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Minimum Energy Consumption Routing Protocol in Multi-Rate Non-Infrastructure Wireless Network

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Abstract-*The wireless ad hoc network and the sensor network are characterized by rapid deployment; dynamic, multi-hop topology; and self-organization without typical infrastructure support. Other important issues are that the fluctuant bit rates cause the power consumptions, throughputs, and transmission times to vary. In addition, shared media only allow one couple of nodes to transmit at the same time, so other nodes must wait. We formulate this as a minimum energy consumption problem in a multi-rate, multi-hop wireless network, utilizing energy-aware routing and a passive mode strategy with Ready to Send (RTS), Clear to Send (CTS), and acknowledge (ACK) control frames. The numerical results show that for various numbers of MHs and packet sizes the energy consumption rate is lower than the original minimum hop routing protocols, such as Ad hoc On Demand Distance Vector (AODV), Dynamic Source Routing (DSR), Temporally-Ordered Routing Algorithm (TORA), and multi-rate aware sub layer (MAS) [26]. The delay is also lower than these methods.*

KEY WORDS: Ad hoc, Multi-rate, Routing, Sensor Network, and WLAN.

1. Introduction

Non-infrastructure wireless networks, such as ad hoc wireless networks and sensor networks, are defined as autonomous systems of mobile routers connected by wireless links. They are characterized by rapid deployment; dynamic multi-hop topology; and self-organization without typical infrastructure support. The media access control (MAC) protocols of these networks include time division multiple access (TDMA) [5], [13], code division multiple access (CDMA) [2], [4], and contention-based protocols, such as the IEEE 802.11 series. Here, we are interested in general contention-based protocols, which have one major issue in that the fluctuant bit rates are subject to signal fading and interference. The issue causes the Mobile Hosts (MHs) or sensors to have different transmission bit rates, such as 11Mbps, 5.5Mbps, 2Mbps, and 1Mbps for 802.11b. A critical design issue of the networks is the development of suitable routing protocols that can efficiently reduce power consumption and thereby increase the operational lifetime of the network.

Multi-rate routing should be energy-aware to extend battery lifetime and improve throughput. If the minimum hop routing approach is considered, such as existing ad hoc network routing protocols (e.g., AODV, DSR, and TORA), the transmission distance is long and requires too much energy to transmit data. Although fewer nodes are affected, the transmission bit rate is low, but power consumption is high. Thus, if we consider the higher transmission rate MH routing first, the short transmission distance only needs low energy to transmit the same amount of data and increase the throughput, but requires more MHs to forward a packet [19]. This is the motivation for this paper.

Javed Aslam et al. proposed series algorithms that relate to online power-aware routing in large wireless ad hoc networks to optimize the lifetime of a network [11], [12], [20], [21], but they do not consider multi-rate issues. A Power-Aware Routing Optimization (PARO) scheme is based on the principle of adding additional forwarding nodes between Original-Destination (O-D) pairs in order to reduce the power consumption. One common property of these routing protocols is that they determine routes using a variety of broadcast flooding protocols by transmitting at maximum power in order to minimize the number of forwarding nodes between any O-D pair [10]. In [26], the multi-rate aware sub-layer (MAS) method is proposed, which changes its next hop node to another node so that higher bit rates are available on the basis of two-hop neighbor information and link stats. They compute the relay neighbor transmission time to determine whether to change their next hop. Unfortunately, they do not consider global multi-rate shortest path routing.

In [3], the authors also show that traditional minimum hop routing strategy is inappropriate for multi-rate networks, and analyze rate aware routing protocols for optimal performance. Figure 1 shows the trade-off between the throughput and the hop count, which means that a greater number of hops (e.g., two hops for A'-B-C') is required to cover the same distance as a smaller number of lower rate hops (e.g., one hop for A-C). The authors suggest that even though high link rate paths must traverse more links to reach the same distance, they still provide more throughputs.

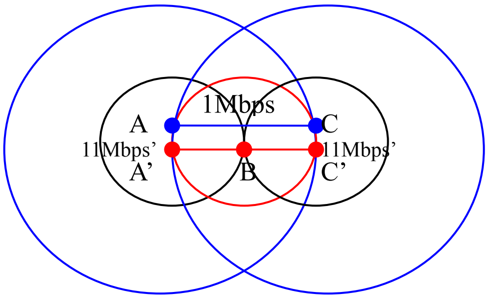

Fig. 1 Multi-rate path selection option

There are four major causes of energy waste: collision, overhearing, control packet overhead, and inefficient idle listening. By applying message passing [24], we can reduce the collision period with RTS/CTS mechanism, utilize Network Allocation Vector (NAV) information to put each node to sleep when its neighbor is transmitting to another node reduce application-perceived latency and control overhead. In this paper, we adopt these concepts to design a minimum energy consumption routing protocol for multi-rate wireless networks.

