Joint Routing and Scheduling Metrics for Ad Hoc Wireless Networks

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Abstract

In this paper we address the problems of routing and scheduling in resource-limited ad hoc wireless networks supporting connectionless traffic. Motivated by the novel challenges and trade-offs introduced by ad hoc wireless networks, we propose link metric-based distributed routing and scheduling algorithms. We consider limited transceiver, energy and unlimited bandwidth conditions and our performance criteria are average consumed energy, delay, network lifetime and communication overhead caused by the scheduling algorithm. We evaluate the performance of the metrics by detailed simulations.

I. Introduction

Efficient utilization of resources is of paramount importance for ad hoc wireless networks, since mobile nodes with limited energy and antennas have an additional function of packet relaying in a shared medium. Nodes have two important network control functions such as routing and medium access, which should be accomplished in a way to save energy, decrease delay and maintain network connectivity in the presence of limited resources.

Routing and scheduling in resource limited ad hoc wireless networks was studied under a variety of assumptions. In [1], a set of metrics was proposed for the computation of the minimum-cost paths in static topologies, for the connection-oriented traffic case. Connectionless traffic was studied for sensor networks in [2]. In [1] and [2] energy-limited operation was also considered as opposed to energy-efficient operation. A majority of the solutions for scheduling is either not amenable to direct implementation or is based on a base station or central controller responsible for executing the proposed scheduling algorithms, as in [4],[5]. The work in [6] is an example for distributed link scheduling algorithms. The basic idea of the algorithm is reserving each slot of control channel for a particular node.

Our contribution with this work is as follows: We study the problem of energy-efficient distributed routing and scheduling for connectionless traffic case, and observe the trade-offs between energy, delay and network lifetime. As a result we propose link metric-based routing and link-activation algorithms that are aware of the above performance trade-offs. In the next section we explain the network model that is used in this study.

Prepared through collaborative participation in the Communications and Networks Consortium sponsored by the U. S. Army Research Laboratory under the Collaborative Technology Alliance Program, Cooperative Agreement DAAD19-010200011. The U. S. Government is authorized to reproduce and distribute reprints for Government purposes nonwithstanding any copyright notation thereon.

II. Network Model

We consider a network with N nodes, randomly spread over a square area forming a static grid topology. Nodes can transmit with any transmission power P such that $P_0 \leq P \leq P_{max}$, where P_0 is the minimum required power for error free reception. Received power (P_{rec}) vs. transmitted power (P_{tr}) characteristics can be expressed by,

$$P_{rec} = \begin{cases} P_{tr}(\frac{d_{tr}}{d_0})^{-\alpha} & d_0 \leq d_{tr} \\ P_{tr} & 0 \leq d_0 \leq d_{tr} \end{cases} \qquad (1)$$

where α is the path loss exponent (Typically $2 \leq \alpha \leq 4$). Here d_0 is assumed to be the minimum transmission distance that causes path loss. Maximum range of transmission, d_{max} can be expressed as $(\frac{P_{max}}{P_0})^{\frac{1}{\alpha}} d_0$. The resources of the network are modeled by:

Transceivers: In this work, we assume that each node has $C_i = 1$ transceivers. Proposed algorithms can easily be updated for multiple transceivers.

Energy: $E_i(0)$ stands for the initial energy of node i. Residual energy of node i at time t is denoted by $E_i^R(t)$. When a node depletes its energy it is dead and can neither generate nor transmit new packets.

Bandwidth: In this work for simplicity, we assume unlimited bandwidth resources so that frequency scheduling and interference is not a problem.

Communication is source-initiated and each node generates new packets with independent *Poisson* distribution of rate λ. Destination node is selected according to a uniform distribution between the rest of the nodes. Service time of a packet over a single link is constant and it is denoted as $1/\mu$, where μ is the service rate. Time is slotted and one slot length is equal to $(1/\mu)$. The nodes are synchronized to start their transmission at the beginning of the slots. Transmission between two adjacent nodes i and j can be made if:

1) Nodes i and j have one available transceiver. If a packet cannot be transmitted due to lack of transceivers then it waits in the queue until a free transceiver pair is allocated to it by nodes i and j. Each node has a separate queue for all its adjacent nodes.

