A beaconless Opportunistic Routing based on a cross-layer approach for efficient video dissemination in mobile multimedia IoT applications

Denis Rosário a,b,⇑, Zhongliang Zhao b, Aldri Santos c, Torsten Braun b, Eduardo Cerqueira a,d

aFaculty of Computer Engineering and Telecommunication, Federal University of Pará, Rua Augusto Corrêa 01, 66075-110 Belém, Brazil
bInstitute of Computer Science and Applied Mathematics, University of Bern, Neubrückstrasse 10, 3012 Bern, Switzerland
cDepartment of Informatics, Federal University of Paraná, Rua Cel. Francisco H. dos Santos 100, 81531-980 Curitiba, Brazil
dComputer Science Department, University of California, Los Angeles, 420 Westwood Plaza, Los Angeles, CA 90095, USA

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A B S T R A C T

Mobile multimedia networks are enlarging the Internet of Things (IoT) portfolio with a huge number of multimedia services for different applications. Those services run on dynamic topologies due to device mobility or failures and wireless channel impairments, such as mobile robots or Unmanned Aerial Vehicle (UAV) environments for rescue or surveillance missions. In those scenarios, beaconless Opportunistic Routing (OR) allows increasing the robustness of systems for supporting routing decisions in a completely distributed manner. Moreover, the addition of a cross-layer scheme enhances the benefits of a beaconless OR, and also enables multimedia dissemination with Quality of Experience (QoE) support. However, existing beaconless OR approaches do not support a reliable and efficient cross-layer scheme to enable effective multimedia transmission under topology changes, increasing the packet loss rate, and thus reducing the video quality level based on the user’s experience. This article proposes a Link quality and Geographical beaconless OR protocol for efficient multimedia dissemination for mobile multimedia IoT, called LinGo. This protocol relies on a beaconless OR approach and uses multiple metrics for routing decisions, including link quality, geographic location, and energy. A QoE/video-aware optimisation scheme allows increasing the packet delivery rate in presence of links errors, by adding redundant video packets based on the frame importance from the human’s point-of-view. Simulation results show that LinGO delivers live video flows with QoE support and robustness in mobile and dynamic topologies, as needed in future IoT environments.

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1. Introduction

Multimedia content, e.g., audio and video streaming, or still images, has been attracting research interest and encouraging the development of new Internet of Things (IoT) architectures and protocols [1]. Mobile multimedia IoT enables a large class of scenarios ranging across diverse areas, including safety & security, environmental monitoring, natural disaster recovery applications, and others [2]. Mobile devices, such as robots or Unmanned Aerial Vehicles (UAVs), support the retrieval of real-time video flows from a monitored area, and also the transmission to the destination node, which is connected to the Internet to share content with headquarters or IoT platforms [3] for further processing and analysis. In this way, multimedia content enables the end-user or end-system to take appropriate actions and be aware of the environmental conditions based on rich visual information.

Content distribution for the above applications demand real-time transmissions, lower frame loss, tolerable end-to-end delay and jitter. They also require Quality of Experience (QoE) support to deliver video flows with a minimal video quality level based on the user’s perspective. In addition, multimedia data are larger than scalar sensor samples, imposing more constraints and greater design challenges to deliver real-time video flows with QoE support [4].

The advances in mobile communications have enhanced the multimedia IoT scenarios with node mobility. Those scenarios have continuously topology changes due to failure or mobility of nodes, as well as changes in the wireless channel conditions. Temporary or permanent topology changes have different impact on the network performance and user’s experience [5]. Hence, the routing service must be adaptive to topology changes and aware of QoE
requirements in order to recover or maintain the video quality on a human acceptable level. Those issues make the design of an efficient, reliable, and robust routing protocol for mobile multimedia IoT applications a nontrivial task.

