Multicost Routing over an Infinite Time Horizon in Energy and Capacity Constrained Wireless Ad-hoc Networks

Christos A. Papageorgiou[1][2], Panagiotis C. Kokkinos[1] and
Emmanouel A. Varvarigos[1][2]

[1] Department of Computer Engineering and Informatics,
University of Patras, 26500 Patras, Greece.
[2] Research Academic Computer Technology Institute, Patras, Greece

Abstract. In this work we study the dynamic one-to-one communication problem in energy- and capacity-constrained wireless ad-hoc networks. The performance of such networks is evaluated under random traffic generation and continuous energy recharging at the nodes over an infinite-time horizon. We are interested in the maximum throughput that can be sustained by the network with the node queues being finite and in the average packet delay for a given throughput. We propose a multicost energy-aware routing algorithm and compare its performance to that of minimum-hop routing. The results of our experiments show that generally the energy-aware algorithm achieves a higher maximum throughput than the minimum-hop algorithm. More specifically, when the network is mainly energy-constrained and for the 2-dimensional topology considered, the throughput of the proposed energy-aware routing algorithm is found to be almost twice that of the minimum-hop algorithm.

1 Introduction

In this work we study the dynamic one-to-one communication problem in energy- and capacity/interference-constrained wireless ad-hoc networks. In the model we consider, packets are generated at each network node according to a random process, over an infinite time horizon. All packets have equal length, and require one slot in order to be transmitted over a link. Each packet transmission consumes an equal amount of energy E. Time is slotted, and a new packet is generated at each node with probability p during a slot. Packet destinations are uniformly distributed over all nodes. In addition to the usual capacity and interference constraints, the network is also assumed to be energy constrained. More specifically, we assume that energy is generated at each node of the network at a *recharging rate* of X units of energy per slot, over an infinite time horizon. We propose a multicost energy-aware algorithm for routing the packets in an ad hoc network, and compare its performance to that of minimum-hop routing.

During our comparisons, we are interested in two performance criteria: a) the maximum stability region, which is defined as the maximum throughput that can be sustained by the network with the node queues being finite and

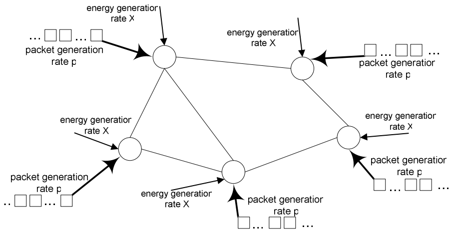

Fig. 1. The infinite-time horizon problem. Packets are generated at each node of the network with probability p during a slot, and have uniformly distributed destinations. Energy is also generated at each node at a rate X units of energy per slot

b) the average delay suffered by the packets for a given throughput, which is defined as the average time that elapses between the generation of a packet at a node and the time it is received at its destination. We obtain results on the way the maximum stability region of the routing protocols examined changes as a function of the energy generation rate X at steady-state. We also obtain results for the average packet delay as a function of the packet generation rate, when the network is both energy and capacity/interference constrained. Figure 1 summarizes the definition of the problem.

Most previous works [7] studied the performance of ad-hoc networks in the context of the *evacuation problem*, where the network starts with a certain number of packets that have to be served and a certain amount of energy per node, and the objective is to serve the packets in the smallest number of steps, or to serve as many packets as possible before the energy at the nodes is depleted. This is different from the *dynamic one-to-one communication problem* considered in this paper where packets and energy are generated at each node continuously.

In the simulations performed for a specific network topology, we find the maximum packet generation probability p_{max} at the network nodes for which the network is stable, and the average delay for a given packet generation probability $p < p_{max}$ in the stability region. In our experiments we examined two routing algorithms: a multicost energy-aware routing algorithm and the traditional minimum-hop algorithm. The results obtained show that the multicost energy-aware algorithm outperforms the minimum-hop algorithm, achieving larger maximum throughput p_{max} for all recharging rates tested, and a smaller average delay for a given $p < p_{max}$. More specifically, we found that for the 2-dimensional topology considered and in the region where the network is energy-constrained, the throughput of the energy-aware algorithm is almost twice that of the minimum-hop routing algorithm. We also obtain results on the way the average packet delay changes as a function of the traffic load for energy and capacity/interference limited ad hoc networks. We find that the average delay increases with the traffic load more abruptly when the traffic reaches its maximum limitation due to the energy constraint, while it increases more smoothly when the traffic reaches its maximum limitation due to the capacity/interference constraint. We also discuss the effect certain network characteristics, such as the node density, the geographical distance, and the transmission range play on network performance. We argue, for example, that the transmission range of the nodes plays a more important role on performance for energy-limited networks than it plays for capacity/interference-limited networks.

