methods in comparison with existing techniques are presented in Section 6. Finally, Section 7 draws the conclusions of the paper.

II. NETWORK MODEL

Assume that the set of n wireless hosts is represented by a point set S in the 3D space. All the network hosts have the same communication range R , which is represented as a sphere volume of radius R . Two nodes are connected by an edge if the Euclidean distance between them is at most R . The resulting graph is called a unit disk graph (UDG). The Gabriel Graph [6] is a subgraph of the graph G that can be constructed locally as follows: given any two adjacent nodes u and v in G , the undirected edge (u, v) belongs to Gabriel Graph if, and only if, no other node $w \in G$ is located in the sphere of minimum diameter circumscribing (u, v) . The Gabriel Graph is planar if G is 2D-UDG.

Position based routing protocols assume that the node knows: (1) the coordinates (x, y, z) of its position, which can be obtained using a method like a global positioning system; (2) the location of its neighbors using a periodical exchange of control messages; and (3) the location of the destination, e.g., by using a location service [13]. The position-based routing task is to find a path from the source node to the destination node. It uses the local information at each node to determine how to route the packet. We are interested in the following performance measures for routing algorithms: the delivery rate, which is the percentage of times that the algorithm succeeds in delivering its packet, and the network survivability, which can be measured by the remaining power in the maximum used node during a set of consecutive routing messages.

III. RELATED POSITION-BASED ROUTING ALGORITHMS

Here we review the related position-based routing algorithms.

Greedy Routing[5]: the current node forwards the packet to the neighboring node that minimizes the remaining distance to the destination. This routing method suffers from the so-called local minimum phenomenon, in which a packet may get stuck at a node that does not have a neighbor that makes a progress to the destination, even though the source and destination are connected in the network.

2D Face Routing[3]: the routing takes place in a planar subgraph of the UDG, such as the Gabriel graph. The packets are routed over the faces of planar subgraph which are intersected by the line between the source S and the destination D , called SD , using the right hand rule. That is, the boundary of f is traversed in the counterclockwise direction, unless the current edge crosses SD at an intersection point closer to the destination than any previously discovered intersection point. In this case, the algorithm switches to the next face sharing the edge and continues with the right hand rule. This algorithm is repeated until the node arrives at the destination. Face routing may be used in practice in combination with algorithms that

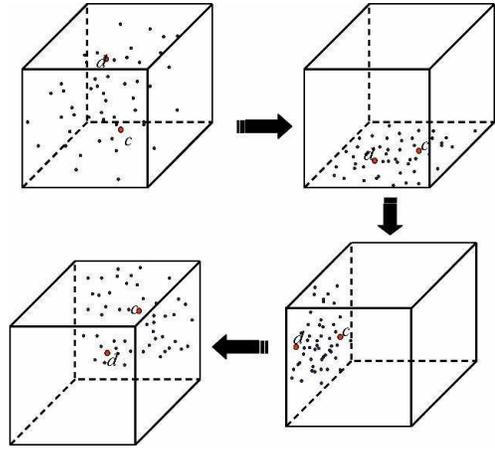


Fig. 1. CFace(3) routing algorithm. The algorithm attempts 2D face routing, cyclically until success, with the points projected onto the xy plane, the yz plane, and then the xz plane.

usually find shorter routes, such as the Greedy algorithm. The idea is to use Greedy routing until a local minimum is reached, whereupon the algorithm enters into recovery mode by switching to face routing. When the local minimum is bypassed, the algorithm switches back to Greedy routing, and so on. This algorithm is termed GFG (Greedy-Face-Greedy) by [3] and GPSR (Greedy Perimeter Stateless Routing) by [10].

The face routing algorithm guarantees delivery only in a 2D planar geometric graph. Since in 3D environments, faces may not exist, this algorithm cannot be directly applied to 3D graphs.

In [1] CFace(3) (Coordinate Face), a heuristic using a projective approach to adapt face routing to 3D graphs has been proposed, see Fig. 1. The algorithm may be summarized as follows. The 3D points are first projected onto the xy plane. Then face routing is performed on this projected graph. If the routing fails, i.e., a loop is detected, the points are then re-projected onto the second plane, the yz plane. Then face routing is performed again. If the routing again fails, the points are projected onto the third plane, the xz plane. The face routing is again performed. A simplified version of CFace(3), called CFace(1), attempts face routing with the points projected once only onto one of the xy , yz , or xz planes, randomly chosen. A more elaborate version of projection-based face routing was proposed in [9]. In [1], the authors propose a combination between CFace(3) and randomized progress-based algorithms.