Figure 2 shows the transition states of the four modes that an MH must be in: transmit, receive, idle, and sleep. When one node is in transmission or receiving mode, it is transmitting or receiving a packet. Idle mode means the node is neither transmitting nor receiving a packet, but is doing channel monitoring. This mode consumes power because the node has to listen to the wireless medium continuously in order to detect the arrival of a packet that it should receive, so that the node can switch to receive mode [23]. When in the sleep mode, nodes do not communicate at all. The idle and receive modes consume a similar amount of power, while the transmit mode requires a slightly larger amount. Nodes in sleep mode consume an extremely small amount power. As an example in Table 1, we illustrate the energy consumption of different modes for the 2.4GHz DSSS Lucent IEEE 802.11WaveLAN PC “Bronze" (2Mbps and 11Mbps) wireless network interface card [14].

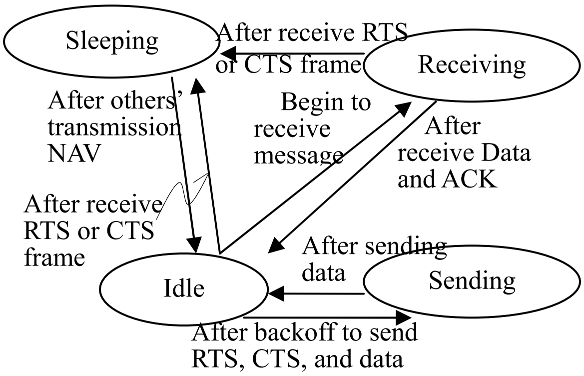

Fig. 2 The transition of MH’s four mode states

Table 1 Energy consumption by different modes

Modes	Energy Consumption	
	2Mbps	11Mbps
Sleep Mode	14mA	10mA
Idle Mode	178mA	156mA
Receive Mode	204mA	190mA
Transmit Mode	280mA	284mA

Many researchers have calculated the energy consummation as about 50% for idle listening. For example, Stemm and Katz calculate that the ratio of idle:receive:send is 1:1.05:1.4 [17], while the 2Mbps Wireless LAN module (IEEE 802.11/2Mbps) specification shows the ratio of idle:receive:send is 1:2:2.5 [18]. Therefore, we can enable MHs’ passive and active modes to reduce energy consummation.

Besides the power consumption in transmitting, receiving and idle listening, there exists other significant energy wastage in the packet retransmission node, overhearing, and protocol overhead. Retransmission is caused by collision and increases energy consumption. Overhearing means a node picks up packets that are destined for other nodes. Wireless nodes will unnecessarily consume energy due to overhearing transmissions of their neighboring nodes. Protocol overhead is generated by packets dedicated for network control and header bits of data packets. It should be reduced as much as possible because transmitting data packet headers or control packets also consumes energy, which results in the transmission of fewer useful data packets.

The remainder of this paper is organized as follows. In Section 2, we briefly describe the proposed method of multi-rate routing. In Section 3, the problem is formulated. In Section 4, we illustrate algorithms to solve the optimal mathematical problem. In Section 5, we compare our numerical results with those of other methods. Finally, in Section 6, we present our conclusions.

2. Proposed method

There is a Duration/ID field contained within each transmitted packet that indicates how long the remaining transmission will take, so we reduce the energy consumption by IEEE 802.11 MAC control frames. Figure 3 shows that RTS, CTS, and ACK packets must be received by all other MHs in order to inform them to stop transmitting and resume their back-off counter. We utilize the mechanism to let neighbor MHs turn to sleep mode. For example, Table 2 shows the 802.11b protocol’s time consumption for the RTS/CTS mechanism. Let T_{DIFS} denote DIFS time (50μs); T_{SIFS} denote SIFS time; T_{ACK} denote ACK time, including PLCP time transmitted on 1Mbps; T_{BT} denote average backoff time for only one transmission of an MH; T_{Data} denote data time, which includes PLCP time and data transmission time; and T_{pro} denote propagation time. The default MSDU size L_k is 1500 bytes and the MAC header length L_h is 34 bytes, as defined in 802.11b standard [9]. Therefore, the neighbouring MHs are set to sleep mode during T_{Data} after receiving the RTS or CTS frame; otherwise, the receiving MH and neighbouring MHs stay in the receive mode.