Several routing approaches have been proposed in the literature to meet the requirements to deliver multimedia content with robustness and QoE support under dynamic topologies. Routing protocols based on flat, hierarchical, or geographical approaches rely on route discovery to find end-to-end routes [6–9]. In mobile networks, those routes may be subject to frequent interruptions or do not exist at any time. On the other hand, the use of Opportunistic Routing (OR) increases network performance by making a distributed hop-by-hop routing decision based on protocol-specific characteristics [10]. OR postpones forwarder selection to the receiver side, and relies on a coordination method to pick up the best candidate to forward packets. We consider both beacon-based and beaconless modes as promising OR coordination methods for mobile multimedia IoT applications, since they do not require a stable end-to-end route, which enables packet transmission even if the topology continuously changes.

Beacon-based OR methods [11–13] select and prioritize a set of candidate nodes by transmitting beacon messages before packet transmission. This enables OR to create and order a relay candidate list prior to packet transmission according to a certain criteria, such as expected transmission count. Then, depending on the received priority, neighbour nodes decide to forward the received packet. This method increases the signalling overhead, and the predefined candidate list may not reflect the real situation at the moment of the packet transmission, due to node mobility and failure or wireless channel changes, especially in mobile IoT scenarios. On the other hand, in beaconless OR [14–18], nodes do not need to be aware of their neighbours. This avoids beacon transmission and saves scarce resources, e.g., battery-power and bandwidth. The nodes decide to forward the received packets based on information contained in the received packet, and also in itself information. In addition, an efficient and reliable beaconless OR protocol must consider multiple metrics for improving the forwarding selection scheme.

The use of an optimisation scheme based on parameters and functionalities of different layers, i.e., a cross-layer approach, enhances the benefits of beaconless OR, as well as provides multimedia dissemination with QoE support in presence of dynamic topologies. For instance, a cross-layer approach based on an error control technique together with the OR scheme improves the video delivery process. In this context, the packet redundancy mechanisms [18–20] use information from the application-layer (video characteristics and requirements) to create redundant packets, and thus achieving robust video distribution by transmitting redundant packets together with the original sequence. Hence, as soon as an original frame is lost, it can be recovered from redundant packets [21]. However, existing redundancy mechanisms [18–20] add redundant packets in a black-box manner, i.e., without considering the frame importance from a users perspective, which increases the overhead and wastes scarce resources. Therefore, an efficient QoE/video-aware cross-layer routing and application-level redundancy scheme for multimedia distribution in dynamic mobile environments is still an open issue.

In this article, we introduce a Link quality and Geographical-aware beaconless OR protocol based on a cross-Layer approach for efficient video dissemination in mobile multimedia IoT applications, called LinGO. The cross-layer approach improves the routing and also packet redundancy decisions according to application-layer (video characteristics and requirements), link layer (link quality), energy, geographical, and human visual system information. We explore the proposed approach in a scenario composed of mobile robots or UAVs equipped with cameras to transmit video flows from monitored areas, such as required in rescue or surveil-lance applications. However, it could be easily adapted for many other mobile multimedia scenarios, including multimedia vehicular and mobile ad hoc networks. LinGO enables efficient and robust multimedia dissemination with QoE support in dynamic scenarios, and it also increases the user's experience and reduces the overhead over a bandwidth-limited and unreliable networking environment. More specifically, we integrate our previous beaconless OR protocol [22] with our QoE-aware application-level packet redundancy scheme [23]. LinGO relies on beaconless OR approach, and uses multiple metrics from different layers to calculate and to establish a reliable virtual backbone, namely, link quality, geographical information, and remaining energy. Moreover, the QoE-aware redundancy scheme adds redundant packets only for important video frames, reducing the network overhead, while maximising the human's experience.

