

End-to-end Reliable Message Transmission Considering Load Balancing in Wireless Networks

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Abstract

This paper proposes a load balanced reliable routing protocol called LBR (Load Balanced Reliable routing) in wireless networks. The LBR protocol transmits messages through a reliable path considering the balancing of the traffic load. Recently, the authors have proposed a multipath-based reliable routing protocol called MRFR, which is an appealing protocol for fault tolerant reliable data transmission. However, MRFR has no concern with the problem of load balancing, which results in increasing congestion and consuming high energy at some network nodes. As a result, the problem affects negatively the performance of the network. Taking account of load balancing as a route selection criteria can avoid routing through the congested nodes and allows to find better routes. In this paper, we extend MRFR by considering load balancing in the route discovery process of reliable communication. The simulation results showed that the proposed protocol outperforms AODV in terms of end-to-end delay, packet delivery ratio, and average jitter. Compared to MRFR, the LBR protocol has the same packet delivery ratio, and obtains a better efficiency of load balancing.

Keywords: Wireless networks, load balancing, reliable communication, routing protocol

1. Introduction

Routing in ad hoc wireless networks has been an active research area for many years. Recently, many interesting commercial applications intended for wireless networks in which most of the nodes being either stationary or minimally mobile have been developed [1, 2]. The aim of routing protocols in such networks tends to improve the data transmission reliability.

The most common link metric being used in ad hoc routing protocols is minimum hop-count [3, 4, 5]. This metric selects a path minimizing hop-count between the source and destination without considering the lossy ratio of wireless links. In static ad hoc wireless networks, several studies have shown the poor performance of minimum hop-count [6, 7]. Several estimators in terms of link quality have been proposed such as ETX [6], RTT (Per-hop Round Trip Time) [8] and BW (Bandwidth) [9, 10]. Among them, the ETX estimator is shown to be the best metric in static wireless networks [7]. To deal with the problem of reliable data transmission, our routing protocol uses ETX as a link metric to select high quality routes.

The problem of balancing load in wireless networks is one of the interesting topics being studied recently [11, 12, 13]. Routing protocols using shortest path can make the center of the network become “crowded”, because of having more paths to transmit data through the center than through the periphery of the network. This issue causes the increase of congestion and energy consumption for nodes near the center. Our routing protocol aims to increase the lifetime of network and has a good load distribution among nodes.

The rest of the paper is organized as follows. Section 2 describes related work. Section 3 gives a detailed description of LBR protocol for both reliable communication and load balancing. Section 4 presents the performance evaluation of the proposed protocol and Section 5 concludes the paper.

2. Related Work

Much work has been done for real-time and reliable data communication [14, 15, 16]. Many routing protocols use the shortest routing path to transmit data packets. Using the shortest path for data transmission may be a good choice for fast delivery, but cannot be a good choice for reliability due to the frequent link failures [6, 17]. Physical layer parameters have been used as a link quality metric for routing in wireless networks. The authors of [18] presented the design and demonstration of a set of routing protocol mechanisms that significantly improves the transmission of real-time multimedia streams in a mobile ad hoc network. Their routing protocol extends DSR protocol [5] by using SNR (Signal-to-Noise Ratio) in route discovery to limit unreliable links. In that protocol, a node that receives a RREQ packet with the SNR of the packet below a threshold will not forward the packet. Some LQI (Link Quality Indicator)-based routing protocols have been proposed [16, 19, 20]. The authors of [21] showed that LQI-based routing could have negative effects on the network performance. Due to the short temporal dynamics of wireless channels, it is difficult to achieve good correlation between physical layer information and real link quality over different links. The ETX was widely adopted as a good link quality estimator for reliable communication in wireless networks [6, 22]. Authors of [7] compared the performance of routing metrics including ETX, RTT, per-hop packet pair, and minimum hop-count. The authors showed that ETX is the best metric in static wireless networks. Authors of [22] used ETX as a link metric to find high

quality paths for collecting data from sensor nodes to sinks. The authors showed that the performance of routing based on ETX outperforms MultihopLQI [19]. The authors of [23] showed that PRR based metrics such as ETX is more suitable in cost-sensitive routing scenarios and proposed an effective method for designing ETX-based multi-hop routing protocols. Recently, the authors of [24] have proposed a reliable routing protocol with fault tolerance capability called MRFR, which uses ETX as a link quality estimator.

Authors of [25] showed that using multiple paths for balancing load will not achieve a good results unless a large number of paths is used. The authors in [26] proposed a load balancing scheme in MANETs for handling congestion and uneven energy consumption of nodes. Depending on the self-traffic load of nodes, the nodes may intentionally give up packet forwarding to save energy. The authors of [27] proposed a grouping algorithm based on AODV [4] such that the routing load is balanced by evenly distributing source nodes into a number of groups. A routing protocol with congestion-aware path selection was proposed in [28]. The authors proposed a solution to the problem of congestion in MANETs by moving the traffic away from the shortest paths, which is usually the most congested area, to a less congested path. By removing congestion, we can minimize the number of data packets drops during transmission and reduce unnecessary delay due to path recovery. The authors of [29] presented a protocol which aims to balance the energy consumption among nodes to ensure the network connectivity and maximize the network life time. This protocol chooses the node with the highest energy level among potential nodes as the next hop for transmitting data.

3. LBR – A Load Balanced Reliable Routing Protocol

3.1 Expected transmission count (ETX)

The ETX of a link is the expected number of data transmissions requiring to send a data packet over that link, including retransmissions. The ETX of a route is the sum of the ETX of links over that route. Each node measures the probability that a data packet is successfully delivered to the receiver, known as the forward delivery ratio and denoted as d_f . The probability that an ACK is successfully received by the sender, which is called the reverse delivery ratio, is denoted as d_r . The ETX value of the link is given by $ETX = \frac{1}{d_f \times d_r}$. Each node broadcasts probe packets of a fixed size to measure the delivery ratios d_r and d_f [6].

