Topology and Link Quality-aware Geographical Opportunistic Routing in Wireless Ad-hoc Networks

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***Abstract*—Opportunistic routing (OR) takes advantage of the broadcast nature and spatial diversity of wireless transmission to improve the performance of wireless ad-hoc networks. Instead of using a predetermined path to send packets, OR postpones the choice of the next-hop to the receiver side, and lets the multiple receivers of a packet to coordinate and decide which one will be the forwarder. Existing OR protocols choose the next-hop forwarder based on a predefined candidate list, which is calculated using single network metrics. In this paper, we propose TLG - *Topology and Link quality-aware Geographical* opportunistic routing protocol. TLG uses multiple network metrics such as network topology, link quality, and geographic location to implement the coordination mechanism of OR. We compare TLG with well-known existing solutions and simulation results show that TLG outperforms others in terms of both QoS and QoE metrics.**

***Index Terms*—Geographical opportunistic routing, Network topology, Link quality, Wireless ad-hoc networks.**

I. Introduction

Wireless ad-hoc networks promise a wide scope of applications in both civilian and military areas, which require scalar and multimedia information in applications such as surveillance, environmental monitoring, emergency recovery, etc. For example, in case of a disaster, such as earthquake or hurricane, the recovery process demands an efficient and rapid deployment of a communication system due to the fact that the standard telecommunication infrastructure might be damaged. In this scenario, wireless ad-hoc networks enable to build a temporary communication network.

As examples of ad-hoc networks, Wireless Sensor Networks (WSNs) [1] and Wireless Multimedia Sensor Networks (WMSNs) [2], received great attention from academic and industry communities in the past decade. Their broad applicability and fast deployment at low cost without relying on existing network infrastructures make them suitable options for a variety of applications. Moreover, mobile robots or Unmanned Aerial Vehicles (UAVs) equipped with scalar or multimedia sensors could be used to set up a multi-hop UAV ad-hoc network (UAVNet [3]) to explore the hazardous area that rescuers cannot reach easily. For example, a swarm of UAVs can be sent to monitor a certain area to transmit scalar/multimedia content to the control center, as shown in Figure 1. In such applications, multimedia data provides civil authorities (e.g., rescuers or polices) more precise information to help them to make suitable decisions. Therefore, in these applications, besides Quality of Service (QoS) metrics that measure the system performance from the network's view, Quality of Experience (QoE) metrics have to be collected to reflect the user's perception.

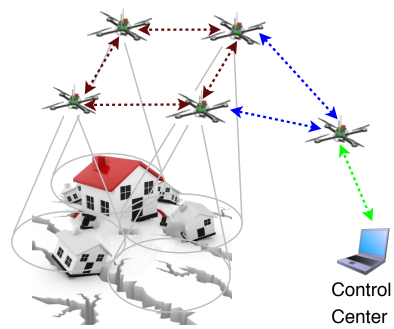

Fig. 1. Ad-hoc network deployment under emergency situation

Routing in multi-hop wireless network is a challenging issue. The main difficulty lies in that wireless links are unstable and unreliable. Traditional wireless routing protocols treat the wireless link like a wired one, and focus on finding a fixed path between a source-destination pair. However, the selected path may be broken if the environment or topology changes. In this context, Opportunistic Routing (OR) [4] was proposed to cope with the unpredictability of wireless links. In OR, instead of sending unicast packets to a specific node, the sender just broadcasts the packet. The neighbors that successfully receive this broadcast transmission have to coordinate with each other to select one node to forward the packet.

Most of the efforts in OR focused on the candidate selection and relay priority assignment. However, existing OR protocols did not fully consider the unreliability of wireless transmission, and most of them assume the connection between nodes will remain constant after the connection has been set up. In reality, wireless links are extremely unreliable, as they often experience significant quality fluctuation or distortion.

Moreover, some OR protocols use geographic data to select a relay node. For example, Dynamic Forwarding Delay (DFD)-based approaches include a dynamic delay for candidates before they forward the packet [5]. This delay function is inversely proportional to the progress of each node such that the node closer to the destination has higher priority. However,

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due to the unreliability of wireless transmission, the most distant node within the radio range of a sender might suffer from a bad connection, which causes high packet loss.

