An Error-aware and Energy Efficient Routing Protocol in MANETs

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***Abstract*— The network lifetime is a key design factor of mobile ad-hoc networks (MANETs). To prolong the lifetime of MANETs, one is forced to attain the tradeoff of minimizing the energy consumption and load balancing. In MANETs, energy waste resulting from retransmission due to high frame error rate (FER) of wireless channel is significant. In this paper, we propose a novel protocol termed error-aware candidate set routing protocol (ECSRP). ECSRP chooses a route in a candidate subset in the route cache in which all the nodes have enough residual battery power. This approach avoids overusing certain routes. If multiple routes exist in the candidate set, ECSRP employs a metric achieving the tradeoff between energy-efficiency and load balancing to select the optimal route. It also takes channel condition into consideration by incorporating packet loss probability in the computation of energy consumption. This helps to reduce the number of retransmissions and save energy. We evaluate the performance of ECSRP under the Gilbert error model. Simulation results demonstrate that ECSRP outperforms the representative protocol conditional min-max battery cost routing (CMMBCR) protocol in terms of total energy consumption and load balancing.**

I. Introduction

A mobile ad-hoc network (MANET) consists of a set of autonomous mobile wireless nodes distributed in a certain area forming a temporary (ad-hoc) network without any infrastructure. Thus every node may have to serve as the intermediate node to relay the packets between a pair of nodes geographically far enough. Any failure of node may result in disconnection between a pair of communicating nodes.

Wireless devices are often battery powered, which means that power should be used extremely efficiently to maintain the connectivity of the network as long as possible. The energy consumption sources within a wireless device include CPU, monitor, hard disk drive, memory, keyboard/mouse, CD drive, floppy disk drive, wireless interface card, etc. Take a Toshiba 410 CDT mobile computer for example, 36% energy is consumed by monitor, 21% by CPU/memory, 18% by hard drive, 18% by wireless interface card [7]. This implies that, the communication related consumption takes a fairly large portion of the total energy consumption. This calls for the design of energy efficient routing protocols. Relevant approaches are power aware source routing (PSR) [13], localized energy aware routing (LEAR) [20], online power aware routing (OPAR) [12], power-aware localized routing (PLR) [16] and Power-Aware Routing Optimization (PARO) for Wireless Ad hoc Networks [4].

The energy efficient routing protocols proposed in literature mainly consider factors like total transmission power, residual energy or combination of them. However, in wireless channels, the channel condition also affects the power consumption. For example, if the BER of a channel is high, packets are retransmitted more frequently, and hence more energy is consumed for retransmission. Therefore, in this paper, we propose an energy efficient routing protocol that also takes into consideration the channel condition of the links when searching for the available routes.

The organization of the paper is as follows. Section II briefly examines the related works. Section III proposes our energy efficient routing protocol termed *error-aware candidate set routing protocol* (ECSRP). Section IV provides the performance comparisons between CMMBCR and ECSRP. Section V summarizes the whole paper and brings out the future work.

II. Related Works

The study of energy efficient wireless devices focuses mainly on the following aspects: design of low energy consuming hardware, reduction of the computational complexity to reduce the energy consumption by CPU/memory, diminishment of communication related energy consumption. Broadly speaking, communication related energy consumption also includes computation related energy consumption. But in this paper we only focus on the energy consumed by pure communication operations. Generally, the optimization of communication related energy consumption can be carried out at any layer of the protocol stack. For example, at physical layer an adjustable transmission range can be implemented based on the distance from the next hop to that allows wireless node to use the minimum energy to transmit packets. This not only preserves the energy but also reduces the interference. At data link layer an efficient sleeping scheme is able to further diminish the energy consumption when nodes are idle [15]. At network layer there exist several energy efficient routing protocols being capable of using energy more efficiently. In addition, load balancing, which implies to use the energy more evenly and thus prevents certain nodes from being overused, is also an important consideration.