The remainder of the paper is organised as follows. In Section 2 we discuss the impact of the capacity and energy constraints on network performance. In Section 3 we describe the routing algorithms tested in our experiments. In Section 4 we outline the environment under which our experiments were conducted. Section 5 presents the simulation results obtained.

2 Capacity and Energy Limitations

The traffic load that can be inserted in a network is restricted by capacity and interference limitations, and by the energy recharging rate at the nodes. Several works have examined the effect these limitations have on the maximum achievable throughput, for a variety of assumptions on the network topology, the routing algorithm, and the traffic pattern [8],[5]. Energy and its best use has also been the subject of several works; see e.g. [10][2] and [4] where the energy reserves at the nodes are among the criteria that the routing algorithms consider.

Capacity/Interference Limitation: According to the IEEE 802.11 protocol under the RTS/CTS mechanism a node before transmitting using a transmission range R, reserves a transmission floor of area at least equal to πR^2 and at most equal to $\frac{4}{3}\pi R^2$ around it (depending on the relative distance of the transmitter and the intended receiver) and the nodes located in this area cannot transmit. Ad hoc networks that do not use 802.11 often use busy tones [3] to avoid the hidden terminal problem. If the node density is high, then all nodes at a distance of approximately $2R$ from a transmitting node (therefore a total area of $4\pi R^2$) are prevented from transmitting. Therefore, the number of other nodes forbidden from transmitting when a given transmission takes place is similar (within a constant factor) when a busy tone mechanism or an RTS/CTS mechanism is used, and is proportional to R^2 (Fig. 2).

Following [1], we define a collision free set as a set of links that can be used simultaneously without causing collisions or excessive interference at the receiving nodes. The number of simultaneous transmissions the network structure permits, is upper bounded by the maximum cardinality C of the collision-free sets. From the preceding discussion and a simple "sphere packing" argument we infer that C is upper bounded by $\frac{A}{kR^2}$, where A is the area covered by the network and k is a constant between π and 4π that depends on the MAC protocol used and the relative location of the nodes.

Assume now that packets are generated at each node of an N-node network with probability p during each slot, and a packet requires an average of $h(p)$ transmissions to arrive at its destination. All transmissions have a transmission range R and require energy E. The mean number of transmissions per slot is given by the product $N \cdot p \cdot a(p) \cdot h(p)$, where $a(p)$ is the ratio of the total number

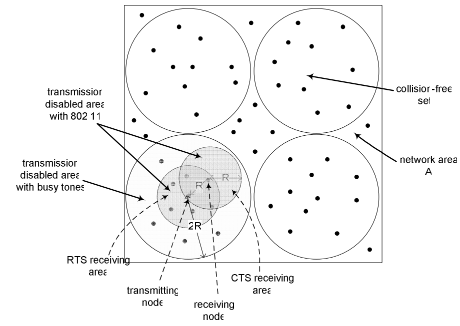

Fig. 2. The division of the network into collision-free sets

of packet transmissions over the number of successful transmissions required to get the packets to their destinations over the paths chosen. Therefore, for the network to be stable the following inequality must hold:

$$N \cdot p \cdot a(p) \cdot h(p) \leq C \leq \frac{A}{kR^2} \tag{1}$$

The number of hops of the paths $h(p)$ is roughly inversely proportional to the transmission range R of the nodes, and we have $h(p) \geq \frac{L}{R}$, where L is the average physical source-destination distance (with the inequality being closer to equality for dense networks and shortest distance routing). Assuming we are in the stable region and there is no buffer limitation, no packets are lost, and we have $a(p) \geq 1$. Consequently, a limit on the packet generation rate p posed by the capacity/interference constraints is given by