Hsu et al. summarize OR protocols and classify them into different categories based on the metrics they use to prioritize and select candidates [6]. We can find out that nearly all existing OR protocols use single metrics to select the relay node, either link quality, or geographic location.

To address the above issues, we propose the Topology and Link quality-aware Geographical opportunistic routing protocol (TLG). TLG takes into account different network metrics to make a joint routing decision. TLG uses the idea of DFD, and it considers link quality, progress, and remaining energy when calculating DFD. Simulations were carried out to show the benefits of considering multiple metrics during the routing process. This paper includes both QoS and QoE evaluation for the proposed protocol. The simulation results show that TLG could improve QoS metrics by nearly 40% and QoE metrics by nearly 30% compared to existing protocols that consider single metrics.

The remainder of this paper is structured as follows. Section II explains the current development of the concepts related with this work, which includes geographical routing, opportunistic transmission, link quality awareness, and topology control. Section III describes the proposed topology and link quality aware geographical opportunistic routing protocol. Simulations and analysis of results are presented in Section IV. The paper concludes with Section V, which summarizes the contributions and results of our work.

II. Related Work

The research of OR mainly focuses on two issues: candidate set selection and priority assignment of candidates. The candidates have to coordinate to avoid duplicated transmission. This is usually achieved by ordering the candidates according to some criteria, such as Expected Transmission Count (ETX) [4]. In location-aware protocols, progress is the most used metric. This leads to the fact that the node that is closer to the destination will have a higher priority. However, the concept of prioritizing a fixed list of candidates reduces the freedom of opportunism. Additionally, the predefined candidate priority list may not hold anymore if the wireless environment or network topology changes.

The fluctuation of wireless channels makes it difficult to route packets in a wireless environment, and the quality of the wireless channel might be affected by many unknown factors, such as interference, fading, etc. Therefore, it is vital to consider the link quality when designing a routing protocol and it has been shown that the link quality fluctuates over time and space [7]. Zhou et al. show that wireless connection between two nodes is typically asymmetric [8]. [9] modifies the ad hoc on-demand distance vector (AODV) routing protocol to avoid routing through bad quality links. [10] uses the Received Signal Strength Indicator as routing metric. It uses historical signal strength information as a factor in BLR [5], which avoids routing into sparse areas, and consequently improves global routing efficiency. ExOR [4] uses Expected Transmission Count (ETX), which is derived from the link delivery rate to select and rank the candidates.

Nowadays, inexpensive and low-power GPS receivers enable wireless nodes to be aware of their location with a precision of a few meters. This leads to geographic routing, a concept in which nodes make use of their location information to help making routing decision. GPSR [11] is one of the earlier works in geographic routing that uses planar graphs to route packets. GeRaf [12] proposed a novel forwarding technique based on geographical location of the nodes involved and random selection of the relaying node via competition among receivers. Beacon-less Routing (BLR) [5] is a geographic routing protocol, which uses location data to minimize the routing overhead by eliminating the periodic beacon message. Data transmission is broadcast and the protocol takes care that for each hop, just one of the receiving nodes forwards the packet. Similarly, the proposals in [13] and [14] classify the candidates according to their distances to the destination.

When nodes become mobile, the network topology will change over time, and this will increase the difficulty to transmit a packet. In this situation, a topology control process is usually needed for each node to keep their connectivity with neighbors [15]. For wireless sensors, the most common way is to increase the transmission power to enlarge the radio range when the connectivity is getting worse due to mobility. Most of the works about topology control are limited to tuning the transmission radius of nodes [16], and few of them analyze how the protocol should manipulate the mobility information to improve network performance.

From the analysis of the related work, we find that it is beneficial to consider multiple network metrics to make a joint routing decision in a wireless environment. In TLG, we design a new opportunistic routing protocol, which selects and ranks the candidates according to network topology, link quality, geographical location, and energy.

III. The TLG Protocol

This section introduces the Topology and Link quality-aware Geographical opportunistic routing algorithm, called TLG. This protocol takes into account different network metrics to make a joint routing decision. TLG uses the idea of DFD by considering link quality, progress, and remaining energy to compute the dynamic delay function.