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Optimization carried out at network layer exists in the following schemes: *minimum total transmission power routing* (MTPR), *minimum battery cost routing* (MBCR), *min-max battery cost routing* (MMBCR), *conditional min-max battery cost routing* (CMMBCR) [18]. MTRP, MBCR and MMBCR all have their advantages and disadvantages. MTRP minimizes the transmission power but are not load balancing while MBCR and MMBCR are load balancing but not energy-saving. CMMBCR combines the advantage of MTPR and MMBCR. It chooses a route whose bottleneck residual energy larger than a certain threshold. If there is more than one route satisfying this condition, then it selects the one with minimum total transmission power, as in the case of MTPR. When no route satisfies the condition, similar to MMBCR, it chooses a route with minimum battery cost. In other words, it divides the whole running time into two phases. In the first phase, energy-saving is the most important task; while in the second phase, load balancing is the main focus among all factors. It was reported that CMMBCR outperforms the other three schemes in most cases.

III. The Proposed Algorithm

A. Energy Model

Most energy-efficient routing protocols are the matters of selecting existing routes between two nodes. The difference is the way of selecting. What this means is that these protocols often rely on other routing protocols to do the route discovery. We focus our attention on this kind of energy-efficient routing. Specifically speaking, we will study the energy-efficient routing protocol using DSR routing protocol [6] to do the route discovery. Other related routing protocols are discussed in [1] and [2]. Furthermore, we assume an environment of an *IEEE* 802.11-like wireless LAN with Virtual Carrier Sensing(VCS) and a basic power control scheme [11]. In this scheme, RTS, CTS are transmitted using the maximum transmission range (hence the maximum energy). DATA and ACK packets are transmitted using minimum required transmission range.

We model the transmission energy using the shadowing model [14]. Under this model the transmission energy per second can be expressed as

$$P_t = \gamma \times d^r, \tag{1}$$

where γ is determined by the frequency of the radio, receiver's threshold and signal-to-noise threshold. As in [17] we assume it is a constant. Also, d is the transmission range, r is the path loss exponent. Transmitting RTS and CTS consumes the following total energy

$$E_{RTS} = \gamma \times d_{max}^r \times T_{RTS}, \tag{2}$$

$$E_{CTS} = \gamma \times d_{max}^r \times T_{CTS}. \tag{3}$$

Data and ACK are transmitted using the following energy

$$E_{DATA}^{ij} = \gamma \times d_{ij}^r \times T_{DATA}, \tag{4}$$

$$E_{ACK}^{ij} = \gamma \times d_{ij}^r \times T_{ACK}, \tag{5}$$

where d_{max} is the maximum transmission range, d_{ij} is the distance between node i and node j, T_{RTS}, T_{CTS},T_{DATA},T_{ACK} are the transmission time of RTS, CTS, data and ACK packets respectively. Assume that there is route between the source $S = x_1$ and destination $D = x_m$ with intermediate nodes $x_2, x_3, ..., x_{m-1}$. Then transmitting a packet along the path requires the total energy

$$\begin{aligned} E_{SD} \;=\; & \sum_{i=1}^{m-1} \gamma \times d_{i(i+1)}^r \times (T_{DATA} + T_{ACK}) \\ & + \sum_{i=1}^{m-1} \gamma \times d_{max}^r \times (T_{RTS} + T_{CTS}) \\ & + \sum_{i=1}^{m-1} P_r \times (T_{DATA} + T_{ACK} + T_{RTS} + T_{CTS}), \end{aligned} \tag{6}$$

where P_r is the receiving energy per second and is assumed to be the same regardless of the packet type. We also assume that the receiving time is the same as the corresponding transmission time. To all energy-efficient routing schemes, E_{SD} is a important metric which should be considered and ideally it should be minimized to some extent. Since we use source routing protocol to do the route discovery, this amounts to choosing a route with minimum E_{SD} in the route cache. However, always choosing a route with minimum E_{SD} also causes problems as we will show in the subsequent sections.

B. Lossy Channel and Its Impact

When channel is lossy, the lost packet may intervene the MAC protocol, causing the energy consumption to be a function of channel loss probability. To this end, average frame error rate (FER) is used to describe channel quality. We use Gilbert error model [3] to generate error packets. Other related error models can also be employed, such as Hierarchical Markov Model [8], Markov-based trace analysis (MTA) [10]. When the channel quality can not be modeled well by an error model, the wireless nodes can measure the error probability of a channel regularly and uses the latest two probabilities to calculate the weighted sum over a time period [5].

Gilbert error model is essentially a two-state Markov chain. One of the states is error state; the other is error-free state. When the channel is in the error state, the probability that a packet gets corrupted is high; while in error-free state packets never get corrupted or get corrupted with a low probability. The channel remains in each state for a period of time and then transfers to another state. Let p denote the transition probability from error-free state to error state, r denote the transition probability from error state to error-free state. Then the Gilbert error model is depicted in Figure 1.