2) Nodes i and j have the sufficient energy to complete data transfer. We assume that this required energy only includes the energy expended by using the *transmission* power. *Processing* energy, E_{proc}, which is spent each time

a transceiver is used ($E_{proc} = P_{proc}/\mu$) is assumed to be negligible.

Each node maintains up-to-date information about the residual energy, available number of transceivers and transmission power requirements of its neighbor nodes. All nodes periodically broadcast this information to their neighborhood. This exchange of information is implemented via an underlying link-level mechanism and through dedicated control channels, which are not the purpose of this study.

III. Energy Efficient Routing Problem

The ad hoc wireless network that we consider is modeled as a directed graph $\mathcal{G}(V, E)$, where V is the set of nodes and E is the set of directed links (i, j) where i,j$\in V$. The routing problem for each node is, selecting the next hop for a packet destined to any given destination so that good communication performance is achieved in terms of: energy consumed per packet, volume of transmitted traffic throughout the network lifetime and delay per packet.

A. Transmission Energy per Packet

We can exploit the ability to adjust the RF transmission power and make transmissions in multiple short hops in order to save energy [1]. In minimum-energy routing there is a single minimum transmission energy path $p^{s,d}$ between each node and any packet generated at node s and destined to node d is routed through this path. Hence, consumed transmission energy (E_{sd}) for any packet routed from s to d can be formulated as follows:

$$E_{sd} = \sum_{(i,j)\in p^{s,d}} (\frac{1}{\mu} \max\{P_0, P_0(\frac{d_{ij}}{d_0})^{\alpha}\}), \forall s, d \in V \quad (2)$$

where, the expression $\max\{P_0, P_0(\frac{d_{ij}}{d_0})^{\alpha}\}$ is the RF power required for error-free transmission from node i to j and d_{ij} is the distance between nodes i and j. Using always some specific minimum power paths can cause early energy depletion of some nodes, causing early loss of connectivity. It is also probable that bottlenecks will occur in these heavy-utilized paths, which causes decrease in the throughput and increase in the average delay per packet.

B. Delivered Volume Throughout the Network Lifetime

Recent works on the sensor networks [2] indicate that after death of the first node, other nodes are loaded more heavily and deaths occur much faster. Therefore maximizing the time until the death of the first node is crucial for ad hoc wireless networks. We should define the Network Lifetime as:

Definition 1—Network lifetime: Network lifetime is the time until the first node dies.

We can formulate the cumulative energy expenditure of node i, E_i, at time t as:

$$E_i(t) = \frac{1}{\mu} \sum_{j\in\mathcal{V}(i)} (f_{ij} \max\{P_0, P_0(\frac{d_{ij}}{d_0})^{\alpha}\})t, \forall i \in V \quad (3)$$

Here $\mathcal{V}(i)$ is the set of neighbors of node i and f_{ij} is the flow rate through link (i, j). The energy expenditure of a node at time t is limited by its initial energy, which can be shown as $E_i(t) \leq E_{init}, \forall i \in V$. Let's denote the maximum possible lifetime of node i as T_i. Then the *Network Lifetime*, T_{net}, which is defined as the lifetime of the earliest dying node is expressed as $\min_{i\in V} T_i$.

If minimum energy routing is made then f_{ij} will be equal to $l_{ij}\lambda/(N-1)$ where l_{ij} be the number of minimum energy paths which contains link (i, j). In minimum energy routing, some nodes on the minimum energy paths will face with larger flows than the others, which increase the energy expenditure as we see from equation (3). We can formulate network lifetime as follows:

$$T_{net} = \min_{i\in V} \frac{E_i(0)\mu}{\sum_{j\in\mathcal{V}(i)}(l_{ij}\frac{\lambda}{N-1} \max\{P_0, P_0(\frac{d_{ij}}{d_0})^{\alpha}\})} \quad (4)$$

From the above expression we can observe that if particular nodes are on a lot of minimum energy paths, their corresponding l_{ij} values increase and they spend too much energy, which decreases the network lifetime. As some nodes deplete their energy resources, their flows should be forwarded to high-residual-energy nodes in order to increase the network lifetime.

C. Delay

Delay is a very important performance criterion for networks with packet traffic. Naturally, delay and congestion over a link is proportional to the number of packets waiting on that link. It has been previously indicated in [4] that selection of paths that minimize the maximum nodal degree in a network permits generation of efficient schedules. This is because each node has an equal, fixed transmission capacity and total network load should be divided among nodes as equal as possible in order to keep each queue in the network stable. Here the degree of node i (L_i) is defined as sum of all flows into and out of the node i.e. $\sum_{j\in R(i)}(l_{ij} + l_{ji})$. In minimum energy routing, this node degree is definitely the number of minimum energy routing paths passing through the particular node.