A. Dynamic Forwarding Delay (DFD)

When the source node has data to transmit, it includes the geographical information of itself and also of the final destination into the packet and broadcasts it. The neighbor nodes that receive the packet, first check whether they are closer to the final destination than the last-hop. If not, they drop the packet. Otherwise, they are considered as possible relay nodes, and apply a Dynamic Forwarding Delay (DFD) function. DFD was first introduced in BLR to give a delay timer before a node rebroadcasts the received packet. The node that generates the smallest delay will rebroadcast the packet first. By overhearing this transmission, other candidates stop the scheduled transmission and drop the packet. In the meantime, the re-broadcasted packet is used as a passive acknowledgement, and the sender knows which node is selected as the forwarder. Therefore, the sender transmits subsequent packets using unicast to reduce the drawbacks introduced by broadcasting [5]. In TLG, the duration of this unicast should depend on the validity time of the link between the sender and the selected relay node.

We propose a **DFD** function based on multiple metric, i.e., *progress*, *remaining energy*, and *link quality*, to increase reliability and energy-efficiency. The proposed DFD is calculated according to (1):

$$\begin{aligned}\text{DFD} = (&\alpha \times \text{Remaining Energy} + \beta \times \text{Link Quality} \\ &+ \gamma \times \text{Progress}) \times DFD_{Max}\end{aligned} \tag{1}$$

α, β, and γ are the weights of each metric and $\alpha + \beta + \gamma = 1$. Depending on the application requirements, TLG assigns different weights for different metrics. DFD_{Max} is the predefined maximum delay allowed at each node. Link Quality, Progress, and Remaining Energy are computed based on (2), (3), and (4), respectively.

1) Link Quality: Existing OR protocols do not consider the instantaneous link quality for the routing decision. These works assume that the transmission will be successful as long as two nodes are within the transmission range of each other. They also ignore the time-varying characteristics of wireless channels. They assume that the channel quality at the moment of selecting and ranking the candidates is identical with the moment when the packet is transmitted. Therefore, TLG considers the instantaneous link quality at the moment of packet transmission to calculate the DFD function. The calculation of the "Link Quality" part of (1) is shown in (2).

Link quality is usually measured by means of physical layer information. For example in WSNs, the CC2420 radio chip, a widely used off-the-shelf low power radio chip, provides the Received Signal Indicator (RSSI) and Link Quality Indicator (LQI) for each received packet. These parameters directly reflect the immediate link quality. In our study, we use LQI as the indicator of link quality between two nodes.

$$\begin{array}{c}\text{Link}\\\text{Quality}\end{array} = \begin{cases} \frac{LQI_{Max} - LQI_t}{LQI_{Max}} & \text{if } LQI_{Bad} < LQI_t < LQI_{Good} \\ 1 & \text{if } LQI_t < LQI_{Bad} \\ 0 & \text{if } LQI_t > LQI_{Good} \end{cases} \tag{2}$$

LQI_t is the LQI value of the link between two nodes and LQI_{Max} is the predefined maximum value of LQI_t. The candidate node must ensure that a minimal link quality is achieved to guarantee successful packet transmission. Therefore, based on the experiment parameters used in the simulation, we classify LQI_t into three ranges, namely bad links (if $LQI_t < LQI_{Bad}$ = 10), good links (if $LQI_t > LQI_{Good}$ = 20), and average links (if $LQI_{Bad} < LQI_t < LQI_{Good}$). When a node receives a packet, it will derive the LQI_t for the incoming link (the link over which the packet is received). Depending on LQI_t, (2) returns a value for "Link Quality" as the input for (1). For example, a node with a good link ($LQI_t > LQI_{Good}$) will return 0 to "Link Quality", which means a node with a good link will produce no input to the delay function. A node with a bad link ($LQI_t < LQI_{Bad}$) will produce a significant impact on DFD.

2) Progress: Eq. (3) computes the progress of each node. The node with a higher progress generates a shorter "Progress" value, which means a small contribution to its DFD.

$$\text{Progress} = \begin{cases} \frac{2R - P_i}{2R} & \text{if } Dist_{Relay-Dest} > R \\ 0 & \text{if } Dist_{Relay-Dest} < R \end{cases} \tag{3}$$

P_i is the progress of a node i, R is the radio range, and $Dist_{Relay-Dest}$ is the distance between the relay node and the destination node.