It is worth mentioning how to obtain average loss probability (ALP) under Gilbert error model. Assume that the error-free period is t_{good}, error period is t_{bad}, loss probability in each state is p_{good} and p_{bad} respectively. The transition matrix is

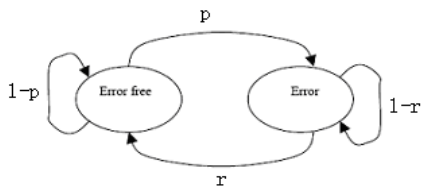

Fig. 1. Gilbert error model

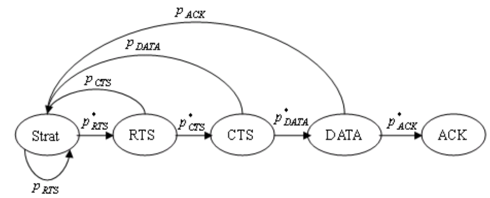

Fig. 2. State transition diagram of VCS

given by

$$R = \begin{pmatrix} 1-p & p \\ r & 1-r \end{pmatrix}. \tag{7}$$

So the duration of error state is a geometric random variable with the mean $\frac{t_{bad}}{r}$ and similarly the mean time in error-free state is $\frac{t_{good}}{p}$. The steady-state probability of the channel being in error state is given by

$$\pi_{bad} = \frac{\frac{t_{bad}}{r}}{\frac{t_{bad}}{r} + \frac{t_{good}}{p}}. \tag{8}$$

The steady-state probability of the channel being in error-free state is given by

$$\pi_{good} = \frac{\frac{t_{good}}{p}}{\frac{t_{bad}}{r} + \frac{t_{good}}{p}}. \tag{9}$$

From Equations (8) and (9), the steady-state loss probability or equivalently ALP is given by

$$\varepsilon = p_{bad} \times \pi_{bad} + p_{good} \times \pi_{good}. \tag{10}$$

If $p_{good} = 0$ then (10) can be simplified to

$$\varepsilon = p_{bad} \times \pi_{bad}. \tag{11}$$

Note that since the length of different packet type is different, the loss probability is also different. The parameters of the above error model should be changed according to different packet types. We denote the ALP obtained by Gilbert error model for RTS, CTS, DATA, ACK as p_{RTS}, p_{CTS}, p_{DATA} and p_{ACK} respectively and denote $(1-p)$ as p^*.

To express the energy consumption accurately we need to explain the behavior of VCS when channel is lossy. When the sender advertises a RTS packet, the receiver responds with a CTS. If the CTS is not received in a predefined interval, the sender retransmits RTS. When the sender receives RTS, it starts to transmit the data packet and waits to receive the ACK. If ACK fails to arrive, the whole process will be repeated again [21]. Thus one has the state transition diagram of VCS shown in Figure 2 where state $Start$ is the initial state, RTS is the state indicating the RTS is received successfully, so are the states CTS, $DATA$ and ACK. From the state transition diagram, the average energy consumption to transmit a packet one hop away is

$$\begin{aligned} E_{ij} \;=\; & \frac{E_{RTS}}{p^*_{RTS}p^*_{CTS}p^*_{DATA}p^*_{ACK}} + \frac{E_{CTS}}{p^*_{CTS}p^*_{DATA}p^*_{ACK}} \\ & + \frac{E^{ij}_{DATA}}{p^*_{DATA}p^*_{ACK}} + \frac{E^{ij}_{ACK}}{p^*_{ACK}} \\ & + P_r \times (\frac{T_{RTS}}{p^*_{CTS}p^*_{DATA}p^*_{ACK}} + \frac{T_{CTS}}{p^*_{DATA}p^*_{ACK}}) \\ & + P_r \times (\frac{T_{DATA}}{p^*_{ACK}} + T_{ACK}). \end{aligned} \tag{12}$$

Given the average energy consumption for one hop transmission, then equation (6), i.e. the energy required for transmitting a packet between source and destination, becomes

$$E_{SD} = \sum_{i=1}^{m-1} E_{i(i+1)}. \tag{13}$$

So when the channel is lossy, we should consider equation (13) instead of equation (6).