$$p \leq \frac{A}{kRNL} = \frac{1}{k\rho L} \cdot \frac{1}{R}, \tag{2}$$

where $\rho = N/A$ is the area node density

Energy Limitation: For a wireless ad-hoc network with energy rechargeable nodes to be stable, the mean energy expended at each time slot must be at most equal to the energy inserted in the network in the same period. The average energy expended in each slot is equal to $N \cdot p \cdot h(p) \cdot a(p) \cdot E$. We assume that all nodes use the same transmission radius R and expend energy equal to E for each packet transmission. The average energy inserted in the network during each slot is equal to $N \cdot X$, where X is the energy recharging rate at each node per slot. Consequently a necessary condition for the network to be stable is

$$N \cdot p \cdot h(p) \cdot a(p) \cdot E \leq N \cdot X \tag{3}$$

The energy expended E for a packet transmission can be expressed as $k'R^{\alpha}$, for some constant k' (which depends on the channel, the sensitivity of the receiver, and the desired BER), where α is between 2 and 4 depending on the power-loss model. Working in the same manner as in the previous paragraph, and using the inequality $h(p) \geq \frac{L}{R}$, we find that a necessary condition for stability due to the energy constraint is

$$p \leq \frac{X}{k'L} \cdot \frac{1}{R^{\alpha-1}} \tag{4}$$

The inequalities (2) and (4) show that the energy limitation depends more strongly on R than the network capacity/interference limitation. The stability region shrinks as R increases, showing that using small transmission range is beneficial both for capacity/interference-constrained and energy-constrained ad hoc networks. That is, the amount of traffic that can be served by the network increases when we decrease the transmission range of the nodes, both due to increasing network capacity (better reuse factor) and due to lower spending of the energy reserves. Since in most wireless environments $a > 2$ (a is close to 4 for urban environments), we conclude (at least for dense networks) that for R sufficiently small the network throughput is mainly constrained by capacity/ interference limitations, while for R sufficiently large it is constrained by energy limitations.

Equations (2) and (4) show that the energy limitation and the capacity/ interference limitation depend in similar ways on the average physical distance L in the network, with the achievable throughput per node falling as L increases. Another conclusion drawn from the above discussion is that even though the capacity/interference limitation decreases as the area node density ρ increases, the energy limitation is independent of ρ. In summary, we expect networks that are sparse or that have a small recharging rate X, or that use a large transmission radius R to be mainly energy-limited as opposed to capacity/interference limited.

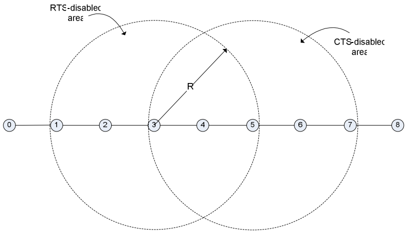

Fig. 3. The case of a linear ad hoc network using the RTS/CTS mechanism

Case of linear ad hoc networks: The preceding discussion assumes a 2-dimensional network. It is worth also studying briefly the case of linear (1-dimensional) ad hoc networks. Depending on whether busy tones or the RTS/CTS mechanism is used, each transmission prevents other nodes in a segment of length $k \cdot R$ from transmitting, where k is a constant between 2 and 4, depending on the MAC scheme used and the distance between the transmitter and receiver (Figure 3 illustrates the case where the RTS/CTS mechanism is used). If L is the length of the linear network, at most $\frac{L}{kR}$ transmissions can take place simultaneously during a slot and a necessary condition for stability is

$$N \cdot p \cdot a(p) \cdot h(p) \leq \frac{L}{kR} \tag{5}$$

Using $h(p) \geq \frac{L}{R}$ and $a(p) \geq 1$ and defining $\rho = \frac{N}{L}$ on the linear node density of the 1-dimensional network, we infer that

$$p \leq \frac{1}{kN} = \frac{1}{k\rho L} \tag{6}$$

for some constant k.

The energy limitation can be formed by arguing in a similar way to the 2-dimensional case obtaining again (4).

From (4) and (6) it can be seen that the capacity/interference constraint for linear networks is largely independent of the transmission range R used by the network nodes. Thus, networks of this kind that use a large R are expected to be energy-limited. The dependence of the throughput upper bounds on the physical dimension L of the 1-dimensional network is similar to that of the 2-dimensional case. We also expect, as in the case for 2-dimensional networks sparse linear networks (small ρ) to be mainly energy-limited.