Let $G = (V, E)$ represent the network. V is the set of all MHs, and E is the set of all edges. Each link $l_{uv} \in E$ has an available transmission rate R_{uv}. When the application starts, the link issues a minimum energy routing request that includes the sender node v_s, and the destination node v_d, The path decision is neither limited by the minimum count of hops, nor decided by next highest transmission rate. For example, Figure 4 shows the sender A route to C by path A-D-B-E-C with highest rate by the MAS method, but not the path A-B-C with minimum hops (3 hops). However, in our proposed method, we might choose A-D-E-C as minimum energy consumption path with our modified dijstract's algorithm. The problem formulations and routing algorithm are described in the next two sections.

3. Problem formulations

Before presenting the problem formulations, we refer to [8] and our previous research extended multi-rate model [25] to calculate the mean backoff slot count and the average number of collisions for successful transmission, i.e., the number of retransmissions as (1) to (4). Table 3 lists the main notation for calculating $E[B_k]$ and N_v which are used in the problem formulations.

$$E[B_k] = \frac{(1-2p_k)(W_k-1) + p_k W_k (1-(2p_k)^m)}{2(1-2p_k)} \tag{1}$$

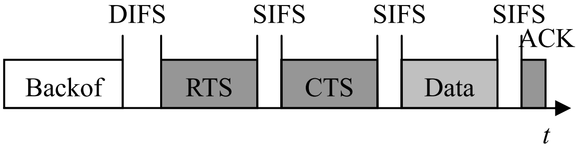

Fig. 3 RTS/CTS original mechanism

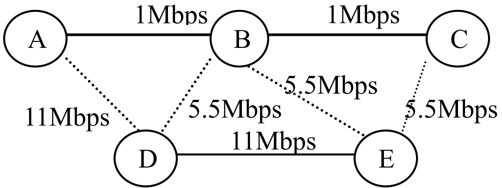

Fig. 4 An example of multi-rate network connection diagram

Table 2 RTS/CTS transmission time [unit: μs]

	Bit Rate (Mbps)	$T_{DIFS}+T_{SIFS}$	$T_{RTS}+T_{CTS}$	T_{BT}	T_{ACK}	T_{Data}	T_{total}
RTS/ CTS	11	50+10	352+304	310	304	1308	2637.6
	5.5	50+10	352+304	310	304	2423	3753.3
	2	50+10	352+304	310	304	6328	7658.0
	1	50+10	352+304	310	304	12464	13794.0

Table 3 Main notation lists

Notation	Descriptions
r	The number of classes with distinct bit rates in the system, where $r \geq 1$.
n_k	The number of MHs that belong to class k, where $1 \leq k \leq r$.
W_k	CW_{min} value of class k station
m	The maximum backoff stage.
B_k	The mean value of the backoff counter
p_k	The collision probability of class k.
q_k	The successful transmission probability of class k
P_c	The collision probability of the MH
N_v	The number of retransmissions of node v.

Let p_c be the collision probability when a mobile station is transmitting a packet. The p_c can be computed at one or more transmitting stations, so that the p_c is [25] :

$$p_c = \frac{1 - \prod_{j=1}^{r} (1-q_j)^{n_j} - \sum_{i=1}^{r} n_i q_i (1-q_i)^{n_i-1} \prod_{j=1, j\neq i}^{r} (1-q_j)^{n_j}}{1 - \prod_{j=1}^{r} (1-q_j)^{n_j}} \tag{2}$$

The distribution of N_c follows a geometric distribution as (3) and yields the expected number of collisions N_v as (4).

$$\Pr\{N_c = i\} = (1-p_c)p_c^i, \quad \text{for } i = 0,\ 1,\ 2, \cdots, \tag{3}$$

$$N_v = \frac{p_c}{1-p_c} \tag{4}$$

We then establish an optimal model to formulate the multi-rate efficient routing problem for wireless ad hoc networks and sensor networks. We study how routing policies which have a critical effect on the routing results and power consumption, influence various transmission rates. Finally, we develop a mathematical model to deal with the multi-rate routing problem to minimize energy consumption and maximize total throughput.

The given system parameters are:

- ✧ The candidate paths of each O-D pair.
- ✧ The 802.11b MAC protocol standard parameters.
- ✧ The energy configuration of the initial level and the consumption rate.