We define the progress as the sum of two segments, as shown in Figure 2. S is the source, D is the destination. A and B are two possible relay nodes for S within its transmission range. A' and B' are the intersection points of the circles that are centralized at the candidate nodes A & B and line S-D. In Figure 2, the progress of candidate A is composed of two parts. One part is the projection of line S-A on line S-D, p_1. Another part is the projection of line A-A' on line S-D, p_2. Therefore, the progress of node A is P_A = p_1 + p_2 and the progress of node B is P_B = p_3 + p_4. With this definition, we solve the possible collision that is caused by two nodes of the same projection progress. For example in Figure 2, candidates A and B have the same projection progress on line S-D (p_1 = p_3). With the progress definition in BLR, A and B will generate the same forwarding delay, and this will introduce collisions since they will rebroadcast packet at the same time. However, with the new definition of progress, even if p_1 = p_3, B is closer to line S-D, and it has a larger progress than A ($P_B = p_3 + p_4 > P_A = p_1$ + p_2). Therefore, in this case, S can reach D via B with only one hop, and this can not be achieved if S chooses A as next hop.

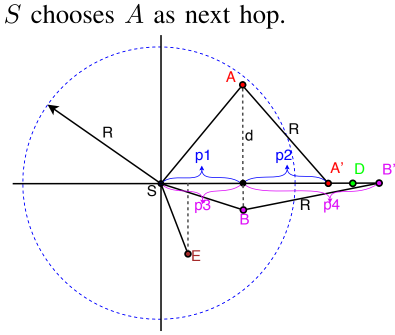

Fig. 2. Candidate progress

3) Energy: Energy is another important issue in wireless ad-hoc networks due to the fact that wireless nodes are usually battery-powered and energy resources are scarce. UAVs have very limited energy resources and they spend most energy for moving and hovering. Thus, energy should also be considered for routing decision to provide energy-efficiency. (4) defines the energy part of the DFD function. A node with high remaining energy (E_r) generates small "Remaining Energy" value, which means a small contribution to the DFD.

$$\text{Remaining Energy} = \begin{cases} \frac{E_0 - E_r}{E_0} & \text{if } E_r > E_{Min} \\ 1 & \text{if } E_R < E_{Min} \end{cases} \quad (4)$$

E_0 and E_r are initial and remaining energy of each node, respectively. In UAVNet [3], a UAV can only be selected as forwarder if: (i) it has enough energy (E_{Min_1}) to transmit packets during the validity time of a link with a sender; and (ii) after the link validity time, the node still has enough energy (E_{Min_2}) to return back to the control center. This means, in (4), E_{min} is composed of two parts: $E_{min} = E_{Min_1} + E_{Min_2}$, and usually E_{Min_2} dominates because movements cost more energy than packet transmission for UAVs.

B. Link Validity Estimation

Even if UAVNet is an example of wireless ad-hoc networks, the mobility of UAVs is not random. Instead, the movements of UAVs should be coordinated and follow certain steering rules. Considering these non-random mobility characteristics, UAVNet performs special movement behaviors. In this context, our algorithm includes the estimation of the validity time of a link between two connected UAVs, and this information will be used in the routing decision. After a node has been selected as the relay node for a sender, the sender will finish the transmission of subsequent packets using unicast to that node. Therefore, the duration of this unicast transmission needs to be determined beforehand. A Link Validity Estimation (LIVE) protocol will run at every node to estimate the validity time (T_{LV}) of each link with its 1-hop neighbors. This value will be used to decide how long the unicast transmission will last. When this link validity timer expires, the sender will start another broadcast process to find a better forwarding node.