3.2 Definitions

The LBR protocol considers both the end-to-end reliability of routes and the load of each node when selecting a path between a source and a destination. The LBR uses ETX as a link quality estimator to measure the packet transmission reliability on the link. The end-to-end ETX of a path from node S to node D, $e2eETX(x,y)$, is defined as the sum of link ETX values in the path. We define the load of node n , $load(n)$, as the number of data packets that the node transmits and receives in a unit time during the previous window w from the current time. The load factor of node n , $lf(n)$, is defined as the ratio between $load(n)$ and the $max_load(n)$. The $max_load(n)$ of node n denotes the maximum number of data packets that node n can transmit and receive in a unit time, which is calculated as follows.

$$max_load(n) = max_transmission_rate(n) / data_packet_size \quad (1)$$

The $max_transmission_rate(n)$ denotes the maximum number of bits that node n can receive or transmit in a unit time and the $data_packet_size$ denotes the average size of data packets including all protocol headers. Thus, $max_load(n)$ indicates the maximum number of data packets that node n can receive or transmit back-to-back in a unit time. The remaining load factor of node n , $rlf(n)$, is then defined as follows.

$$rlf(n) = 1 - lf(n) = 1 - load(n)/max_load(n) \quad (2)$$

The higher remaining load factor of node n means that it has smaller congestion. The LBR protocol uses $rlf(n)$ and link-ETX values to find a path which has the smallest end-to-end ETX value and the minimum remaining load factor of the nodes in the path is the highest. Node n keeps its $rlf(n)$ by calculating the number of data packets being received and transmitted during the previous window. Node n also calculates $ETX(n,m)$ by exchanging and measuring beacon packets between its neighbor m and keeps $ETX(n,m)$ in its neighbor table.

3.3 Route Discovery

The LBR protocol uses ETX as a link quality estimator and considers the remaining load factor of a node as a criterion for balancing load when selecting a path from a source to a destination. Route discovery process is performed by exchanging RREQ (Route REQuest) and RREP (Route REPLY) control packets between the source and the destination. Each node maintains a routing table for routing data packets. The routing table consists of a reverse route entry, $RE[id, pHop, srcETX, srcMRF]$, and a forward route entry, $RE[id, nHop]$. The id denotes the identifier of the path and $pHop$ and $nHop$ the previous and the next node of the path. The $srcETX$ denotes $e2e_ETX(S,x)$ of the path from the source of the path id to the node x and $srcMRF$ denotes the minimum remaining load factor of nodes in the path id that we call the minimum remaining load factor of path id .

When a source node S wants to transmit data to a destination node D , it tries to set up a path by broadcasting RREQ packet. The RREQ packet carries $RREQ[id, etx, mrf]$ where id denotes the ID of the path, etx denotes the sum of the ETX values of links over which the RREQ packet has traversed, and mrf indicates the minimum remaining load factor of nodes in the path through which the RREQ has been traveled. Initially, node S broadcasts $RREQ[id, etx=0, mrf=rlf(S)]$ packet. When a node Y with the remaining load factor $rlf(Y)$ receives $RREQ[id, etx, mrf]$ from its neighbor X , it performs as described in **Fig. 1**.

When node Y receives $RREQ[id, etx, mrf]$ packet from X for a new path id , it creates a reverse routing entry for the path id as $RE[id, pHop = X, srcETX = etx+ETX(X,Y), srcMRF = mrf]$. After that, if node Y receives another $RREQ[id, etx, mrf]$ packet from Z , it compares the routing information in the new RREQ packet with that of the path id in the routing table. If the routing information in the new RREQ packet is better than that of the path id in the routing table, it updates the reverse routing entry for the path id . We determine the better path in terms of two factors. The first one is the load balancing factor (*Condition 1*). That is, if the minimum remaining load factor of the new RREQ packet (mrf) is greater than the existing minimum remaining load factor in the routing table ($srcMRF$) by more than $H2$ threshold, the path of the new RREQ packet is better than the existing path in the routing table. The second factor is the $e2e_ETX$ values of the paths (*Condition 2*). If *Condition 1* is not true, LBR compares the $e2e_ETX$ value of the new RREQ packet with the $e2e_ETX$ value in the routing table and select the better (smaller) one. In the case of *Condition 2*, however, we accept the new path in the RREQ packet only when it has smaller $e2e_ETX$ value and the minimum remaining load factor in the RREQ packet is not lower than the existing one by more than $H1$ threshold.

Algorithm 1 LBR Route Request

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1: When Y receives RREQ[id, etx, mrf] packet from X
2: If it is the first RREQ packet of path id then
3:   Y creates a reverse routing entry of path id
4:   RE[id, pHop:= X, srcETX := etx + ETX(X,Y), srcMRF = mrf]
5:   Y updates RREQ as follows
6:   RREQ[id, mrf = min{mrf, rlf(Y)}, etx = etx + ETX(X,Y)]
7:   Y rebroadcasts the updated RREQ[id, etx, mrf] and sets the timer ΔdelayRREQ
7: else if a reverse entry RE[id, pHop, srcETX, srcMRF] exists then
8:   if ((mrf - srcMRF ≥ H2) //Condition 1
        Or ((etx+ETX(X,Y) < srcETX) and (mrf + H1 ≥ srcMRF))) //Condition 2
        then
9:     Y updates the reverse entry of path id
10:    RE[id, pHop=X, srcETX = etx+ETX(X,Y), srcMRF = mrf]
11:    Y updates and keeps RREQ until ΔdelayRREQ becomes 0
        RREQ[id, mrf = min{mrf, rlf(Y)}, etx = etx + ETX(X,Y)]
13: else
14:   Y drops the new RREQ packet
15: end if
16: end if

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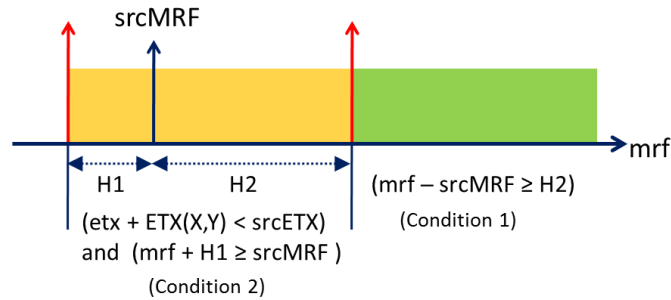
Fig. 1. The process of LBR Route Request.**Fig. 2.** Route selection conditions of LBR protocol.

Fig. 2 shows the two route selection conditions of the LBR protocol. The values of the two H1 and H2 thresholds may affect the performance of LBR protocol. H2 is defined as the load balancing factor. In which, routing table is updated if the minimum remaining load factor in RREQ packet is larger than the minimum remaining load factor in routing table entry by more than H2 threshold. H1 is defined as the end-to-end reliability factor. The routing table is updated if the RREQ packet has smaller e2eETX and the minimum remaining load in the RREQ is not smaller than the minimum remaining load in routing table by more than H1 threshold. Given H1, if H2 is small, the load balancing factor affects more than the end-to-end reliability factor in choosing route. Given H2, if H1 is small, the end-to-end reliability factor affects more than the load balancing factor in choosing route. We need to choose the optimal values of H1 and H2 parameters, which will depend on the application. We performed a

simulation to see the impact of H1 and H2 threshold values to the performance of LBR protocol.