Let us assume a transmission scheduling policy similar to processor sharing, in which each adjacent link (i, j) of node i is served periodically with a rate proportional to f_{ij}. By using Little's result and Kleinrock independence approximation this system can be approximated by an $M/G/1$ queueing system. Assuming no inefficiency and idleness due to conflicts with other nodes' transceiver availabilities we can use the *P-K* formula in order to calculate the average delay through each link. , we can write the average queue length over a directed link i,j, namely Qij as follows:

$$Q_{ij} = \frac{\lambda}{N'} l_{ij} T_{ij} = \frac{\lambda}{N'} l_{ij} \frac{1}{\mu} [\frac{l_{ij}\frac{\lambda}{N'}}{2(\mu - \frac{\lambda}{N'})} + \frac{L_i}{2l_{ij}} + \frac{3}{2}], \forall i, j \in V \quad (5)$$

where the expression $V_{ij} = \frac{\sum_{j\in\mathcal{V}(i)}(l_{ij}+l_{ji})}{l_{ij}} \frac{1}{\mu} = \frac{L_i}{l_{ij}\mu}$ is the average vacation time between two consequtive serving times of the queue (i, j) and $N' = N - 1$.

Looking at the above expression, decreasing the maximum nodal degree in the network is possible by redirecting flows from the congested nodes to the less congested ones.

D. Algorithmic Solution

Considering the limited resources and distributed nature of Ad Hoc wireless networks, an alternative methodology of routing may be relying only on local information and assigning each link (i, j) a value that indicates the cost of using that link according to a link cost metric. Based on the assigned link metrics, distributed Bellman-Ford algorithm [3] can be applied for shortest path computation. To these ends, a combined link cost metric can be proposed as follows:

$$D_{ij} = \begin{cases} \left(\frac{P_{ij}}{P_{max}}\right)^{W_p} \left(\frac{E_0}{E_i^R}\right)^{W_e} {Q_{ij}}^{W_d} & if {E_i}^R, {E_j}^R \neq 0 \\ \infty & otherwise \end{cases} \quad (6)$$

$\forall i, j s.t i \in \mathcal{V}(j)$

Link metric is composed of three terms, as seen. W_p, W_e and W_d are the coefficients that are adjusted to favor any of the three terms. This metric reflects congestion on that link (delay and stability), transmission power requirements (energy) and residual energy (volume of delivered traffic). We will make detailed simulations and evaluate the performance of our routing algorithm in Section V.

IV. Problem of conflict free scheduling

A. Assumptions and Definitions

For the problem of scheduling (link activation) we use the same network model as we have defined in the previous section. We consider scheduled medium access schemes as opposed to random. Therefore we should first define collision rigorously in order to study the conflict-free link activation problem:

Definition 2—Collision: Links (i, j) and (k, l) are competing if:

$i = k$ or $i = l$ or $j = k$ or $j = l$, in other words, two links have common node or nodes.

The set of links that can be activated in a conflict-free manner is called a conflict-free transmission set. We consider communication performance as a utility and assign each link (i, j) a dynamically changing utility value, W_{ij} according to a predefined link activation utility metric. The ultimate goal is maximizing the sum of the utility values of the links in the resultant set of scheduled set of links S, i.e. the total utility of the link activation set $U(S)$. However, previous work on scheduling indicates that the solution for finding the maximum weight link activation set is an *NP-Complete Independent Set Problem*. It requires a high computational complexity and knowledge of all other nodes to be solved in a distributed manner. So we should define a problem, which has a more practical solution, with the trade-off of losing the optimality.

Definition 3—Maximal Utility Link Activation: Find a link activation set S such that if any node tries to activate an outgoing link with higher utility than the present activated outgoing link, the resulting activation set S' has lower utility than S.

B. Algorithmic Solution

For the execution of the distributed algorithm, we assume that a processor exists at each node, obeying the same algorithm and knowing initially the link utility values (W_{ij}) of the adjacent $outgoing$ links. The dedicated control channel consists of control slots and a control slot is divided into two sub-slots as in Figure 1.