3 Routing Strategies

The behavior of the network in the context of the infinite-time horizon problem is evaluated under two routing algorithms: the traditional *minimum-hop* algorithm and a multi-cost routing algorithm, to be referred to as the *energy-aware* algorithm, which takes energy considerations into account. The multi-cost routing approach is fully described in [6].

Multi-cost Routing The multi-cost energy-aware routing algorithm considered in this paper uses two cost metrics: The residual energy R_i, and the transmission power T_i at the transmitting node i of a link (i, j). These cost metrics are combined using the "min" and the "+" operators, to obtain the minimum residual energy $R = \min_{i \in P} R_i$ on the nodes of path P and the total energy $T = \sum_{i \in P} T_i$ consumed on path P, respectively. The optimization function f used in order to produce the final scalar path cost is

$$\textit{Energy-Aware}: \quad f(T, R) = \frac{\sum_{i \in P} T_i}{\min_{i \in P} R_i}, \tag{7}$$

where the index i runs over all the nodes on path P.

4 Simulation Environment

In our experiments we used the Network Simulator [9] to simulate a wireless multihop network of 49 nodes arranged in a 7x7 grid topology. Neighboring nodes at the grid were placed at a distance of 50m from each other. The transmission range of the nodes is variable and follows a uniform distribution between 50 and 100 meters. We assume Bernoulli arrivals, where a packet is generated at each node during each slot with probability p. The duration of the slot is 0.08 seconds, while the packet transmission time is 0.016576 seconds, for the 2000 bytes sized packets we use in our experiments. We chose this slot time in order for the RTS/CTS handshake mechanism and packet transmission to have been completed by the time the next packet is generated. Each node has zero initial energy, and the recharging rate X is the same for all nodes. Finally we assume that every node has full knowledge of the network topology and all other information needed for the route computation.

Furthermore, we define a threshold on the residual energy of a node, and when the energy at a node falls below this threshold, the node stops forwarding packets and starts storing them in its queue. The same holds when the next-hop node's residual energy is below this threshold. Each node periodically checks its energy reserves and those of its neighbors, and if they both exceed the threshold the node starts forwarding its packets, decreasing its queue.

5 Results

The performance of the minimum-hop and the energy-aware algorithms was evaluated in the context of the infinite-time horizon problem, for varying recharging rates and packet generation probabilities. We are interested in the steady-state performance of the proposed schemes; the network was assumed to be in steady state when the variance in the packet delivery delay was below some threshold.

The performance metrics of interest were the largest packet generation probability p_{max} for which the network remains stable (maximum throughput) and the average packet delivery delay for a given packet generation probability. By stability we mean that the volume of the incoming traffic can be served appropriately: with small average packet delivery delay and high packet delivery ratio. When either of these conditions is broken, the network is assumed to enter an unstable region, so there is no point in further studying it.

In Fig. 4 the average packet delay is depicted for $X = 5{\cdot}10^{-3}$ and $X = 9{\cdot}10^{-3}$ Joules per slot[3] with respect to the packet generation rate p, for both the minimum-hop and the energy-aware routing algorithms. For both recharging rates, the energy-aware algorithm outperforms the minimum-hop algorithm, by enabling the network to remain stable for heavier traffic loads. For the 2-dimensional topology considered, the traffic generation probabilities that the energy-aware algorithm is able to handle with adequately small packet delivery

---

[3] To be more specific energy equal to 0.005 joules and 0.009 joules was offered every 10 seconds in the experiments.

delay are nearly twice those of the minimum-hop algorithm for both recharging rates considered. Figure 5 illustrates the received-to-sent packets ratio for both recharging rates and routing schemes.