If the path of the new RREQ packet is better than the existing one in the routing table in terms of *Condition 1* or *Condition 2*, node Y updates its routing table. After that, it has to rebroadcast the new RREQ packet to its neighbors to notify the better route. However, if node Y rebroadcasts the new RREQ packet immediately, the number of RREQ broadcast packets can be large. Thus, we use $\Delta\text{delayRREQ}$ timer to reduce the number of RREQ broadcast packets. After broadcasting the first RREQ packet, node Y sets $\Delta\text{delayRREQ}$ timer and, it collects all the RREQ packets arriving during that time, and selects the best route and rebroadcasts it when $\Delta\text{delayRREQ}$ timer expires. The value of $\Delta\text{delayRREQ}$ timer can affect the performance of the LBR protocol. If it is set to small value, each node cannot receive enough number of RREQ packets during that time, so the number of RREQ packets can increase. If it is given a large value, each node can select the best route by collecting enough number of RREQ packets, but the route establishment delay can increase. We evaluated the impact of $\Delta\text{delayRREQ}$ timer to the performance of the LBR protocol in the performance evaluation section.

On receiving the first RREQ packet, the destination sets $\Delta\text{delayDEST}$ timer, and collects all the RREQ packets arriving during that time, and selects the best route and transmits a RREP packet through the reverse of the selected path when $\Delta\text{delayDEST}$ timer expires.

3.4 Route discovery example of LBR

As an example, a network with ETX value in each link and the remaining load factor in each node is given as shown in Fig. 3, and the parameters H1 and H2 are chosen to be 0.1 and 0.2, respectively. The source S transmits $\text{RREQ}[id, etx=0, mrf=0.9]$ packet by broadcasting to find a route to the destination D.

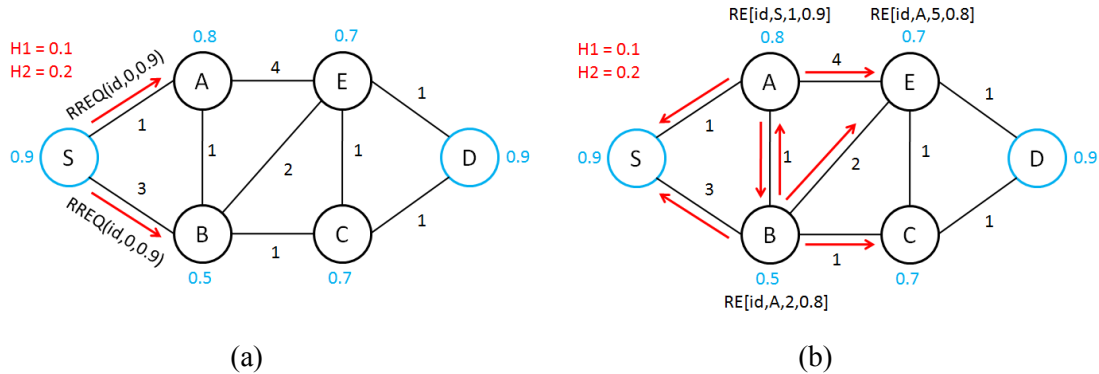


Fig. 3. Route discovery example.

When receiving $\text{RREQ}[id, 0, 0.9]$ from S, node A and B will create the reverse routing entries for the path id , $\text{RE}[id, S, 1, 0.9]$ and $\text{RE}[id, S, 3, 0.9]$, respectively. After that, node A and B will update and rebroadcast the RREQ packet immediately, $\text{RREQ}[id, 1, 0.8]$ and $\text{RREQ}[id, 3, 0.5]$ respectively. Afterwards, when receiving $\text{RREQ}[id, 3, 0.5]$ from B, node A will check *Condition 1* and *Condition 2* to compare the quality of the two paths, the path of the new RREQ packet and the existing path in the routing table. Because both *Condition 1* and *Condition 2* are not true, node A drops the new RREQ packet. On the other hand, when node B receives $\text{RREQ}[id, 1, 0.8]$ from A, it checks *Condition 1* and *Condition 2* to compare the

quality of the two paths. Even though the *Condition 1* is not true ($mrf - srcMRF = 0.8 - 0.9 < H2$), the *Condition 2* is true ($etx + ETX(A,B) = 2 < srcETX$) and ($srcMRF - mrf = 0.9 - 0.8 \leq H1$). Thus, node B updates its routing entry as $RE[id, A, 2, 0.8]$ as shown in **Fig. 3-(b)**. Likewise, when node E receives first $RREQ[id, 3, 0.5]$ from B and $RREQ[id, 1, 0.8]$ from A next time, it first creates its routing entry for path id as $RE[id, B, 5, 0.5]$, and updates it as $RE[id, A, 5, 0.7]$ because the *Condition 2* is satisfied ($mrf - srcMRF = 0.8 - 0.5 \geq H2$).

If RREQ packets are forwarded like this, the destination node D receives multiple RREQ packets from its neighbors. After receiving the first RREQ packet for path id , the destination D sets $\Delta delay_{DEST}$ timer, and collects all the RREQ packets arriving during that time. In the example of **Fig. 4**, node D receives $RREQ[id, 5, 0.7]$ and $RREQ[id, 3, 0.5]$ from E and C, respectively. Node D chooses $RREQ[id, 5, 0.7]$ as the better path because it is better in terms of load balance ($0.7 - 0.5 \geq H2$), and when $\Delta delay_{DEST}$ timer expires, it sends a RREP packet through the reverse path set up while the $RREQ[id, 5, 0.7]$ was broadcasted. Thus, the established path from S to D is S-A-E-D with $e2e_ETX = 6$, $mrf = 0.7$.

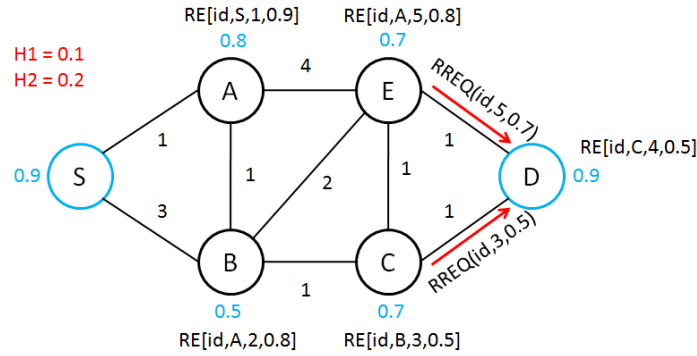


Fig. 4. Route selection at the destination.