In the *request slot*(t_r) a particular node broadcasts a $REQUEST$ signal, intended to one of its neighbors, in order to activate the link between each other. In the *confirmation slot*(t_c), the node receiving the request message broadcasts $CONFIRM$ message. All of the broadcasted control messages include the source, destination id's of the message

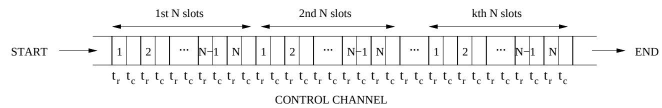

Fig. 1. The control channel.

and the utility value of the link between these two nodes. The algorithm lasts for $k \times N$ *slots*, where N is the number of nodes and k is the number of iterations. Any node i reserves the control slots $jN + i \; \forall j < k$. The execution of the algorithm is based on the *ranks* of nodes:

Definition 4—Rank: Let $j \in \mathcal{V}(i)$. *Rank* of node i at control slot n is equal to:

$$Rank_i^n = \begin{cases} W_{ij}, & if (i,j) activated \\ W_{ji}, & if (j,i) activated \\ 0, & otherwise \end{cases} \quad (7)$$

Therefore total utility of the link activation, U_{ij}^n at n^{th} control slot, is equal to $\frac{1}{2}\sum_{i \in V} Rank_i^n$.

Neighbors hear the broadcasted control messages and update the rank information at every control slot. Suppose that node i wants to activate link (i, j), and that currently link (m, i) and (j, k) are active. When link (i, j) is activated, then the other two links should be deactivated. The difference in total utility of the link activation set by activating link (i, j) is $\Delta U_{ij}^n = U_{ij}^n - U_{ij}^{n-1} = \frac{1}{2}(2W_{ij} - rank_i^n - rank_j^n)$. If each node i tries to activate a link (i, j) in a way to satisfy $\Delta U_{ij}^n > 0$, then at each control slot total utility improves or at least stays constant. A maximal utility link activation set is obtained by this algorithm because at the end of the algorithm, if any node wants to activate a higher-utility outgoing link, the total utility decreases.

Communication overhead is of crucial performance criteria for this algorithm. We assume that only message broadcasts causes an overhead, and reception does not cause any. Each message consists of the source and intended destination id's of the message and the utility value of the link that is desired to be activated.

C. Link Activation Utility Metric

To these ends, we propose a link activation utility metric to be used in the distributed algorithm. It is formulated as follows:

$$W_{ij} = \begin{cases} \frac{(Q_{ij})^{\gamma}(E_j^R)^{\beta}}{(F_{ij})^{\theta}(P_{ij})^{\alpha}}, & if {E_i}^R \neq 0 \\ \infty, & otherwise \end{cases} \quad (8)$$

$\forall i, j s.t i \in \mathcal{V}(j)$

Here, α, β, γ and θ are the weighting exponents. The expression ${Q_{ij}}^{\gamma}$ encourages the activation of congested links. ${E_j^R}^{\beta}$ discourages activation of links with high-energy destination nodes. By this way queue sizes of these links remain high and they are not preferred in routing, which prevents those nodes from early death. ${P_{ij}}^{\alpha}$ encourages activation of links requiring low RF power, so that their queue sizes remain low and they are preferred for routing consequently. As seen here, interaction of MAC and Network Layers is utilized in increasing the network performance. Finally $(F_{ij})^{\theta}$

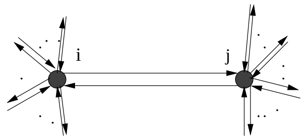

Fig. 2. Link (i,j) and its adjacent links.

indicates the number of non-empty links adjacent to link (i,j) powered by θ as in Figure 2.

If we activate a link then its adjacent links can not be activated at the same time. Therefore links having many non-empty adjacent links should be discouraged from activating which can lead to increase the transceiver utilization and decrease average delay. We present the performance characteristics of the algorithms in the next section.