IV. EXISTING POWER AWARE ROUTING ALGORITHMS

A general wireless model has been proposed in [14] in which the power consumption between two nodes at distance d is expressed as $u(d) = d^\alpha + c$ for some constant α and c . In [12], [17], [18] several power aware routing algorithms, that try to minimize the total energy consumed by the packet and also increase the network life time, have been proposed.

Let the current node be C , A is a neighbor of C , and the destination is D . Let $r = |CA|$, $d = |CD|$ and $s = |AD|$, where $s < d$. Let the cost of transmitting a packet between two nodes at distance k be $ak^\alpha + c$, where a, α, c are constants that depend on the wireless model. Let \bar{k} be the average length of all edges out from the source S . Let $f(A) = \frac{1}{g(A)}$, where $g(A)$ is the remaining lifetime for the node A . Also, $\bar{f}(A)$ is the average value of $f(x)$ for A and all neighbors x of A , $\bar{g}(A)$ is the average value of $g(x)$ for A and all neighbors x of A , R is the transmission radius.

The existing algorithms are summarized as follows [18]:

Power Algorithm: This algorithm tries to minimize the total energy consumed by the packet in the routing process, regardless of the available energy at the nodes. With the Power algorithm, the current node C chooses as a next node A which minimize the expression: $P(C, A) + P(A, D)$, where $P(C, A) = ak^\alpha + c$ is the cost to reach A and $P(A, D) = sc(a(\alpha - 1)/c)^{1/\alpha} + sa(a(\alpha - 1)/c)^{(a-\alpha)/\alpha}$, which is an assumption that the rest of the routing process is cost optimal.

Cost- i Algorithm: This algorithm uses the cost metric. It tries to maximize the network life time by carefully choosing the next node from the set of neighbors with plenty of energy. In this algorithm the current node chooses a next node A which minimizes the equation: $cost(A) = f(A) * t/R$, where $t = \bar{f}(A)$.

Cost- ii Algorithm: Since the factor t is network dependent, there are different versions of the previous algorithm. One of those algorithms is called *Cost-ii*. In this algorithm, the current node chooses one of its neighbors, A , which minimizes the equation: $cost(A) = f(A) * t/R$, where $t = 1/\bar{g}(A)$.

There is two ways to combine power and cost metrics into a single metric, based on the product or sum of the two metrics.

Power*Cost: In this algorithm, the current node chooses one of its neighbors, A , which minimizes the following equation: $Power*Cost(A) = Power*Cost(C, A) + Power*Cost(A, D)$, where $Power * Cos(C, A) = f(A) * (ar^\alpha + c)$ and $Power * Cost(A, D) = (sc(a(\alpha - 1)/c)^{1/\alpha} + sa(a(\alpha - 1)/c)^{(a-\alpha)/\alpha}) * \bar{f}(A)$.

Power+Cost: In this algorithm the current node chooses one of its neighbors A which minimize the equation: $Power+Cost(A) = (Power + Cost(C, A)) + (Power + Cost(A, D))$, where $Power + Cos(C, A) = [\bar{f}(A) * (ar^\alpha + c)] + [f(A) * (ar^\alpha + c)]$ and $Power + Cost(A, D) = (sc(a(\alpha - 1)/c)^{1/\alpha} + sa(a(\alpha - 1)/c)^{(a-\alpha)/\alpha}) * \bar{f}(A)$.

All the previous algorithms have a very low delivery rate (less than 50%) in a sparse network, because the next node may not make progress to the destination. So, Kuruvila *et al.* [12] proposed another set of power and cost aware routing algorithms that guarantee progress to the destination. In **Power Progress algorithm** the current node forwards the packet to one of its neighboring nodes that is closer to the destination than itself and minimizes $(r^\alpha + c) * d / (d - x)$. Similarly, in **Cost Progress algorithm**, the next node is the one that minimizes $f(A) / (d - x)$.