4. Performance Evaluation

In this section, we used the Qualnet simulator [30] to evaluate the performance of our protocol and compared with the AODV [4] and MRFR [24] protocols. AODV protocol uses the shortest path to transmit data, meanwhile, MRFR protocol is a reliable routing protocol, which uses ETX as a link quality metric. MRFR discovers routes that have the smallest end-to-end route-ETX value. Our simulations were implemented on a static 125-node network of 1500m*1500m. In all simulations, we set up five simultaneous flows with sources and destinations chosen randomly. The network traffic scenario is illustrated in **Fig. 5**. Note that, because of space limitation, we only labeled some nodes used in our simulations. The results of almost all simulations were calculated as the average of the five flows. The data rate of each node is 5.5 Mbps. The data packet size is 512 bytes. The MAC layer model is 802.11 and the physical layer model is 802.11b. In most of the simulations, we use the transmission power of 15dBm (32mW) for all of the nodes. At the application layer, the constant bit rate (CBR) traffic is used. Source nodes of each flow send data packets from 1 CBR (1 packet per second) to 14 CBR (14 packets per second), depending on the simulation. During the first 30 seconds, the nodes just broadcast probes to measure link metrics and establish network stability. At the time of 30 seconds, the LBR protocol uses ETX to discover routes for the five flows. After routes have been established, the five flows start to transmit data. During the running time, in

the event that a route failure occurs at any flow, the source of the corresponding flow broadcasts a RREQ packet to find a new route. In most of the simulations, the total running time is 240 seconds. The performance of LBR protocol depends on the two thresholds H1 and H2 for considering load balance. We performed a simulation to show the impact of H1 and H2 thresholds to the network performance.

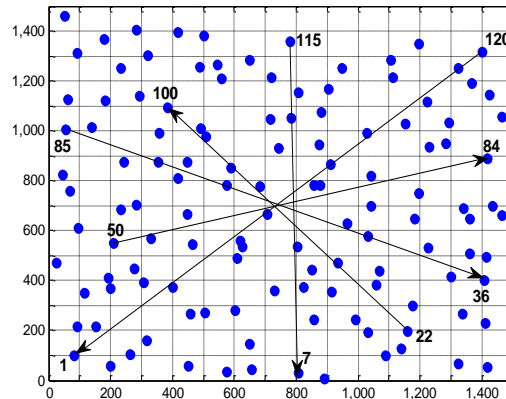


Fig. 5. The network traffic scenario with 125 nodes and 1500m*1500m range.

4.1 Impact of H1 and H2 thresholds

The H1 and H2 threshold values can affect to the performance of the LBR protocol. To find the proper values of H1 and H2 thresholds, we conducted the following simulations. At first, we measured the end-to-end packet delivery ratio in terms of H2 threshold values after fixing H1 threshold value. Fig. 6-(a) shows the result when H1= 0.1, H1= 0.2, and H1= 0.3. For all of the three cases, the end-to-end packet delivery ratio is small if the H2 threshold value is small. This shows that if the H2 threshold value is small, the load balance factor (*Condition 1*) affects more than the end-to-end reliability factor (*Condition 2*) when selecting paths, thus, it becomes difficult to find more reliable path. When the H2 threshold value increases, the end-to-end packet delivery ratio also increases as shown in Fig. 6-(a). However, from the point of 0.2, even though we increase the H2 threshold value, there is no difference in the end-to-end packet delivery ratio. If we use a large H2 threshold value, it becomes difficult to find the better path in terms of load balance factor (*Condition 1*), thus, we can see that the proper value of the H2 threshold is 0.2 in Fig. 6-(a).

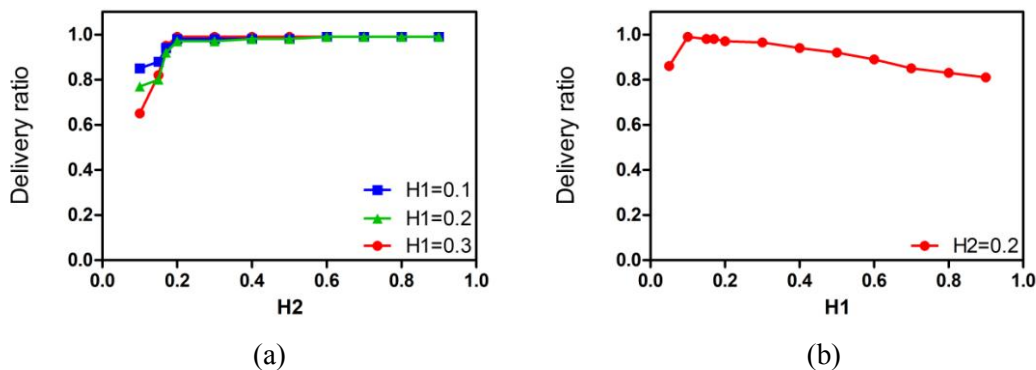


Fig. 6. Packet delivery ratio in terms of H1 and H2 threshold values.

As the next step, we measured the end-to-end packet delivery ratio in terms of H1 threshold values after fixing the H2 threshold to 0.2. As shown in **Fig. 6-(b)**, we can see that the proper value of the H1 threshold is 0.1. When we increase the H1 threshold value more after 0.1, the end-to-end packet delivery ratio has been decreased. The reason can be explained that as the H1 threshold value becomes larger, from 0.2 to 0.9, the end-to-end reliability factor (*Condition 2*) becomes easier to be satisfied. However, if the new RREQ packet with low *mrf* value is accepted, the *srcMRF* value of the reverse routing entry for the path will be replaced with the *mrf* value. Afterwards, the path becomes easier to be replaced by the upcoming RREQ packets only by considering the *Condition 1*, thus, it becomes easily replaced by the next path with high *e2e_ETX* value.

Fig. 7 shows the impact of H2 threshold on balancing load after fixing the H1 threshold to 0.1. In **Fig. 7**, the horizontal axis denotes node ID and the vertical axis is the total number of data packets that each node forwards by the end of the simulation. As we can see in **Fig. 7**, the load distribution is more even and better when H2 is 0.2 than when H2 is 0.4. This result shows that when we use a large H2 threshold value, the LBR protocol cannot find the better path in terms of the load balance factor because it becomes difficult to satisfy *Condition 1*.