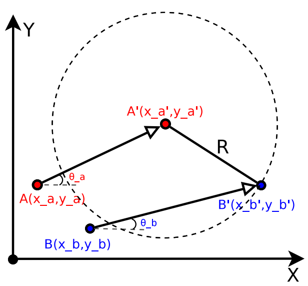

Fig. 3. Link validity estimation calculation

Let us assume that every node knows the moving direction and speed of itself. Using the information collected from the neighbors (position and mobility information), every node can calculate the distances to neighbors and this will enable it to predict the validity time of each link with neighbors. As shown in Figure 3 , suppose that two nodes A and B are flying with speed V_a, V_b and direction θ_a , θ_b. Given the initial location of A (X_A,Y_A) and $B(X_B$,Y_B), A and B can easily calculate the link validity time of the link between them:

$$\begin{aligned} &[(X_B + V_b \times \cos\theta_b \times T_{LV}) - (X_A + V_a \times \cos\theta_a \times T_{LV})]^2 \\ &+[(Y_A + V_a \times \sin\theta_a \times T_{LV}) - (Y_B + V_b \times \sin\theta_b \times T_{LV})]^2 \\ &= RadioRadius^2 \end{aligned} \quad (5)$$

IV. Performance Evaluation

A. Simulation Description and Evaluation Metrics

In this section, TLG is evaluated through OMNeT++ simulations by using the framework proposed in [17][18]. We perform the experiments with scalar data and multimedia data separately to evaluate our protocol based on both QoS and QoE metrics. Since QoS metrics alone can not reflect the user's perception, we collect also the QoE metrics to capture the subjective aspects associated with the humans' experience.

In both simulations, 31 nodes are randomly placed over a flat area, where the simulation runs for 300 s. The source node generates constant bit rate UDP packets and video sequences in two experiments. We use the CSMA implementation from Castalia as the MAC protocol. The physical parameters of the antenna, such as transmission power, antenna gain, and receiver sensitivity are set to obtain a nominal transmission range of around 11 m. The results are averaged over 20 simulation runs with different random-generated seeds to provide a confidence interval of 95% (vertical bars in the figures). It is important to highlight that we focus on the new formula to calculate DFD in this work, and thus we assume the link validity time between nodes are fixed and assign a constant value for T_{LV}. Table I shows the simulation parameters.

TABLE I
Simulation parameters

Parameter	Value	Parameter	Value
Field Size	40 × 40 m	Radio model	CC2420
BS location	(38,38)	Video sequence	Hall
Source location	(5, 5)	Frame rate	26 fps
Node deployment	Uniform	Video encoding	H.264
UDP source rate	2 Pkt/s	Video format	QCIF (176×144)
Transmission power	-10 dBm	T_{LV}	4 s
Path loss model	Lognormal	DFD_{max}	0.1 s

To prove that TLG achieves the best performance only when multiple metrics are considered, we give a detailed study on different coefficients (α, β, γ) in the DFD formula (1). A large coefficient in (1) means the corresponding metric is of more importance when calculating the forwarding delay function. We define 18 combinations with different values of α, β, γ to show the importance to consider multiple metrics. Table II shows the values of each combination. Moreover, to show the superiority of TLG over the routing protocols that consider single metrics, we compare the performance of TLG with the well-known GPSR and BLR protocols.

We use the Packet Delivery Ratio (PDR) and goodput as QoS metrics when the source generates scalar data, and two well-known objective QoE metrics, i.e. Structural Similarity (SSIM) and Video Quality Metric (VQM) when multimedia data is produced from the source. SSIM measures the structural distortion of the video. SSIM has values ranging from 0 to 1, and a higher value means better video quality. VQM measures the "perception damage" of video experienced, and a value closer to 0 means a video with a better quality.

B. Result: Scalar data

First, we analyze the performance of TLG when the source node sends UDP packets with a constant packet rate of 2

TABLE II
COMBINATIONS OF COEFFICIENTS IN FORMULA (1)

Combination #	α (Energy)	β (Link Quality)	γ (Progress)
1	0	0	1
2	0.1	0.05	0.85
3	0.1	0.1	0.8
4	0.1	0.15	0.75
...	...	...	...
18	0.1	0.85	0.05

packets/s. PDR and goodput are measured at the destination. Results are shown in Figure 4. We can observe that combination $\#1$ has the worst performance of PDR and goodput. This is because combination $\#1$ gives all the weights to progress and therefore ignores link quality and energy ($\alpha = \beta = 0$, $\gamma = 1$). This means a node considers only progress when calculating the DFD function. Therefore, a node always chooses the neighbor that is closest to the destination as next hop. However, the most distant neighbor has the highest probability of suffering from a bad channel quality and thus leads to higher packet loss rate. Therefore, packet delivery ratio and goodput of combination $\#1$ are the worst.