V. Simulation and Discussions

In this section we give an illustration of the behaviour of the proposed routing and scheduling algorithms under changing network conditions and for various link metric coefficients. Simulations are made with the system parameters listed in Table I. Figure 3 depicts the average consumed energy performance of the routing algorithm versus network load. We can observe that if congestion state is included in the routing metric, energy expenditure increases with increasing network load. This is expected because as network load increases, flows are redirected to the less congested paths that are not minimum-power paths. We also observe that if we consider residual energy, spent energy increases, because we redirect flows from low energy nodes to high energy nodes as energy resources deplete, and these new paths again require more power. Figure 4 shows the average delay performance versus network load. We see that delay increases exponentially with increasing network load. We also see that delay performance is the best if we consider queue sizes in routing. Minimum energy paths usually consist of multiple hops, which causes congestion and larger delays as in the case $(W_p, W_e, W_d) = (1, 0, 0)$.

TABLE I
SYSTEM PARAMETERS

Common Parameters	
Number of Nodes (N)	15
Slot Duration	1 msec
Packet Arrival Rate (λ)	0.04-0.065 p/ms
Length of the square area	100 meters
Transmission Range (d_{max})	50 meters
Number of Iterations (k)	2
Total Number of Packets	100000
Routing Simulation	
$(\alpha, \beta, \gamma, \theta)$	(1,1,1,1)
Scheduling Simulation	
(W_p, W_e, W_d)	(1,1,1)

In the above two cases, energy reserves were limited, but enough to keep nodes alive for the duration of the simulation. Figure 5 shows the number of succesfully transmitted packets (volume) vs. time for a more strict energy condition. We observe that as time passes some nodes die and as modelled in Section II, some packets begin to drop. Points A, B and C correspond to node deaths. We can easily see that if we include residual energy into the routing metric, network lifetime (time of first node death) increases significantly. Total volume of transmitted packets also increase in this case. Table II shows the time of first and second node deaths. Here we see numerically that in the case of $(W_p, W_e, W_d) = (1, 0, 0)$, early node deaths occur.

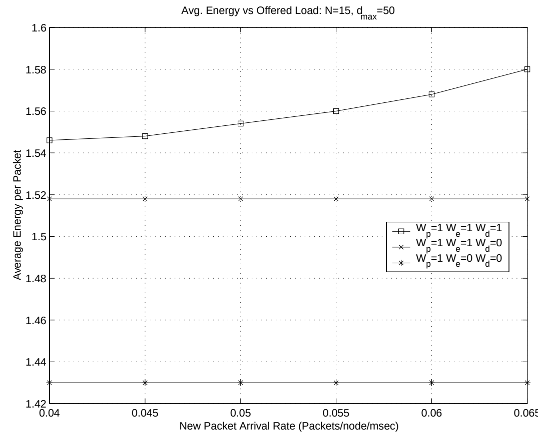

Fig. 3. Average energy per packet for different routing metric coefficients

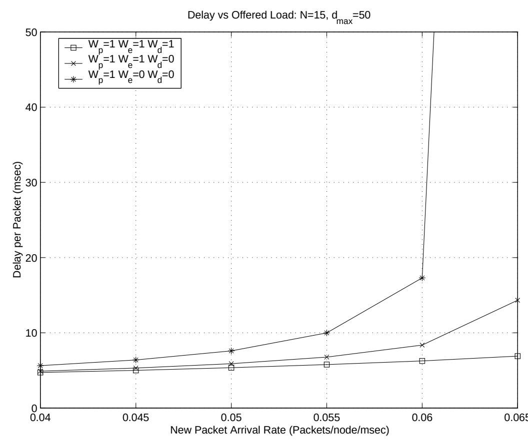

Fig. 4. Average delay per packet for different routing metric coefficients

Secondly, we simulated the performance of the proposed scheduling algorithm, for a constant routing policy (namely $(W_p, W_e, W_d) = (1, 1, 1)$) and different scheduling metric coefficients.

Figure 6 depicts the consumed energy performance. As we can see, joint considering of link power and congestion results in best energy performance.

Figure 7 shows the average delay characteristics versus network load. As in the energy characteristics we see that scheduling schemes have a relatively modest performance difference. However we can observe that considering queue sizes and blocking effects together in scheduling, results in the best delay performance among the tested coefficient cases.