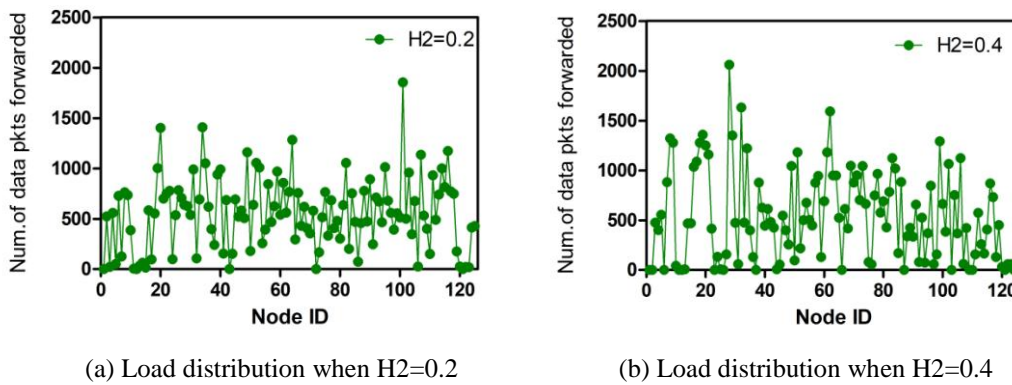


Fig. 7. The impact of large H2 threshold value to the load distribution.

4.2 End-to-end packet delivery ratio

Fig. 8 compare the packet delivery ratio of the routing protocols. The simulation result was calculated as the average of five flows. We measured the delivery ratio at different data loads, varying from 2 CBR to 14 CBR. The parameters H1 and H2 of the LBR protocol were chosen as 0.1 and 0.2, respectively.

The results show that our protocol and MRFR have almost the same delivery ratios at different loads and both two protocols obtain high delivery ratios (almost above 98%). Because both MRFR and LBR use ETX as a link metric for finding high quality paths, routes discovered by the two protocols are reliable. While our protocol and MRFR maintain the same performance at the different cases of load, the AODV protocol has a low delivery ratio when the data load is increased. For example, at a load of 14 CBR, MRFR and LBR have approximately delivery ratios of a 0.97, while delivery ratio using AODV is 0.83. This presents an performance improvement of 14%. AODV uses shortest paths for routing; however, it does not consider link loss ratios. Therefore, AODV can use routes with a high probability of route failure. In contrast to AODV, MRFR and LBR take into account the link loss ratios. This is why they find high quality routes and obtain a good performance.

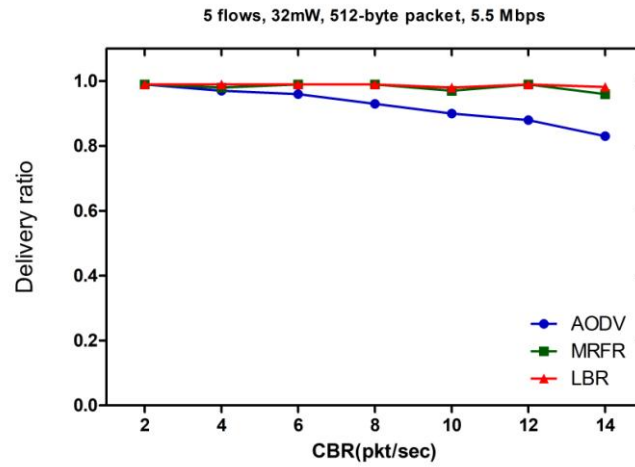
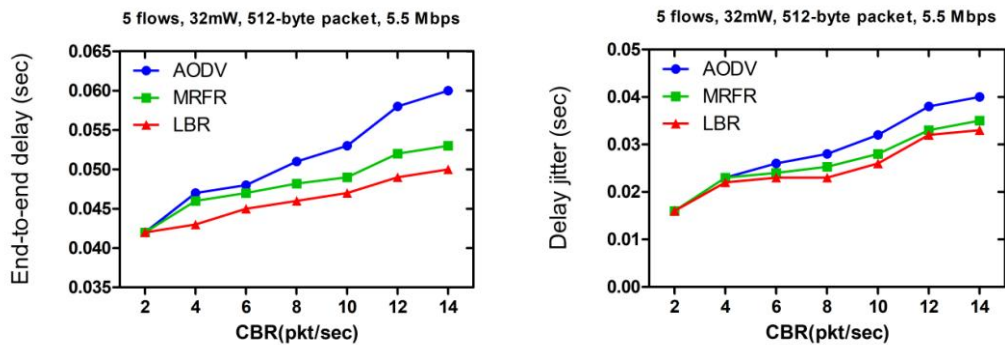


Fig. 8. The end-to-end packet delivery ratio in terms of the packet traffic load.

4.3 Average end-to-end packet delay and jitter

We compared the average end-to-end packet delay and delay jitter of the three protocols. Fig. 9 shows the simulation result. As the data traffic is increased, the average end-to-end packet delay of the three protocols is increased. Although AODV protocol uses the shortest path routing, the average end-to-end packet delay is shown to be the highest in most cases. This is because, in the case of AODV, the route fault happens more frequently, which incurs the large average end-to-end packet delay. Besides using the e2e_ETX, our protocol uses the load balancing factor when selecting paths. As a result, congestion avoidance is better than that of MRFR. Therefore, as shown in Fig. 9, our protocol has a little smaller average end-to-end delay and delay jitter than that of MRFR.



(a) Average end-to-end packet delay.

(b) Average packet delay jitter.

Fig. 9. Average end-to-end packet delay and delay jitter.

4.4 Load balancing efficiency

Our protocol uses an end-to-end reliable path while considering load balance to transmit data packets. To compare the load balancing efficiency of LBR and MRFR, we measured the number of data packets being forwarded during the simulation by each node. In our simulation,

five flows transmit data simultaneously. Source nodes send data at rate of 10 CBR. **Fig. 10** shows the distribution of the number of data packets forwarded at each node.

As shown in **Fig. 10**, the load distribution of our protocol is more even than that of MRFR. This result indicates that our protocol takes paths that avoid congested nodes near the network center while providing reliable data transmission.