Combinations $\#2$ to $\#18$ have identical coefficients for energy ($\alpha = 0.1$) since energy is not a vital metric in our experiments, and they differ in the weights for link quality (β) and progress (γ). We can find out that the combination $\#18$, which gives more importance for link quality, has also a bad performance. This is because it gives severely unbalanced weights to progress and link quality ($\beta = 0.85$, $\gamma = 0.05$). This coefficient combination means that a node will always choose the neighbor with the best channel quality as next hop, which is the closest neighbor. However, this behavior might encounter the problem that all nodes make short progress at each hop by choosing the closest neighbor, even if there might be more distant neighbors that successfully receive the packets. This means that a packet will need more hops to reach the destination and a longer delay will occur in a sparse environment. Another reason for the bad performance of combination $\#18$ is that, during the unicast transmission phase to the selected forwarder, there will be higher interference introduced by the closer nodes. On the other hand, combinations $\#2$ to $\#18$ perform better than combination $\#1$. This is because they have different weights for link quality and progress. Then, by tuning the coefficients for link quality and progress, TLG can achieve the best trade-off between large progress and good link quality.

We can also observe that the combinations that assign fairly balanced weights to progress and link quality perform better, i.e., combinations $\#7$ to $\#14$. This is because under these situations, TLG will make a joint fair consideration of link quality, distance progress and remaining energy when calculating DFD with no great preference to any factor. This could avoid the occurrence of the bad situations, such as choosing the most distant neighbor, which has a poor link quality, or choosing the nearest neighbor with small progress. The best performance is achieved at combination $\#13$, which can improve the performance of PDR and goodput by nearly 50% against the worst combination $\#1$.

However, it is interesting to notice that, the best performance is not achieved by the combination with the most

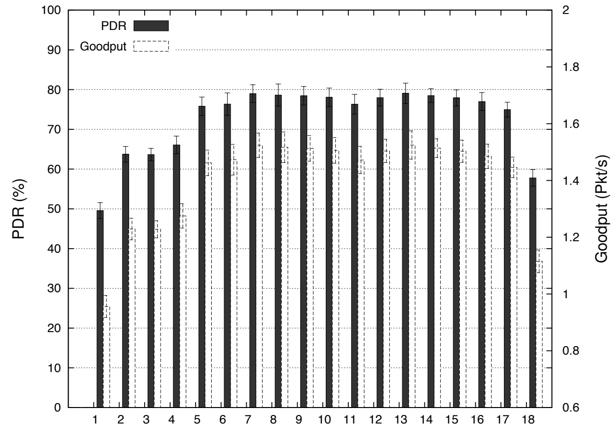

Fig. 4. PDR and Goodput of different coefficient combinations

balanced coefficients for progress and link quality, which is combination $\#10$ ($\beta = \gamma = 0.45$). Instead, combinations with slight imbalance between progress and link quality, such as $\#13, \#7, \#8, \#14$, produce the best performance. A deep investigation into the coefficients of those combinations can reveal the fact that if a node wants to achieve the best performance, it has to give certain preference to one of the competing factors. If all the competing factors have the same weight, such as combination $\#10$ ($\beta = \gamma = 0.45$), then the best performance can not be reached. However, the coefficient imbalance must not be too large, otherwise the performance will degrade significantly, as for $\#1, \#2, \#3, \#4, \#18$. Therefore, depending on the application requirements, users could assign different priorities to progress, link quality, or remaining energy, to give a controlled preference to the interested factor.