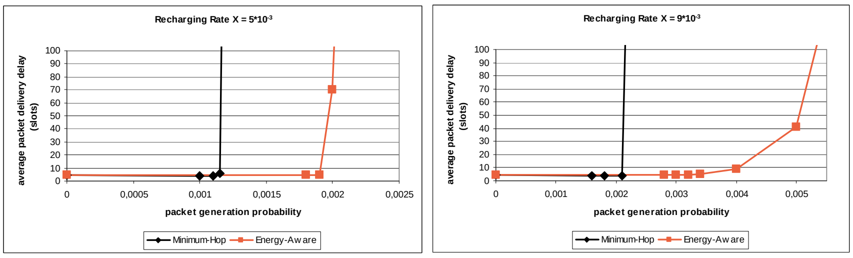

Fig. 4. The packet delay (in slots) for recharging rates $X = 5 \cdot 10^{-3}$ and $X = 9 \cdot 10^{-3}$ Joules per slot

The transition of the network to the unstable region as indicated by the rise in the average packet delay in Fig. 4 is extremely steep for the minimum-hop algorithm for both recharging rates $X = 5 \cdot 10^{-3}$ and $X = 9 \cdot 10^{-3}$ Joules per slot: from values of the delay around 4 or 5 slots in the stable region, there is an almost instant increase to practically infinite values above 100 slots. This is because when the minimum-hop algorithm is used, the network for both values of the recharging rate X is energy constrained; when the energy at some nodes gets depleted, the energy of many other nodes also start getting depleted soon afterwards, and the rise in the delay is very abrupt. In this state the connectivity of the network is weakened and the delivery of the incoming packets becomes difficult (large delays) or impossible (dropping of packets).

When the energy-aware algorithm is used and for $X = 5 \cdot 10^{-3}$ Joules per slot the network is again energy-constrained, but because it uses energy more efficiently, the rise in the delay is less abrupt than with the minimum-hop algorithm. When the energy-aware algorithm is used and the recharging rate is relatively high, $X = 9 \cdot 10^{-3}$ Joules per slot, the network is mainly capacity-constrained and the rise in the delay is rather smooth.

Figure 5 shows the number of received packets with respect to the number of packets that were sent, for $X = 9 \cdot 10^{-3}$ and $X = 15 \cdot 10^{-3}$ Joules per slot[4]. It can be observed that the energy-aware algorithm achieves a higher throughput than the minimum-hop algorithm, since the degration of the received to sent packets ratio begins later than with the minimum-hop algorithm. For both algorithms, the number of packets delivered to their destination grows linearly, initially, with the number of packets that enter the network, since for relatively light traffic they are nearly identical. For probabilities greater than p_{max}, however, there is a steep decline in the ratio. The number of packets successfully delivered to their

---

[4] To be more specific energy equal to 0.009 joules and 0.015 joules was offered every 10 seconds in the experiments.

destinations not only stops increasing as the number of incoming packets grows, but it even declines after the network enters the unstable region.

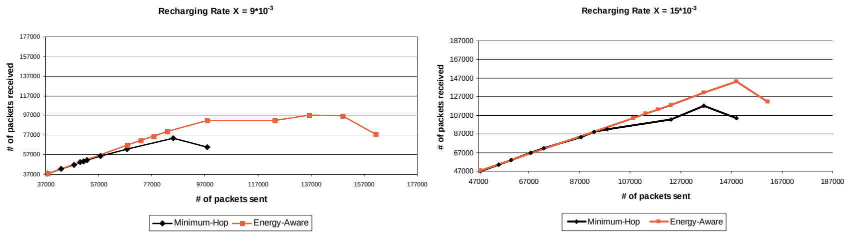

Fig. 5. The number of the packets received versus the number of packets sent for recharging rates $X = 9 \cdot 10^{-3}$ and $X = 15 \cdot 10^{-3}$ Joules per slot

Figure 6 illustrates the maximum packet generation probability (that is, the maximum throughput) p_{max} for which the network remains stable as a function of the recharging rate X at the network nodes, for both the minimum-hop and the energy-aware routing algorithm, along with a detail of the figure for smaller recharging rates. p_{max} is taken to be the highest packet generation probability for which the network manages to serve the incoming traffic appropriately, meaning with small average packet delivery delay and high packet delivery ratio. The thresholds set for these two metrics used for detecting experimentally when the network enters the unstable region (above 100 slots for the average packet delivery delay and under 80% for the delivery ratio) are not important qualitatively for the results obtained, since we found that a different setting of the thresholds only causes a small shifting in the values presented without altering any of the conclusions drawn.