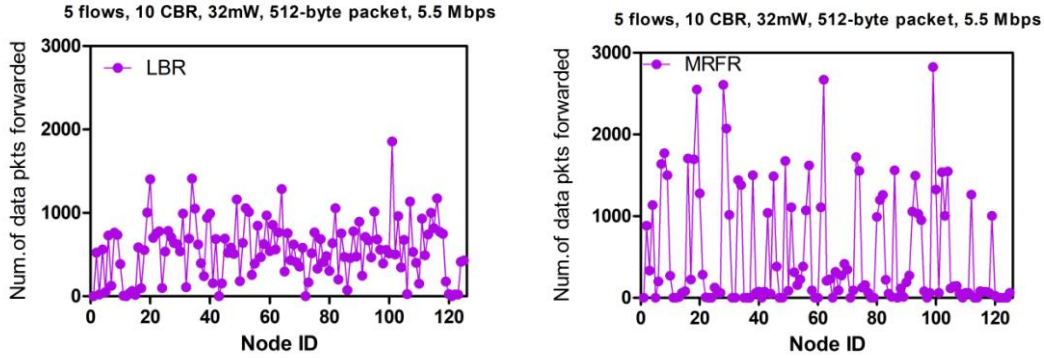


Fig. 10. Comparison of load distribution of LBR and MRFR.

Table 1 shows the comparison between our protocol and MRFR in term of the minimum, the maximum, the average value, and the variance of the number of forwarded data packets, respectively. The LBR and MRFR have the same minimum and average values. However, the maximum and the variance of MRFR are larger than those of our protocol, which shows that our protocol has more even load distribution compared to MRFR.

Table 1. Comparison of load distributions of MRFR and LBR.

| | MRFR | LBR |
|-------------------------------------------------------|----------|----------|
| Min | 0 | 0 |
| Max | 2826 | 1856 |
| Average | 538.24 | 538.744 |
| Variance ($s^2 = \frac{\sum (x_i - \bar{X})^2}{N}$) | 432971.5 | 125799.8 |

Fig. 11 compares the average *mrf* (minimum remaining load factor) of routes using LBR and MRFR. The *mrf* of a route is minimum of remaining load factors of nodes in the route. A route with high *mrf* value means that it has a low probability of congestion and nodes of high remaining energy. Note that MRFR only uses route-ETX values to choose the best route. In contrast, LBR uses both *mrf* of route and route-ETX in its route discovery process. To calculate the average *mrf* of routes for each protocol, we performed as follows. For each flow, we measured the *mrf* of routes used for that flow. Note that, due to route failure, each flow can use many different routes in the running time. The average *mrf* of routes for each protocol was then calculated as the average of *mrf* of routes used for all flows (see the network scenario in **Fig. 5**). As shown and compared to MRFR in **Fig. 11**, LBR creates routes with larger average *mrf* at different loads. For example, at a load of 8 CBR, the average *mrf* of routes using LBR is 0.925, while the *mrf* using MRFR is 0.631. This means the probability of congestion on routes using LBR is lower than that using MRFR.

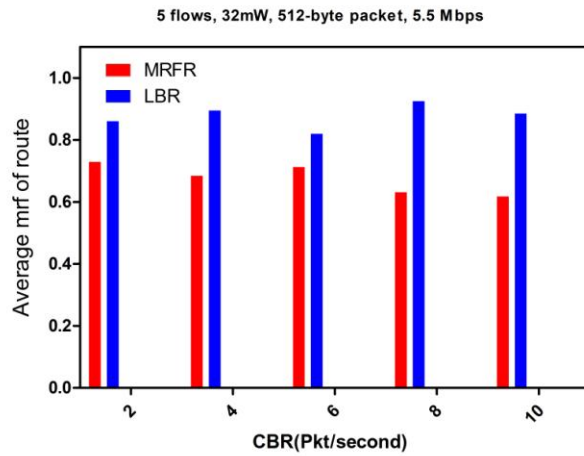


Fig. 11. Comparison of the minimum remaining load factor of route using LBR and MRFR.

4.5 Route failure and average inter-route failure time

Fig. 12-(a) compares the average inter-route failure time using MRFR and LBR. The results present for the five flows (see the scenario in Fig. 5). In which, the average inter-route failure time of each flow was calculated as the following. For each flow, during the data transmission, in the case that a route used for the flow is broken, the source of the flow will broadcast RREQ packets to discover a new route. The average inter-route failure time of each flow is then the average of durations of active route, in which a duration of active route is time during two successive route discoveries. Note that a route failure occurs in two following events. First, a link in that route is broken. Second, a node on the route is out of energy. When the average inter-route failure time of a protocol is large, it implies that the protocol uses reliable and stable routes. As shown in Fig. 12-(a), the average inter-route failure time using LBR is larger than that using MRFR at different flows. For instance, the inter-route failure time at flow 5 (22-100) for LBR and MRFR are 46.9 sec and 20.08 sec, respectively.

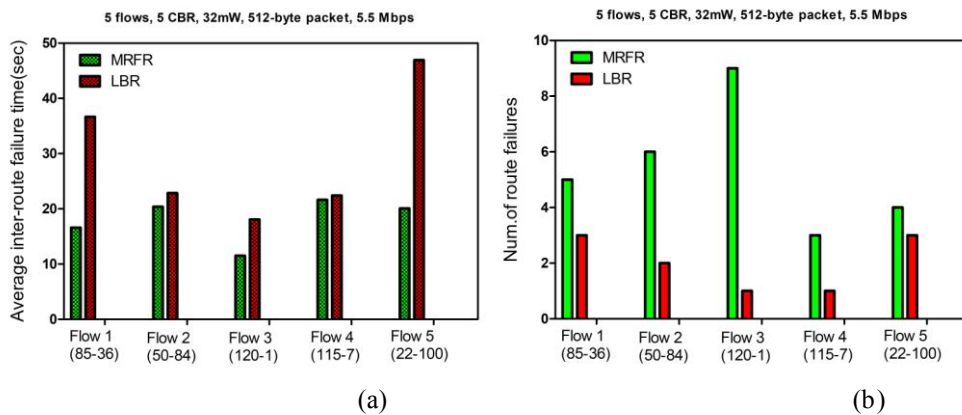


Fig. 12. Comparison of the inter-route failure times (a) and the number of route failures (b).

Fig. 12-(b) shows the comparison of the number of route failures due to out of node energy. In our simulation, every node was given an equal initial energy. During the data transmission, in the case that a node is out of energy, it stops working. Thus, a route of any flow containing that node will be broken. The results in **Fig. 12-(b)** present the number of route failures in each flow, in which a route failure is caused by out of energy of any node on that route. Because our protocol obtain a better load balancing than MRFR, LBR voids nodes of heavy load better than MRFR. As we can see in **Fig. 12-(b)**, the number of route failures at each flow using LBR is smaller than that using MRFR.