Given the wireless non-infrastructure network architecture mention above, we formulate the multi-rate energy consumption routing problem as a complex nonlinear programming problem. The objective function in the program formulation is to minimize the total energy consumption subject to:

- ✧ A routing constraint.
- ✧ A multi-rate constraint.
- ✧ An energy consumption constraint such as transmit, receive, overhead, or overhearing.

Since our objective is to minimize the energy consumption in a multi-rate wireless network, the objective is formulated as (5) and the constraints are shown as (6) to (11). The given parameters are listed in Table 4, the notation descriptions for the indication function are listed in Table 5, and the decision variables are listed in Table 6.

Objective function:

$$Z = \min \sum_{v \in V} \begin{array}{l} (g_v + N_v * (T_{RTS} + T_{CTS}))(E_t + E_r) + \\ hr_v E_r + hs_v E_s + T_c E_i \end{array} \tag{5}$$

Table 4 The given parameters

Notation	Description
V	The set of mobile nodes;
P	The set of paths in the wireless network;
L	The MSDU size (e.g., 1,500 bytes).
L_h	The overhead lengths, which include RTS, CTS, the MAC header, and the PHY header.
$R_{i,j}$	The bit rates from node *i* to node *j*.
E_s	The logical unit energy consumption to send a packet.
E_r	The logical unit energy consumption to receive a packet.
E_i	The energy required in the sleep mode

Table 5 Notation descriptions for indicator functions

Notation	Description
δ_{np}	0-1 variable. If node *n* is on path *p* then set to 1; otherwise, 0.
σ_{nm}	0-1 variable. If node *n* and node *m* are neighbors, then set to 1; otherwise, 0.

Table 6 Notation descriptions for decision variables

Notation	Description
c_v	The capacity of traffic flow on node *n*.
g_v	The aggregate flow on node *n*;
x_v	Set to 1 if path p is selected; otherwise, 0.
h_v	The aggregate flow on the neighbors of node *n*;
q_v	The proportion of node life time that node *n* is in passive mode.

Subject to:

$$\sum_{p \in P} \sum_{u \in V} \left(\frac{8L}{R_{uv}} + \frac{L_c}{2}\right) \delta_{vp} x_p = g_v \qquad \forall v \in V \tag{6}$$

$$\sum_{u \in V} L_c (1 - \delta_{up}) \sigma_{uv} = hr_v \qquad \forall v \in V \tag{7}$$

$$\sum_{u \in V} \frac{8L}{R_{uv}} (1 - \delta_{up}) \sigma_{uv} = hs_v \qquad \forall v \in V \tag{8}$$

$$\delta_{vp} = 0 \text{ or } 1 \qquad \forall v \in V, \forall p \in P \tag{9}$$

$$x_p = 0 \text{ or } 1 \qquad \forall p \in P \tag{10}$$

The objective function minimizes the total energy consumption from the source to the destination, which is constrained by multi-rate routing and the capacity of the nodes. The constraints are as follows:

- ✧ Equation (6) calculates the number of logical time units to forward packets via node *v* from all O-D pairs.
- ✧ Equation (7) calculates the number of logical time units for the neighbors to receive the RTS, CTS, and ACK frames.
- ✧ Equation (8) calculates the number of logical time units for a neighbor to enter sleep mode in order to avoid overhearing.
- ✧ Equation (9) requires that exactly one node is selected for one O-D pair.
- ✧ Equation (10) requires that exactly one path is selected for each O-D pair.

4. Minimum power consumption routing algorithm

Figure 5 shows the multi-rate energy-aware routing algorithm described in the previous section It modifies the cost concept of the dijkstra's algorithm to the transmission energy in our proposed method. To calculate the shortest path, the cost functions are on the edges (not the nodes).

```
Energy_Aware_Multi-Rate_Shortest_Paths(G,s,d)
Input: G=(V,E) (a weighted undirected graph), s (the
  source vertex), d (the destination vertex).
Output: for destination vertex, d.SP is the length of
  the shortest path (SP) with the given minimum
  energy consumption from s to d;
{all lengths are assumed to be non-negative. }
begin
  for all vertices w do
      w.mark := false;
      w.SP := Infinite;
  end-for
  while the vertex d is unmarked do
```

```
        find an unmarked vertex w with minimal w.SP;
        w.mark := true;
        Update overhearing energy of w's neighbor;
        z.ME := Infinite;
//ME denote minimum aggregate Energy of O-D pair
        for all edges (w,z) such that z is unmarked do
            if w. MinEnergy + Energy(w,z)+
               NeighborOverHear(w) < z.ME then
               z. ME := w. ME + Energy(w,z);
            end-if
        end-for
    end-while
end
```