C. Achieving Tradeoff between Energy Efficiency and Load Balancing

Choosing an energy-efficient route is certainly a reasonable consideration. However, under some circumstance, it may result in a hot route depleting its nodes' battery power much faster than the others and cause it to die quickly. This is undesirable because it increases the possibility of disconnection. On the contrary, to evenly use all available routes we should use less energy-cost routes. So there is a tradeoff between these two issues. We achieve this tradeoff by the proposed approach.

First some symbols are defined. Denote all available routes in the route cache as R. For each route $r \in R$, N_r is the set of nodes on that route. Further, define $b_i(t)$ as the residual battery power of node i at time t, $b^r_{min}(t)$ as the minimum residual battery power of the nodes along route r, that is

$$b^r_{min}(t) = \min_{i \in N_r} b_i(t) \tag{14}$$

Let $B_{max}(t)$ and $B_{min}(t)$ be the maximum and minimum values among all $b^r_{min}(t)$ in the route cache respectively, i.e.

$$B_{max}(t) = \max_{r \in R} b^r_{min}(t) \tag{15}$$

$$B_{min}(t) = \min_{r \in R} b^r_{min}(t) \tag{16}$$

Without causing confusion, we omit t in the further analysis. For each route r, let E_r denote the energy required by transmitting a packet along that route which can be calculated using equation (13). E_{min} is the minimum value among all E_r, i.e.

$$E_{min} = \min_{r \in R} E_r \tag{17}$$

We use $E_r - E_{min}$ to define how efficiently the route r uses the energy. To save energy, this value should be as small as possible and by definition a route r which has the smallest E_r corresponding to 0 of this value. Also, we use $b^r_{min} - B_{min}$ to show how frequently the route is chosen to be the active route. A less frequent used route may have larger $b^r_{min} - B_{min}$. Thus finding the most suitable route can be formulated as the following problem,

$$\begin{aligned} \max \quad & b^r_{min} - B_{min} \\ \min \quad & E_r - E_{min} \\ s.t. \quad & \\ & r \in R \end{aligned} \tag{18}$$

Usually these two objectives can not be met simultaneously. Our method is to bound $B_{max} - b^r_{min}$ and search for a route in a candidate set

$$C = \{r | r \in R \ and \ B_{max} - b^r_{min} < \beta\} \tag{19}$$

that maximizes the following metric

$$m = \frac{b^r_{min} - B_{min}}{E_r - E_{min}}, \quad \text{where} \quad E_r - E_{min} \neq 0 \tag{20}$$

If there is a route in the set C whose $E_r = E_{min}$, we always choose this route.

Choosing from the candidate set C forces us to choose a route with enough b^r_{min}. The parameter β defines how much weight we should put on the load balancing. The maximization of metric (20) implies that a favorable route should have large b^r_{min} and small E_r, thus its $\frac{b^r_{min} - B_{min}}{E_r - E_{min}}$ is relatively larger than the other routes. When using this metric it is also possible for a route with small b^r_{min} to be chosen because its E_r is much smaller than the other routes with large b^r_{min}. This argument also holds for a route with large E_r. But in this case it should have a large b^r_{min} to compensate the use of a high energy route.

An interesting issue is how the candidate set C evolves during the time. Figure 3 demonstrates the set C. Note that

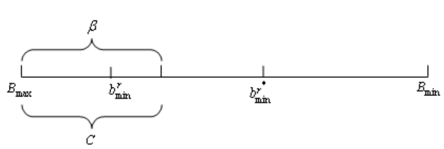

Fig. 3. Candidate set C

B_{max}, B_{min}, b^r_{min} and $b^{r^*}_{min}$ in Figure 3 are not constants but variables whose values are decreasing as time goes. Denote $v_{B_{max}}$, $v_{B_{min}}$, $v_{b^r_{min}}$ and $v_{b^{r^*}_{min}}$ as the decreasing speed for B_{max}, B_{min}, b^r_{min} and $b^{r^*}_{min}$ respectively. We have the following remarks.

1. There is at least one route in the candidate set C. The route r whose $b^r_{min} = B_{max}$ will be always in C. This means that there is always a route to be chosen from C.

2. Given β fixed, if $v_{B_{max}}$ is larger than $v_{B_{min}}$ for a sufficient large time period, the candidate set C will be equal to the set R. This happens when $B_{max} - B_{min} \leq \beta$ and indicates that the routes whose nodes' battery power is relatively sufficient is under more heavily use than the other routes (in this case , the load balancing effect is achieved) and eventually all the routes in the route cache are comparably usable in terms of load balancing.