Since all the above algorithms are deterministic algorithms

which suffer from the local minimum, they do not guarantee the delivery of the message in a connected graph. Stojmenovic *et al.* [17] propose a guaranteed delivery algorithms in 2D space, which combine **Power (P)**, **Cost (C)**, and **Power*Cost (Pc)** algorithms with Face routing algorithm, similar to the way Greedy algorithm is combined with Face to define the GFG algorithm. Those algorithms start with **P,C**, or **Pc** forwarding decisions. Once the packet reaches a local minimum, the face routing starts. If the message arrives to a node closer to the destination than the local minimum node, the algorithm switches back to **P,C**, or **Pc** forwarding again. These algorithms have been called **PFP**, **CFC**, and **PcFPc** respectively.

V. NEW POWER AWARE ROUTING ALGORITHMS

Most of the routing algorithms without power awareness use a fixed transmission range for all the nodes, so the nodes may waste power by transmitting more than is needed for correct reception. The above power aware algorithms use an adaptive transmission range to transmit the data messages during the routing process, but they still use a fixed (maximum) transmission range for the control messages (periodic hellos) to tell neighboring nodes about its location. In this paper, we extend our previous work on 3D position-based routing algorithms for ad hoc networks to achieve higher packet delivery rates while increasing the life time of the network. Our new power aware routing protocols are based on the adjustments of the node transmission power at two stages – (*i*) while discovering the neighboring nodes; and (*ii*) during the routing process.

1)Power Adjusted Greedy algorithm (PAG): This algorithm can be summarized as follows:

- All nodes use the low transmission range μ , which equals half of their maximum transmission range, to discover their neighbors. This process is done periodically.
- Greedy routing is started between the source and the destination.
- If the packet reaches a local minimum (packet stuck at a node that does not have a neighbor that makes progress to the destination) at low transmission level, then the current node increases its transmission range by a factor of β and runs neighbor nodes discovery step again. Fig. 2 gives an example of this point: when the message arrives to the node B that does not have any neighbor that make a progress to the destination, B will increase its transmission range by a factor of β to find a new neighbors. Each node can adjust its transmission range just one time while routing a single packet.
- If the node does not discover a new neighbor that makes progress to the destination, then the algorithm fails, otherwise Greedy routing continues.

There are two main differences between this algorithm and the non-power aware Greedy algorithm. First, during the neighbor discovery phase, in *PAG* all the nodes exchange periodic hello messages with low transmission range. In *Greedy*, all the nodes are exchanging information by transmitting and receiving using the maximum transmission range. Also, during the routing phase (data packet routing process), in *PAG* the

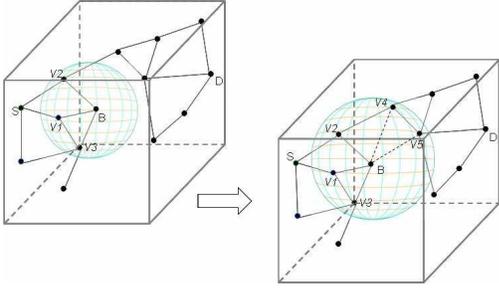


Fig. 2. A node may increase its transmission range in PAG algorithm

current node C forwards the message with power cost equal to $ad^\alpha + c$, where d is the distance between C and the next node A , while *Greedy* forwards the message with power cost equal to $ar^\alpha + c$, where r is the maximum transmission range.

2)PAG:CFace(3) The previous algorithm *PAG* and its associated fixed power *Greedy* has a great advantage in terms of power saving. In our simulations it suffers from a low delivery rate if the network is very sparse. Our solution is to use *CFace* routing if the *PAG* algorithm fails to deliver the message. The combination is called **PAG:CFace(3)** and can summarized as follows:

- The algorithm starts with *PAG* routing algorithm.
- If the current node adjusts its transmission range, and after that, it stays in the local minimum situation, then the algorithm changes to *CFace(3)* algorithm.
- If *CFace(3)* fails to deliver the message the algorithm fails.

3)PAG:CFace(1):PAG The only difference between this algorithm and *PAG:CFace(3)* is that instead of trying another projective plane if the first projective plane fails, it returns immediately back to the *PAG* algorithm. **PAG:CFace(1):PAG** is summarized in detail as follows:

- Our second hybrid algorithm starts with *PAG* algorithm.
- Once it arrives at a local minimum, and the adjusted transmission range does not help to get a new neighbor to make a progress to the destination, the algorithm switches to *CFace(1)*.
- *CFace(1)* traverses one projective plane, which is randomly one of the xy , yz , or xz planes starting from the local minimum C as the new source node.
- If the destination is not reached during *CFace(1)* and looping occurs, the algorithm goes back to *PAG*.