To show that TLG outperforms existing approaches that consider single metrics, we compare TLG with the well-known GPSR and BLR protocols. The implementation of GPSR and BLR uses a default beacon interval of 4 s, which equals to T_{LV}. The greedy mode of BLR is implemented such that a node can always find relay candidates. Figure 5 shows the PDR and goodput of three protocols when the source generates UDP packets. We choose only the worst ($\#1$) and the best ($\#13$) coefficient combinations of TLG to show its advantage. TLG performs much better than GPSR, which can deliver only 20% of the packets. This is because GPSR greedily chooses the neighbor that is closest to the destination as next hop. However, the farthest neighbor has the highest probability to suffer from a bad connection with the packet sender, which leads to packet loss. The non fully-covered network might be another reason for GPSR's bad performance. BLR performs better than GPSR, because it does neither have to discover and maintain routes nor to maintain a neighbor table that may be outdated and inconsistent. We can also see that BLR is better than the worst case ($\#1$) of TLG, this may be because BLR defines a "forwarding area" such that only the nodes within the region are the candidates. In TLG, any nodes that are closer to the destination could be the candidates, which increases the coordination overhead and thus reduces the performance. However, BLR is still worse than the best case of TLG ($\#13$), since it uses only progress to compute DFD.

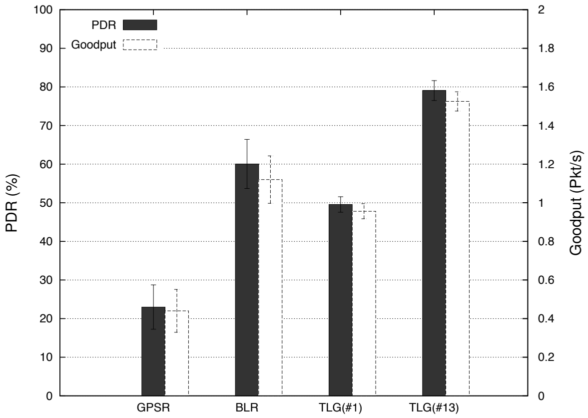

Fig. 5. PDR and goodput of three protocols

C. Result: Multimedia data

Applications involving multimedia transmission should be evaluated from the user's perspective via QoE metrics. Therefore, we also compare TLG to GPSR and BLR using video data. The Hall video sequence was chosen as the video source and it uses the QCIF format with H.264 encoding technique. Details of the video transmission can be found in Table I.

Similar observations to scalar data can be found for different coefficient combinations of TLG, and to save space, we skip the presentation of results. Figure 6 shows the SSIM and VQM of GPSR, BLR, and TLG (only the worst and the best cases of combination #1 and #13). We find that TLG outperforms GPSR and BLR, by nearly 30% in the best case. This is because TLG uses multiple metrics to calculate DFD. This increases the reliability and improves system performance. Therefore, TLG enables the transmission of video content with QoE level assurance from a user's perspective.

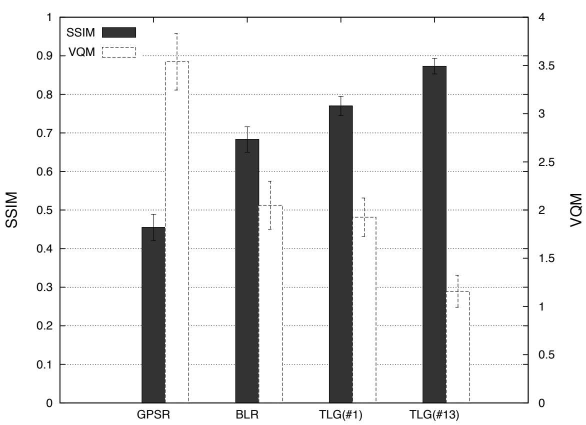

Fig. 6. SSIM and VQM of three protocols

V. Conclusion

This paper proposes a new opportunistic routing protocol called TLG: Topology and Link quality-aware Geographical opportunistic routing protocol for wireless ad hoc networks. TLG uses the concept of DFD, and each node applies a forwarding delay timer before it rebroadcasts received packets. The calculation of this delay timer at each node is based on multiple network metrics: remaining energy, link quality, and progress. We evaluated TLG using both scalar and video data. QoS and QoE measurements are collected respectively to analyze protocol performance. The simulation results show that TLG achieves the best performance when multiple metrics are used to calculate DFD, and it could improve QoS metrics by nearly 40% and QoE metrics by nearly 30% compared to other routing protocols that consider single metrics.

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References

[1] W. Dargie and C. Poellabauer, "Fundamentals of wireless sensor networks: theory and practice," *John Wiley and Sons*, pp. 168 – 183, 2010.