3. If $v_{b^r_{min}} > v_{B_{max}}$, route r will eventually be eliminated from the candidate set C. Since in this case, some nodes on route r are under heavily use, the battery power of them is drained very quickly. Eliminating this route from the candidate set C can help preventing its nodes from being overused.

4. Route r^*, which is outside the candidate set C initially, may or may not enter C depending on its decreasing speed $v_{b^{r^*}_{min}}$. If $v_{b^{r^*}_{min}} \geq v_{B_{max}}$, route r^* will never enter C, otherwise it will enter C. This means $v_{B_{max}}$ acts as a reference. Any route whose $v_{b^{r^*}_{min}}$ is larger than $v_{B_{max}}$ is considered to have some heavily used nodes on it and should be avoided.

From the above discussion, the combination of B_{max} and β can be considered as some form of "sliding window" which can include or eliminate routes not only based on their nodes' residual battery power but also on the usage of those nodes. In this sense, we also achieve the effect of "drain rate" proposed in [9]. The pseudocode of the above algorithm is described in Table I.

IV. Simulation Results

In this section, we will compare the performance between CMMBCR and ECSRP. We conduct a series of simulations using the ns2 simulator [19]. In order to implement the power control scheme employed in this paper, we modified the wireless physical layer and energy model. Other configurable parameters of energy model and wireless interface card are listed in Table II.

In the simulations, we assume that 49 wireless nodes are randomly distributed over an $150m \times 150m$ area. Each node initiates a transmission session with another randomly chosen node with a random probability. This means that only some nodes can initiate transmission session, which is like in a real environment. Moreover we use Gilbert error model to generate loss event in each receiving channel. For simplicity, we assume that different packet types have the same loss probability, i.e. $p_{RTS} = p_{CTS} = p_{DATA} = p_{ACK}$. The following transition matrix is used in the Gilbert error model:

$$R = \begin{pmatrix} 0.9 & 0.1 \\ 0.8 & 0.2 \end{pmatrix}. \tag{21}$$

Three sets of parameters corresponding to three different channel conditions are listed in Table III and assigned randomly to each receiving channel. We run the simulations under 50 randomly generated instances of topology according to the above description and the averages are computed for comparison purpose.

TABLE I

PSEUDOCODE OF ECSRP

```
Algorithm of ECSRP
Energy(r): return E_r
Bottleneck(r): return b^r_min
max: the maximum optimization metric

for all available route r in the route cache do
    b^r_min = Bottleneck(r)
    E_r = Energy(r)
    if B_max < b^r_min then
      B_max = b^r_min
    endif
    if B_min > b^r_min then
      B_min = b^r_min
    endif
    if E_min > E_r then
      E_min = E_r
    endif
endfor

for all available route r in the route cache do
  b^r_min = Bottleneck(r)
  E_r = Energy(r)
  if B_max - b^r_min < β then
    if E_r == E_min then
      route = r
      break
    endif
    m = (b^r_min - B_min) / (E_r - E_min)
    if m > max then
      max = m
      route = r
    endif
  endif
endfor
return route
```

TABLE II

PARAMETERS OF ENERGY MODEL AND WIRELESS INTERFACE CARD

Parameters	Description
$RXThresh = 3.1622777e - 11$	Receiver's threshold
$CSThresh = 3.1622777e - 12$	Carrier sense threshold
$CPThresh = 10.0$	Capture threshold
$pathlossExp = 4.0$	Path loss exponent
$freq = 2.472e9$	Radio frequency
$Pt = 3.3622777$	Maximum transmission energy per second
$Pr = 1.0$	Receiving energy per second

Specifically, two metrics are compared, i.e. residual battery power and node death speed. To compare the residual battery power, a fixed number of packets are sent by every source to ensure that none of nodes is dead (If there are dead nodes then the number of packets sent by certain nodes may be smaller than others. The comparison is inaccurate in this case) and the battery power of every node is obtained after all the packets are sent out. Node death speed traces how many nodes are still alive after certain time. From load balancing perspective, this speed should be as slow as possible. In order to measure it, a sufficient large number of packets are sent to ensure that there are dead nodes in either ECSRP or CMMBCR or in both of them.