Fig. 3 shows an example of above mentioned algorithm, when the increasing of the transmission range at the local minimum node B did not give it any new neighbor, the algorithm switches to *CFace(1)*. If face routing on the pointed projected onto single plane does not lead to success then the algorithm switches back to *PAG*.

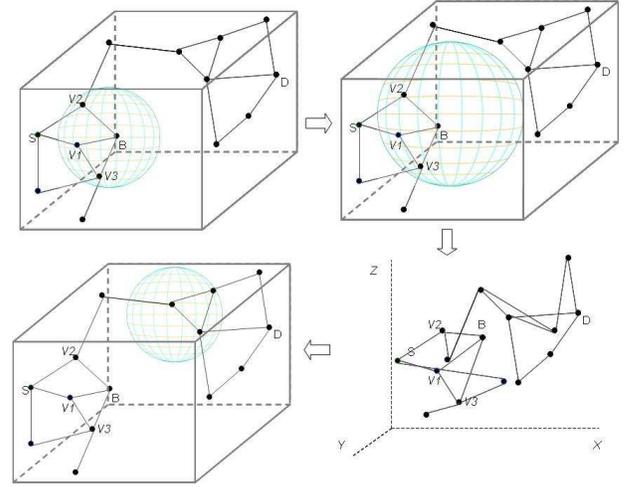


Fig. 3. PAG:CFace(1):PAG algorithm steps.

VI. PERFORMANCE EVALUATION OF POWER AWARE ROUTING ALGORITHMS

A. Simulation Environment

We use in our simulation the wireless model that has been proposed by Heinzelman et al. [8]. We assume the radio dissipates $E_{elec} = 50nJ/bit$ power to run the transmitter or receiver circuitry. Both transmitter and receiver nodes consume E_{elec} to transmit one bit. The radio dissipates $E_{amp} = 100pJ/bit/m^2$ to run transmit amplifier, and assume d^2 energy loss due to channel transmission, where d is the distance between nodes. This implies the sender consumes $(E_{amp} * d^2)$ power to transmit one bit. According to the above wireless model transmitting a k - bit message at distance d the transmitter expends $E_{Tx}(k, d) = E_{elec}(k) + E_{amp}(k, d)$, which equals $E_{elec} * k + E_{amp} * k * d^2$. To receive it, the receiver node expends $E_{Rx}(k) = E_{elec}(k)$, which equals $E_{elec} * k$.

In the simulation experiments, a random UDG with 95 points is generated in a cube with sides of size 100. Initially, for the algorithms with an adjusted transmission power, the transmission range for all nodes is set to $\mu = 25$, with the possibility that the node will increase its transmission range by the factor β , β being a fixed value between 1 and 2. For the algorithms with a constant transmission power, their transmission range is set to $\beta * 25$. Fig. 4 illustrates a histogram of the average nodes degrees for different transmission range, $\beta * 25$. A fixed size data packet of length 16 bytes is used in addition to a 6 bytes control packet that contains the ID, position, and current battery level of the node. Initially, all the nodes have an equal energy level. After generating a fully connected UDG, a set of 100 source-destination pairs is randomly chosen. All the routing algorithms are then applied in turn on the chosen source-destination pairs. An algorithm succeeds if a path to the destination is found. We compute the power cost of the maximum used node after applying the algorithms on these 100 source-destination pairs. To compute the packet delivery rate, this process is repeated with 100 random graphs and the percentage of successful deliveries determined.

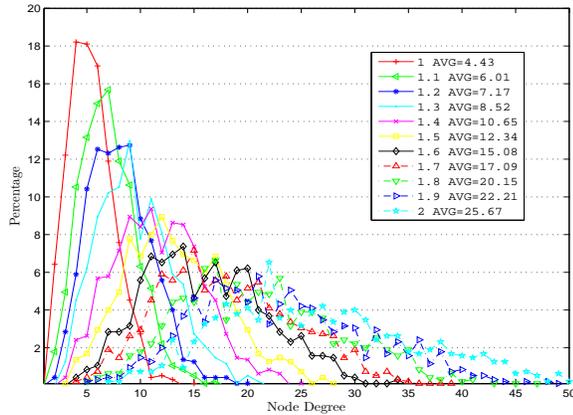


Fig. 4. Histogram of the average node degree with different transmission ranges, $\beta * 25$.