The scheduling algorithm has also a slight positive effect on the network lifetime, throughput. Table II shows

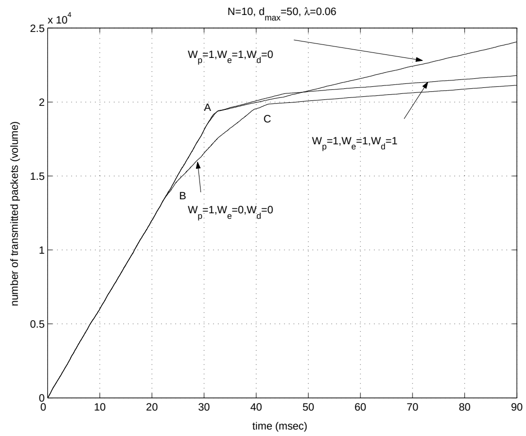

Fig. 5. Network Lifetime for different routing metric coefficients

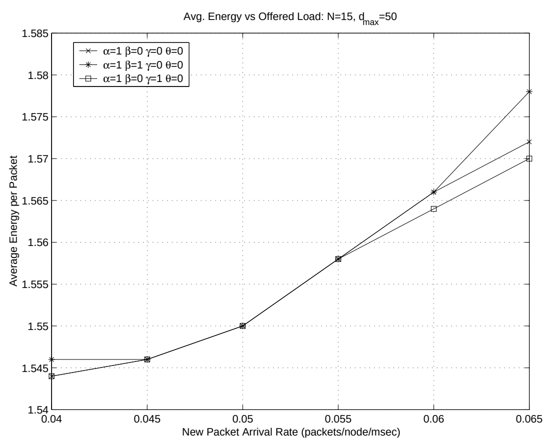

Fig. 6. Average energy per packet for different scheduling metric coefficients

the time of the first and second node deaths. We see that if

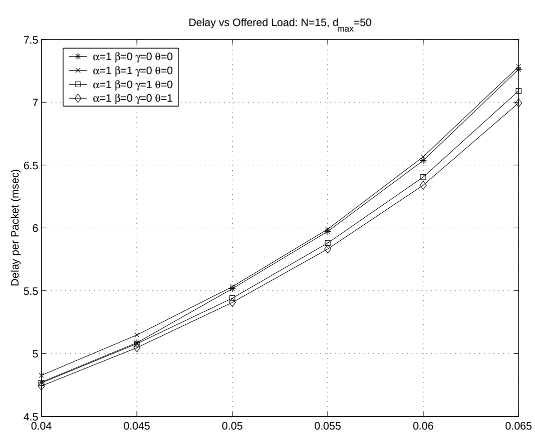

Fig. 7. Average delay per packet for different scheduling metric coefficients

we choose $\beta = 1$, network lifetime increases significantly, when compared to the case $\beta = 0$, where β is the coefficient corresponding to the residual node energy.

Table III depicts communication overhead characteristics for changing network size and number of links. We can observe that as the ratio $\frac{d_{max}}{N}$ increases, the overhead decreases because nodes have a greater coverage of the network.

TABLE II
NODE DEATH TIMES: $(W_p, W_e, W_d) = (1, 1, 1)$.

$(\alpha, \beta, \gamma, \theta)$	(1,0,0,0)	(1,1,0,0)	(1,0,1,0)	(1,0,0,1)
$1^{st}node$	31.31	31.55	31,27	31.30
$2^{nd}node$	31.83	31.93	31.91	31.78

TABLE III
AVERAGE NUMBER OF CONTROL PACKETS (PACKETS/NODE/TIME SLOT): $k = 2$, $(\alpha, \beta, \gamma, \theta) = (1, 1, 1, 1)$

$k = 1$	$N = 10$	$N = 15$	$N = 20$	$N = 25$	$N = 30$
$d_{max} = 40$	0.393	0.413	0.545	0.904	0.928
$d_{max} = 50$	0.301	0.329	0.415	0.545	0.638
$d_{max} = 60$	0.297	0.318	0.391	0.516	0.616
$d_{max} = 70$	0.295	0.317	0.388	0.513	0.616

VI. Conclusions

Energy efficiency in wireless ad hoc networks involves numerous trade-offs and requires a multilayer strategy to be maintained. In this paper we have adressed some of these trade-offs and proposed link metric-based energy-efficient distributed routing and scheduling algorithms for ad hoc wireless networks supporting connectionless traffic. Based on the simulation study, we conclude that a link metric-based policy jointly considering transmission power requirements, residual energy information, link queue sizes and transceiver utilization provides a better performance in terms of energy consumption, average delay and delivered traffic volume.[1]

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[1] The wiews and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the Army Research Laboratory or the U. S. Government.