The main contributions of this article compared to our previous works [22,23] are the integration of beaconless OR with a QoE-aware redundancy mechanism into LinGO, as well as an extended evaluation of LinGO under dynamic mobile multimedia topologies. First, we evaluated the impact of temporary or permanent node failures on the video quality level. Next, we assessed the impact of node mobility with different moving speeds, as well as the transmission of videos with different characteristics, including motion and complexity levels. Simulation results showed that LinGO achieves robust multimedia dissemination with QoE support and reduced overhead in presence of dynamic topologies.

The remainder of this article is structured as follows. Section 2 outlines existing OR protocols, the main drawbacks to provide reliability, robustness, and QoE support in dynamic topologies. Section 3 presents the network and failure model. Section 4 describes the LinGO protocol and its operation. Section 5 shows an extensive evaluation by means of simulations. Section 6 summarises the main contributions and results of this article.

2. Related work

Mao et al. presented an energy-efficient OR strategy, which focuses on selecting and prioritizing the forwarder list to optimise the network performance [11]. Lu et al. introduced an analytical model to study the performance of multi-hop video streaming [12]. Seferoglu et al. proposed a video-aware opportunistic network, which takes into account the decodability of network codes by several receivers and the importance of the video packet deadlines [13]. However, beacon OR schemes do not provide robustness and QoE support in presence of dynamic topologies, as experienced in mobile multimedia IoT. This is because the candidate list is computed before the data dissemination by transmitting beacons, and thus it may not reflect the real situation at the moment of the packet transmission. Moreover, some works [12,13] lack of a QoE-based evaluation to show the real impact of their schemes based on user's perception.

Heissenbüttel et al. introduced the idea of Dynamic Forwarding Delay (DFD) timer for forwarding decisions in the Beacon-less Routing protocol (BLR) [14]. The source broadcasts the data packet, and the possible forwards compute the DFD timer based on location information before forwarding the received packet. The node closer to the destination generates the shortest delay, and thus transmits the packet first. The neighbour nodes recognise the occurrence of relaying, and cancel their scheduled transmission for the same packet. In addition, only nodes located within the forwarding area participate in the forwarding process, preventing the destination to receive many duplicated packets. Moreover, Aguilar et al. introduced different forwarding areas and a three-way handshake mechanism to determine the forwarder node [15]. Zhang and Shen, and Chen et al. considered three-way handshakes and
DFD before broadcasting a beacon message, which suppress the broadcasting of beacons by other unsuitable neighbours [16,18]. Those proposals rely on a single metric to compute the DFD timer, which reduces reliability and system performance. In addition, [15,16,18] include an extra overhead and delay for the three-way handshake mechanism.

The unreliable nature of wireless links makes the packet forwarding difficult in dynamic wireless environment, since the wireless channel quality can be affected by several unknown factors, such as interference and fading [24]. Hence, reliable beaconless OR should also consider link quality for forwarding decisions. In this context, Al-Otaibi et al. proposed Multipath Routeless Routing protocol (MRR) [17]. It defines a forwarding area as a rectangle and uses multiple metrics to compute the DFD. When a given node receives a packet with weaker signals, it receives the priority to forward packets, reducing the reliability and the video quality level.

Regarding cross-layer schemes, [18,19] combined multipath routes with redundancy mechanisms to tackle the unreliability of wireless links, and Tsai et al. introduced a mechanism to recover lost packets [20]. These approaches [18–20] lack in terms of QoE-based evaluation and they add redundant packets in a black-box manner without considering video characteristics. This increases the overhead and wastes resources, such as battery and bandwidth.