4.6 Impact of $\Delta\text{delayRREQ}$ and $\Delta\text{delayDEST}$ parameters

In the following simulations, we conducted the impact of $\Delta\text{delayRREQ}$ and $\Delta\text{delayDEST}$ timers to the performance of the LBR protocol. For that purpose, we measured the path establishment delay and controlling the number of RREQ control packets broadcasted while increasing $\Delta\text{delayRREQ}$ and $\Delta\text{delayDEST}$ timer values from 0. In this simulation, the value of $\Delta\text{delayDEST}$ is fixed to 25ms and the value of $\Delta\text{delayRREQ}$ is changed from 0 to 25ms. In the process of route discovery, we set $\Delta\text{delayRREQ}$ timer at each intermediate node for collecting multiple RREQ packets and finding better routes while limiting the number of RREQ packets rebroadcasted. During the $\Delta\text{delayRREQ}$ time, the LBR protocol just updates and stores the RREQ packet with smaller $e2e_ETX$ without rebroadcasting. After that, it rebroadcasts this RREQ packet when $\Delta\text{delayRREQ}$ is expired. If this parameter is large, we can reduce the number of RREQ control packets generated, however, the route establishment delay can be increased. Therefore, it is necessary to find a proper $\Delta\text{delayRREQ}$ value. In **Fig. 13**, the left vertical axis represents the RREQ rebroadcasting ratio that is calculated as the ratio between the number of RREQ packets rebroadcasted and the total number of RREQ packets received, and the right vertical axis depicts the route establishment delay. As show in in **Fig. 13-(a)**, when we set $\Delta\text{delayRREQ}$ to value 0, the RREQ rebroadcasting ratio is equal to 1. When we increase $\Delta\text{delayRREQ}$, the RREQ rebroadcasting ratio is decreased, however, the route establishment delay increased.

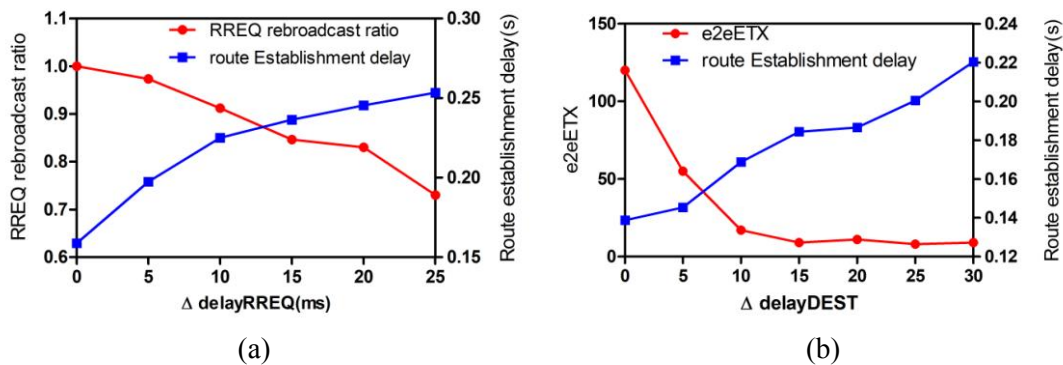


Fig. 13. The impact of $\Delta\text{delayRREQ}$ and $\Delta\text{delayDEST}$ timers.

Fig. 13-(b) shows the impact of $\Delta\text{delayDEST}$ parameter to the $e2e_ETX$ of the selected path and the route establishment delay. In this simulation, we set $\Delta\text{delayRREQ}$ to 5ms and alter $\Delta\text{delayDEST}$ from 0 to 30ms. In our protocol, when the destination node receives the first RREQ, it sets the $\Delta\text{delayDEST}$ timer to collect RREQ packets arriving during that time and

select the path with the smallest $e2e_ETX$ value. When the $\Delta delay_{DEST}$ timer expired, it replies with a RREP packet through the reverse of the chosen path. As shown in **Fig. 13-(b)**, when we vary the $\Delta delay_{DEST}$ timer from 0 to 30ms, the $e2e_ETX$ value of the selected path decreases greatly while the route establishment delay varies from 0.13 sec to 0.21 sec. However, if the $\Delta delay_{DEST}$ is higher than 15ms, the $e2e_ETX$ value remains almost the same. This result shows that at high $\Delta delay_{DEST}$ values, our protocol could not find better routes anymore, therefore, the quality of the paths remain the same after 15ms.

5. Conclusions

We have proposed an effective reliable routing protocol while considering balancing load. For load balanced reliable communication, our protocol selects a path that has the small $e2e_ETX$ value and the minimum remaining load of the nodes in the path is large. We have evaluated the performance of our protocol using Qualnet and compared with AODV and MRFR protocols. The simulation results shows that our protocol has better performance than the comparing protocols in terms of the packet delivery ratio, the average end-to-end packet delay and delay jitter, and the load balancing efficiency.

References

- [1] Seattle wireless. <http://www.seattlewireless.net>.
- [2] R. Karrer, A. Sabharwal and E. Knightly, "Enabling Large-scale Wireless Broadband: The Case for TAPs," *SIGCOMM Comput. Commun. Rev.*, vol. 34, no. 1, pp. 27-32, January, 2004. [Article \(CrossRef Link\)](#).
- [3] C. E. Perkins and P. Bhagwat, "Highly dynamic destination-sequenced distance vector routing (dsv) for mobile computers," in *Proc. of Int. Conf. on Communications Architectures, Protocols and Applications*, pp. 234-244, September, 1994. [Article \(CrossRef Link\)](#).
- [4] C. E. Perkins and E. M. Royer, "Ad-hoc on-demand distance vector routing," in *Proc. of 2nd Int. Workshop on Mobile Computing Systems and Applications*, pp. 90-100, February 25-26, 1999. [Article \(CrossRef Link\)](#).
- [5] D. B. Johnson and D. A. Maltz, "Dynamic source routing in ad-hoc wireless networks," in *Proc. Of Conf. on Mobile Computing*, pp. 153-181, 1996. [Article \(CrossRef Link\)](#).
- [6] D. Couto, D. Aguayo, J. Bicket and R. Morris, "A high-throughput path metric for multi-hop wireless routing," *Wireless Networks*, vol. 11, no. 4, pp. 419-434, July, 2005. [Article \(CrossRef Link\)](#).
- [7] R. Draves, J. Padhye and B. Zill, "Comparison of routing metrics for static multi-hop wireless networks," in *Proc. of Int. Conf. on Applications, Technologies, Architectures, and Protocols for Computer Communications*, pp. 133-144, 2004. [Article \(CrossRef Link\)](#).
- [8] A. Adya, P. Bahl, J. Padhye, A. Wolman and L. Zhou, "A multi-radio unification protocol for IEEE 802.11 wireless networks," in *Proc of 1st Int. Conf. on Broadband Networks*, pp. 344-354, October 25-29, 2004. [Article \(CrossRef Link\)](#).
- [9] S. Keshav, "A control-theoretic approach to flow control," in *Proc. of Int. Conf. on Communications architecture and protocols*, pp. 3-15, 1991. [Article \(CrossRef Link\)](#).
- [10] S. M. Das, H. Pucha, K. Papagiannaki and Y. C. Hu, "Studying wireless routing link metric dynamics," in *Proc. of 7th ACM Conf. on Internet Measurement*, pp. 327-332, 2007. [Article \(CrossRef Link\)](#).
- [11] A. Sankar and Z. Liu, "Maximum lifetime routing in wireless ad-hoc networks," in *Proc. of 23rd IEEE Conf. on Computer and Communications Societies*, pp. 1089-1097, March 7-11, 2004. [Article \(CrossRef Link\)](#).
- [12] L. Popa, A. Rostamizadeh, R. Karp, C. Papadimitriou and I. Stoica, "Balancing traffic load in wireless networks with curveball routing," in *Proc. of 8th ACM Int. symposium on Mobile ad hoc*