[2] I. T. Almalkawi, M. Guerrero Zapata, J. N. Al-Karaki, and J. Morillo-Pozo, "Wireless multimedia sensor networks: Current trends and future directions," *Sensors*, vol. 10, no. 7, pp. 6662–6717, 2010.

[3] S. Morgenthaler, T. Braun, Z. Zhao, T. Staub, and M. Anwander, "Uavnet: A mobile wireless mesh network using unmanned aerial vehicles," in *3rd International Workshop on Wireless Networking for Unmanned Autonomous Vehicles*, Anaheim, USA, December 2012.

[4] S. Biswas and R. Morris, "Exor: opportunistic multi-hop routing for wireless networks," *ACM SIGCOMM Computer Communication Review*, vol. 35, no. 4, pp. 133–144, August 2005.

[5] T. Braun, M. Heissenbttel, and T. Roth, "Performance of the beaconless routing protocol in realistic scenarios," *Ad Hoc Networks*, vol. 8, pp. 96–107, 2010.

[6] C.-J. Hsu, H.-I. Liu, and W. K. G. Seah, "Survey paper: Opportunistic routing - a review and the challenges ahead," *Computer Network*, vol. 55, no. 15, pp. 3592–3603, Oct. 2011.

[7] K. Srinivasan, P. Dutta, A. Tavakoli, and P. Levis, "An empirical study of low-power wireless," *ACM Transactions on Sensor Networks*, vol. 6, no. 2, pp. 1–49, March 2010.

[8] G. Zhou, J. A. Stankovic, and S. H. Son, "Crowded spectrum in wireless sensor networks," in *Proceedings of the 3rd Workshop on Embedded Networked Sensors (EmNets)*, 2006.

[9] H.-M. Tsai, N. Wisitpongphan, and O. Tonguz, "Link-quality aware ad hoc on-demand distance vector routing protocol," in *1st International Symposium on Wireless Pervasive Computing*, Jan. 2006.

[10] G. Chen, K. Itoh, and T. Sato, "Enhancement of beaconless location-based routing with signal strength assistance for ad-hoc networks," *IEICE Trans. on Communications*, vol. E91, no. 7, pp. 2265–2271, 2008.

[11] B. Karp and H. T. Kung, "Gpsr: greedy perimeter stateless routing for wireless networks," in *Proceedings of the 6th annual international conference on Mobile computing and networking*. New York, NY, USA: ACM, 2000, pp. 243–254.

[12] M. Zorzi and R. Rao, "Geographic random forwarding (geraf) for ad hoc and sensor networks: multihop performance," *IEEE Transactions on Mobile Computing*, vol. 2, no. 4, pp. 337 – 348, Oct.-Dec. 2003.

[13] X. Yang, J. Yin, and S. Yuan, "Location-aided opportunistic routing for mobile ad hoc networks," in *Proceedings of the 5th International Conference on Wireless communications, networking and mobile computing*, Sep. 2009.

[14] S. Yang, C. K. Yeo, and B. S. Lee, "Robust geographic routing with virtual destination based void handling for manets," in *IEEE 71st Vehicular Technology Conference*, May 2010, pp. 1 –5.

[15] Q. Guan, F. Yu, S. Jiang, V. Leung, and H. Mehrvar, "Topology control in mobile ad hoc networks with cooperative communications," *IEEE Wireless Communications*, vol. 19, no. 2, pp. 74 –79, April 2012.

[16] Z. Mir, D. Shrestha, G. Cho, and Y. Ko, "Mobility-aware distributed topology control for mobile multi-hop wireless networks," *Advances in Data Communications and Wireless Networks*, pp. 257–266.

[17] D. Rosario, Z. Zhao, C. Silva, E. Cerqueira, and T. Braun, "An omnet++ framework to evaluate video transmission in mobile wireless multimedia sensor networks," in *Proceedings of the 6th International Workshop on OMNeT++*, Cannes, France, March 2013.

[18] Z. Zhao, T. Braun, D. Rosario, E. Cerqueira, R. Immich, and M. Curado, "Qoe-aware fec mechanism for intrusion detection in multi-tier wireless multimedia sensor networks," in *1st International Workshop on Wireless Multimedia Sensor Netrworks (WMSN)*, Oct. 2012.