TABLE III

PARAMETERS FOR GILBERT ERROR MODEL

t_{bad}	t_{good}	p_{bad}	p_{good}
N/A	N/A	0	0
0.03	0.03	0.540001	0
0.04	0.04	0.720001	0

All the nodes have an initial battery power of 100. The threshold for CMMBCR is assumed to be 50 which implies load balancing is paramount among all considerations when half of battery power is dissipated. Since $T_{DATA} = 0.001321s$ in the simulations, even it is transmitted using the maximum range, the energy consumption for transmitting data packet is only 0.004. Thus the energy for transmitting a packet across one hop using VCS can not exceed 0.016. In light of this, we should set the parameter β in ECSRP to a small value, otherwise the effect of the "sliding window" is diminished. In the simulation, we set it to 1.0. Simulation results are shown in Figures 4 - 5.

From Figure 4, we can see the average residual battery power of ECSRP is much higher than that of CMMBCR. Furthermore ECSRP outperforms CMMBCR in terms of node death speed, as shown in Figures 5. It can be seen that ECSRP achieves better load balancing and prolongs the lifetime of individual wireless node.

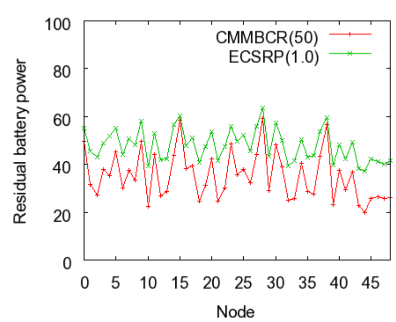

Fig. 4. Residual battery power

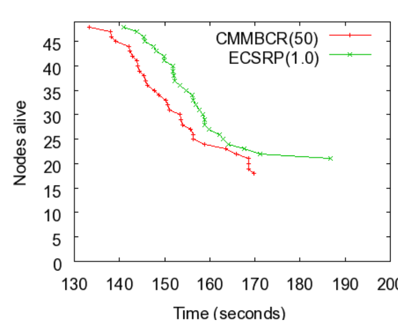

Fig. 5. Node death speed

Next, the impact of parameter β of ECSRP on the residual battery and node death speed is shown in Figure 6 and Figure 7, respectively. As we expected, a larger β does increase

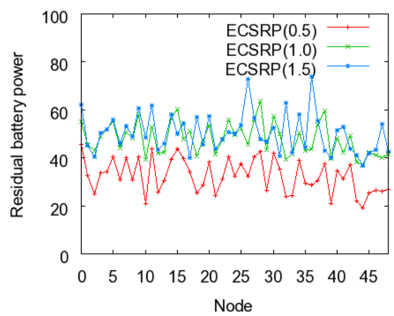

Fig. 6. Impact of the parameter β on residual battery power

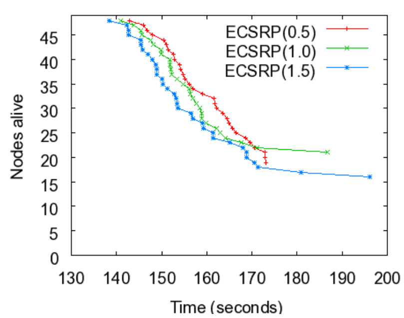

Fig. 7. Impact of the parameter β on node death speed

the chance for the candidate set to include more routes and more energy-efficient effect is achieved as β increases, while a smaller β can result in more balanced usage of energy.

V. Conclusion

This paper has proposed ECSRP which achieves the tradeoff between energy efficiency and load balancing. The candidate set C in ECSRP behaves like a "sliding window" which can dynamically include or eliminate routes based on their nodes' residual battery power and nodes' usage. In C, a metric taking into account both energy efficiency and load balancing is used to select the most suitable route. The "error-aware" means when it computes the energy required by transmitting a packet along the route, the channel condition is considered and the average energy consumption under random packet loss is used to choose an energy-efficient route. We have evaluated the performance of ECSRP under Gilbert error models. Through simulation, we have shown that our proposed scheme consumes energy in a more balanced manner. Unlike CMMBCR which only considers the energy consumption E_r when B_{min} is larger than a certain threshold, our proposed scheme minimizes energy consumption E_r through the entire running process, so it also leads to nodes with more residual battery power. Besides, the error-aware feature of ECSRP also helps to reduce the energy consumption due to the retransmission of packets.

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