- networking and computing*, pp. 170-179, 2007. [Article \(CrossRef Link\)](#).
- [13] J. Luo and Y. He, "GeoQuorum: Load Balancing and Energy Efficient Data Access in Wireless Sensor Networks," in *Proc. of IEEE Conf. on Computer and Communications Societies*, pp. 616-620, 2011. [Article \(CrossRef Link\)](#).
- [14] X. Li and L. Cuthbert, "Stable Node-Disjoint Multipath Routing with LowOverhead in Mobile Ad hoc Network," in *Proc. of IEEE Int. Symposium on Modeling, Analysis & Simulation of Computer and Telecommunication Systems*, pp. 184-191, October 04-08, 2009. [Article \(CrossRef Link\)](#).
- [15] M. Al-Rabayah and R. Malaney, "A New Hybrid Location-Based Ad Hoc Routing Protocol," in *Proc. of IEEE Conf. on Global Telecommunications*, pp. 1-6, December 6-10, 2010. [Article \(CrossRef Link\)](#).
- [16] B. Mainaud, M. Zekri and H. Affi, "Improving Routing Reliability on Wireless Sensors Network with Emergency Paths," in *Proc. of 28th IEEE Conf. on Distributed Computing Systems Workshops*, pp. 545-550, June 17-20, 2008. [Article \(CrossRef Link\)](#).
- [17] P. P. Pham and S. Perreau, "Performance analysis of reactive shortest path and multipath routing mechanism with load balance," in *Proc. of 22nd IEEE Conf. on Computer Communications*, pp. 251-259, March 30-April 3, 2003. [Article \(CrossRef Link\)](#).
- [18] Y.-C. Hu and D. B. Johnson, "Design and demonstration of live audio and video over multi-hop wireless networks," in *Proc. of Int. Conf. on Military Communications*, pp. 1211-1216, October 7-10, 2002. [Article \(CrossRef Link\)](#).
- [19] The MultiHopLQI protocol, <http://www.tinyos.net/tinyos-2.x/tos/lib/net/lqi/>.
- [20] G. Tolle and D. Culler, "Design of an application-cooperative management system for wireless sensor networks," in *Proc. of 2nd Workshop on Wireless Sensor Networks*, pp. 121-132, January 31-February 2, 2005. [Article \(CrossRef Link\)](#).
- [21] A. Gupta, C. Diallo, M. Marot and M. Becker, "Understanding topology challenges in the implementation of wireless sensor network for cold chain," in *Proc. of IEEE Symposium on Radio and Wireless*, pp. 376-379, January 10-14, 2010. [Article \(CrossRef Link\)](#).
- [22] O. Gnawali, R. Fonseca, K. Jamieson, D. Moss and P. Levis, "Collection tree protocol," in *Proc. of 7th ACM Conf. on Embedded Networked Sensor Systems*, pp. 1-14, 2009. [Article \(CrossRef Link\)](#).
- [23] A. Woo, T. Tong and D. Culler, "Taming the underlying challenges of reliable multihop routing in sensor networks," in *Proc. of 1st ACM Conf. on Embedded Networked Sensor Systems*, pp. 14-27, 2003. [Article \(CrossRef Link\)](#).
- [24] P. N. Hoai, M. K. Kim, "MRFR - Multipath-based routing protocol with fast-recovery of failures on MANETs," *KSII Transactions on Internet and Information Systems*, vol. 6, no. 12, pp. 271-287, December, 2012. [Article \(CrossRef Link\)](#).
- [25] Y. Ganjali and A. Keshavarzian, "Load balancing in ad hoc networks: single-path routing vs. multi-path routing," in *Proc. of 21st IEEE Conf. on Computer and Communications Societies*, pp. 1120-1125, March 7-11, 2004. [Article \(CrossRef Link\)](#).
- [26] Y. Yoo and S. Ahn, "A simple load-balancing approach in cheat-proof ad hoc networks," in *Proc. of IEEE Conf. on Global Telecommunications*, pp. 3573-3577, November 29-December 3, 2004. [Article \(CrossRef Link\)](#).
- [27] B. C. Kim, J. Y. Lee, H. S. Lee, and J. S. Ma, "An ad-hoc routing protocol with minimum contention time and load balancing," in *Proc. of IEEE Conf. on Global Telecommunications*, pp. 81-85, December 1-5, 2003. [Article \(CrossRef Link\)](#).
- [28] M. S. Obaidat, S. K. Dhurandher and K. Diwakar, "CASPER: Congestion Aware Selection of Path with Efficient Routing in Multimedia Networks," *Information Processing System*, vol. 7, no. 2, pp. 241-260, 2011. [Article \(CrossRef Link\)](#).
- [29] M. M. Azim, "MAP: A Balanced Energy Consumption Routing Protocol for Wireless Sensor Networks," *Information Processing Systems*, vol. 6, no. 3, pp. 295-306, 2010. [Article \(CrossRef Link\)](#).
- [30] Qualnet simulator, <http://web.scalable-networks.com/content/qualnet>.



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