Fig. 5 The algorithm of multi-rate minimum energy consumption shortest path routing

5. Numerical results

In this section, we compare the transmission power consumption with different numbers of MHs. We also compare the transmission power consumption with various packet sizes to the MAS [26] and original minimum shortest path routing approaches. The topology is generated by randomly assigning the position of each MH within a 2000 * 2000 meters square area. Table 7 shows the distance to determine the bit rate [7]. Then the same O-D pair is chosen to evaluate our proposed algorithm with a variable number of MHs and packet sizes.

Figure 6 shows the energy consumption (mA) with fixed packet size 1,500 bytes sent from the source to the destination by each algorithm. In the original shortest path routing methods, as the number of MHs increases, the energy consumption is much higher than other methods. The wasted energy comes from the neighbors overhearing the control frames (e.g., RTS, CTS, and ACK). The MAS method, described in [26], is only improved when the number of MHs is increased. But, the method is limited by finding the shortest path first, and then finds a higher bit rate forward node between the node and next hop node to improve the performance. Amount these methods that our method keeps the minimum energy consumption routing path.

Figure 7 shows the energy consumption versus the packet size. When we increase the packet size, the transmission time and energy consumption also increase. But, the increase rate of our method is lower than the other two methods. Figure 8 shows the transmission delay versus the number of MHs. The original method maintains a high delay. The MAS method changes the path to the next higher bit rate MHs and improves the delay, but the path is constrained by minimum hops and is not better than our proposed method. Since the algorithm considers bypassing the affected neighbor node, the delay might increase when the number of MHs is between 70 and 100.

Table 7 The distance to determine the bit rate

Bit rate(Mbps)	11	5.5	2	1
Range(m)	160	270	400	550

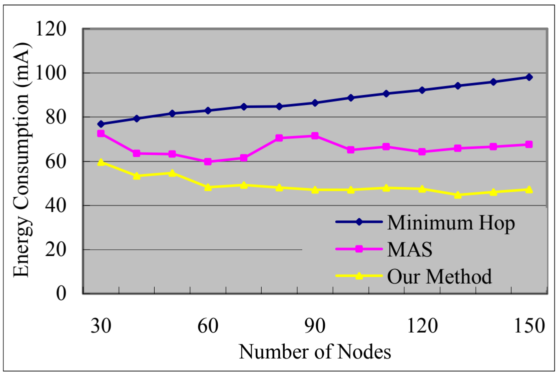

Fig. 6 Energy consumption v.s. the number of MHs

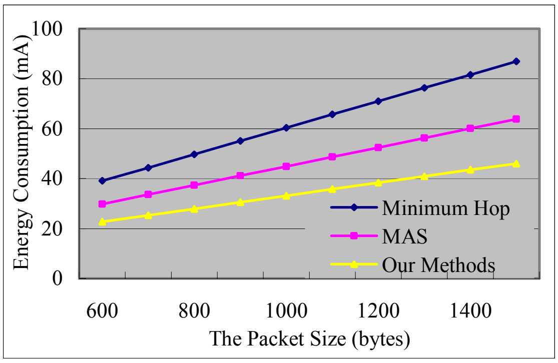

Fig. 7 Energy consumption v.s. the packet size

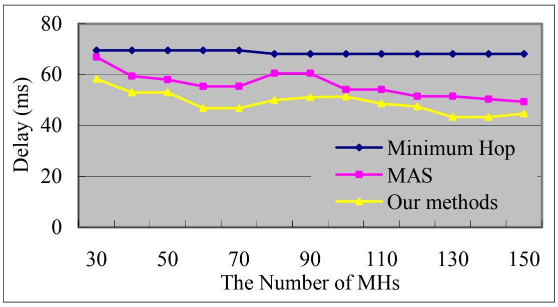

Fig. 8 Transmission delay v.s. the number of MHs

6. Conclusions

Multi-rate, multi-hop wireless and power consumption issues are discussed in this paper. We formulate the problem as a minimum power consumption problem in multi-rate ad hoc networks or sensor networks. It considers energy-aware routing and a passive mode strategy with RTS, CTS and ACK control frames. Accordingly, we propose a minimum energy consumption routing algorithm which is an extension of the dijkstra algorithm. The numerical results show that our method not only achieves our objective, but also achieves a lower delay than the minimum hop and MAS methods.

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