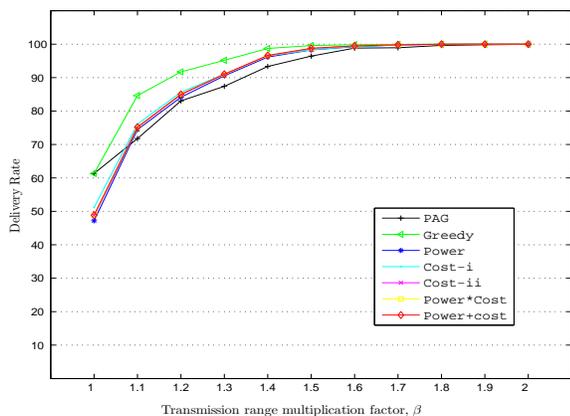


Fig. 5. The average delivery rate of PAG and different power aware routing algorithms.

B. Observed Results

Fig. 5 shows the delivery rate of *PAG*, *Greedy* and the other power aware routing algorithms. Fig. 6 show the average cost of the maximum used node. It is immediately evident from these figures that the delivery rate of *PAG* reaches about 100% (the same as fixed radius *Greedy*) when β is greater than 1.5, but with a decrease of the average max cost by more than 50%, which in turn increases the network life time to more than twice compared to that with a fixed transmission radius. The other power aware routing algorithms do not gain more than a 4% increase in the network life time. From Fig. 5, it can be seen that *PAG*, *Greedy* and all other studied algorithms have a low delivery rate if the network is sparse and have a 100% delivery rate in dense network ($\beta \geq 1.7$). This can be explained by the number of neighbors (the degree of the nodes as shown in Fig. 4); fewer neighbors implies less chance to chose a good route that makes progress to the destination.

Figs. 7 and 8 show the exact expected results that our second routing algorithm *PAG:CFace(3)* increases the delivery rate to around 100% for both sparse and dense networks. The drawback is an increase of the average maximum cost over *PAG*. Still *PAG:CFace(3)* has a network life time of almost

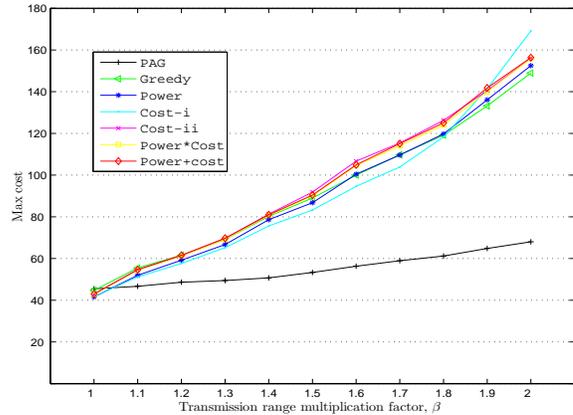


Fig. 6. The average cost of the maximum used node after 100 source-destination pairs routing process of *PAG* and different power aware routing algorithms.

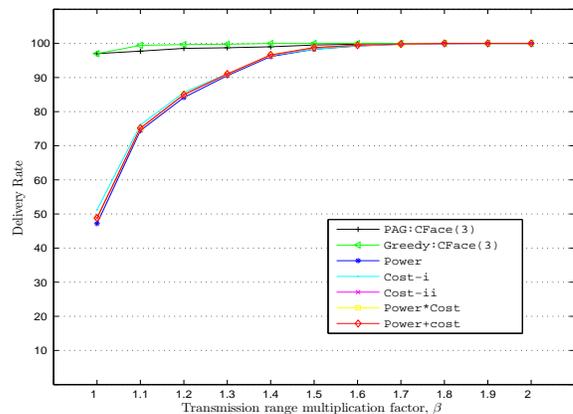


Fig. 7. The delivery rate for *PAG:CFace(3)*, *Greedy:CFace(3)* and the other power-aware routing algorithms.

twice that of the regular *Greedy:CFace(3)* if β is greater than 1.5.