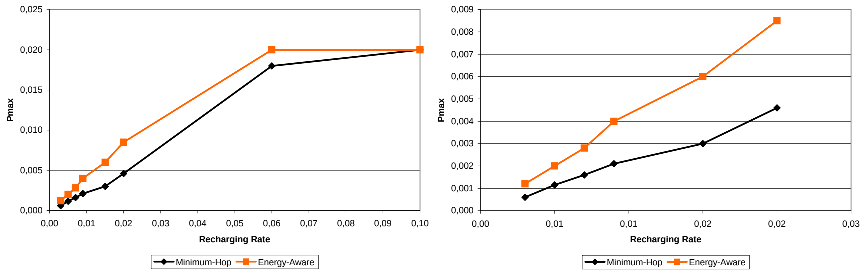

Fig. 6. The maximum traffic generation probability p_{max} versus network nodes' recharging rate X (Joules per second) for the Minimum-Hop and Energy-Aware algorithms and a detail for smaller recharging rates.

Figure 6 shows that the energy-aware algorithm outperforms the minimum-hop algorithm, achieving significantly larger p_{max} for all recharging rates considered. The maximum throughput p_{max} seems to depend on the recharging rate almost linearly until the very end, for both routing algorithms. This verifies that the network in this region is energy-constrained since its performance, expressed by p_{max}, increases proportionally with the energy that is offered to it. When the recharging rate increases beyond some point, the network starts getting constrained by capacity/interference limitations, and the rate at which p_{max} grows with respect to the recharging rate is slowed, until it reaches a plateau indicating that the capacity/interference limitation has been reached.

The performance difference between the energy-aware and the minimum-hop algorithm is larger for low energy recharging rates, and the difference is gradually reduced as the limitation posed by the network capacity is approached. The detail part of Fig. 6 highlights the difference between the two algorithms. It can be observed that for the whole range of recharging rates presented in the detail part of Fig. 6, the p_{max} achieved by the energy-aware algorithm is nearly twice that of the minimum-hop algorithm. This is because the further away the network is from the capacity-constrained region, the more important energy efficiency becomes. When energy is the factor defining the ability of the network to serve incoming traffic, the energy-aware algorithm performs better. However, as energy becomes abundant and the capacity limitation starts constraining network performance, the performance gap between the energy-aware and the minimum-hop algorithm is narrowed.

References

1. Bertsekas, D., Gallagher, R.: Data Networks Englewood Cliffs, NJ: Prentice-Hall
2. Chang, J-H., Tassiulas, L.: Maximum lifetime routing in wireless sensor networks IEEE/ACM Trans. Netw. **12** no 4, 2004 609–619
3. Deng, J., Haas, Z.: Dual Busy Tone Multiple Access (DBTMA): A New Medium Access Control for Packet Radio Networks IEEE ICUPC'98, Florence, Italy, 1998
4. Gupta, N., Das, S.R.: Energy-Aware On-Demand Routing for Mobile Ad Hoc Networks Proc. 4th Int'l Workshop on Distributed Computing, Mobile and Wireless Computing 2002), 164–173
5. Gupta, P., Kumar, P.: Capacity of wireless networks Technical report, University of Illinois, Urbana-Champaign, 1999
6. Gutierrez, F.J., Varvarigos, E., Vassiliadis, S.: Multi-cost routing in Max-Min fair share networks Proc. Vol.2. 38th Ann. Allerton Conf. on Communication, Control and Computing 2000 1294–1304
7. Kokkinos, P., Papageorgiou, C., Varvarigos, E.: Energy Aware Routing in Wireless Ad Hoc Networks Proc. of the IEEE Int'l Conf. on a World of Wireless, Mobile, and Multimedia Networks (WoWMoM 2005) Taormina, Italy 2005
8. Li, J., Blake, C., De Couto, D.S.J., Lee, H.I., Morris, R.: Capacity of Ad Hoc wireless networks Proc. 7th Ann. Int'l Conf. on Mobile Computing and Networking, 2001, 61–69
9. NS - Network Simulator: http://www.isi.edu/nsnam/
10. Rodoplu, V., Meng, T.: Minimum energy mobile wireless networks Proc. IEEE Int'l Conf. on Communications 1998 1633–1639

This article was processed using the LaTeX macro package with LLNCS style