The result of the third algorithm are shown in Figs. 9 and 10. This algorithm tries to compromise between the two groups of algorithms *Greedy* and *PAG* on one side, and *PAG:CFace(3)* and *Greedy:CFace(3)* on the other side. First, in terms of delivery rate, as expected, *PAG:CFace(1):PAG* has nearly a 100% delivery rate if β is greater than 1.5. The delivery rate for the sparse network is very high, more than 95% compared with less than 80% for *PAG*. This algorithm still increases the network life time by decreasing the power consumption from the nodes. The most important advantage of all our new algorithms is the great increase of the network life time while preserving the delivery rates. The same simulations have been done using the Compass routing algorithm [11] in place of the *Greedy* algorithm, generating new routing algorithms, called *PAC*, *PAC:CFace(3)*, and *PAC:CFace(1):PAC*. The results are nearly the same as for the *Greedy*-based algorithms.

VII. CONCLUSION

This paper describes three localized power-aware routing algorithms for 3D ad hoc and sensor networks under two

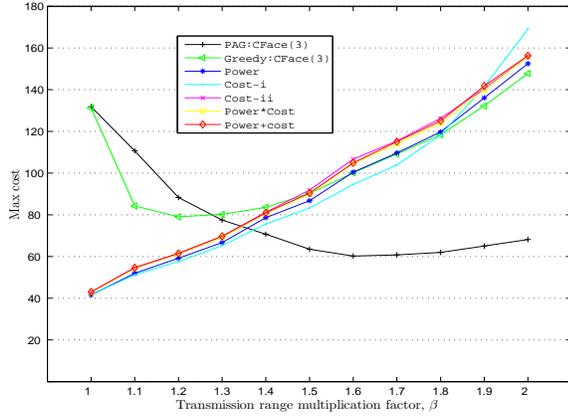


Fig. 8. The average maximum cost for PAG:CFace(3), Greedy:CFace(3) and the other power-aware routing algorithms.

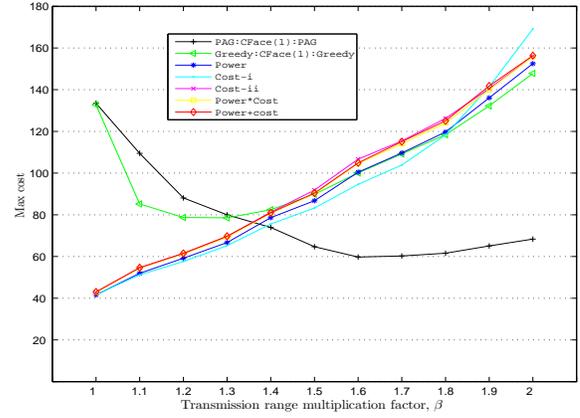


Fig. 10. The average maximum cost for PAG:CFace(1):PAG, Greedy:CFace(1):Greedy and the other power-aware routing algorithms.

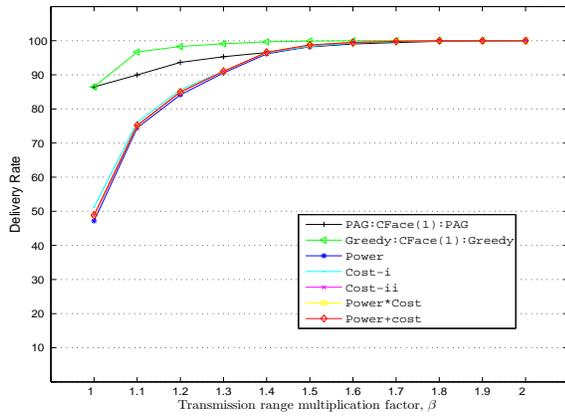


Fig. 9. The delivery rate for PAG:CFace(1):PAG, Greedy:CFace(1):Greedy and the other power-aware routing algorithms.

concurrent constraints: maximize the delivery rate while maximizing the life time of the network by minimizing the energy consumption by the nodes. Our new algorithms are based on the idea of replacing the constant transmission power of the node to an adjusted transmission power. The simulation results demonstrate that the new routing algorithm PAG with $\beta \simeq 1.5$ has a delivery rate near (100%) and increases the network life time to at least two times that for the Greedy algorithm. Our second and third algorithms, *PAG:CFace(3)* and *PAG:CFace(1):PAG*, increase the delivery rate for sparse networks to more than 95% as compared with 80% for *Greedy*. This is achieved while increasing the network life time by almost twice with $\beta \simeq 1.5$.

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