From our related work analysis, we conclude that an integrated beaconless OR protocol with application-level packet redundancy mechanism appears as a promising cross-layer approach for mobile multimedia IoT applications. However, existing beaconless OR approaches do not efficiently combine cross-layer multiple metrics to compute DFD in order to provide multimedia dissemination with QoE support, such as proposed by LinGO. For instance, some beaconless OR protocols [14–16,18] select nodes closer to the destination as relay nodes. However, due to the unreliability nature of the wireless channel, where the most distant node suffers a higher packet loss rate due to bad link quality connectivity. MRR [17] prefers a forwarding node that receives a packet with weaker signals, reducing its reliability. Moreover, LinGO introduces a different progress calculation approach compared to existing proposals [14–16,18], i.e., it takes into account both the progress of a given forwarding node towards the destination with respect to the last-hop, as well as the radio range. In this way, LinGO reduces the number of required hops, bringing many benefits, such as reduced interference. In contrast to other approaches [18–20], LinGO adds redundant packets only to priority frames, increasing the packet delivery probability of key video frames in link error periods, while reducing the overhead. Hence, all of these main features are not provided in a unified cross-layer approach so far, and also the existing proposals lack of robustness and QoE measurements in presence of dynamic topologies.

3. System model

Mobile multimedia IoT applications demand mobile nodes to support environmental monitoring, as soon as the standard fixed network infrastructure is not available due to a natural disaster, as illustrated in Fig. 1. The multimedia content in those services plays an important role to enable multimedia event detection by systems, and to help control centre and end-users to plan actions based to visual information. Hence, it would be possible to explore the hazardous area, where rescuers cannot reach easily and fast, and helping the rescue procedures.

3.1. Network model

We consider a mobile multimedia network composed of \( n \) mobile nodes deployed in the monitored area, as depicted in Fig. 1. We assume that each node has an individual identity \( i \in \{1, n\} \), and those nodes are represented in a dynamic graph \( G(V, E) \), where vertices \( V = \{v_1, v_2, \ldots, v_n\} \) build a finite set of nodes and edges \( E = \{e_1, e_2, \ldots, e_m\} \) build a finite set of wireless links between the nodes. In addition, the links are typically asymmetric, as experienced in mobile IoT scenarios. We define \( N(v_i) \subset V \) as a subset of neighbourhood nodes within the radio range of a given node \( v_i \). Each mobile node \( v_i \) is able to estimate the link quality communication at the physical layer for a given link \( e_{ij} = 1, \ldots, m \). For instance, the physical layer of a widely used radio chip in IoT applications, i.e., CC2420, provides RSSI, Signal to Noise Ratio (SNR), and Link Quality Indicator (LQI) for each received packet [24].

Mobile nodes are equipped with a camera, an image encoder, radio transceiver, and limited energy supply, processing, and memory space. Moreover, we assume a network composed of one Destination Node (DN) equipped with a radio transceiver, an image decoder, and unlimited energy supply. DN acts as a base station. Each node \( v_i \) has a battery with initial energy power \( P_b \) and uses energy \( P_r \) to move with a certain speed \( s \). Moreover, each node \( v_i \) spends energy \( P_{sn} \) to transmit a packet and \( P_{re} \) to receive a packet. It should be highlighted that node movements require more energy than packet transmissions. They move with a certain speed \( s \) ranging between a minimum \( \min \) and a maximum \( \max \) speed limit, and each node is aware of its own location by means of GPS, Galileo, or any other positioning service. Each node \( v_i \) knows the DN location, since we assume a static DN.

As expected in many mobile multimedia IoT scenarios, the Source Node (SN) is responsible for capturing video flows and transmitting them to DN in a multi-hop fashion. At the beginning of every data transmission in beaconless OR, SN broadcasts video packets to its neighbours N(SN). Then, the forwarding selection process selects one of those neighbours as the forwarding node \( (F) \), i.e., next hop. For convenience of notations, we consider that \( F \) acts as SN, and repeats the same procedure until the video packet reaches the DN, and thus SN is responsible for receiving and also for forwarding video packets from its predecessor node. In addition, we represent \( RN_i, i = 1, \ldots, N(SN) \), as a subset of candidate forwards of SN, and one of them will cooperate with SN whenever needed. Table 1 summarize the main symbols used in this article.

3.2. Failure model

Mobile multimedia IoT scenarios might involve a dynamic topology due to failures, damage and/or mobility of individual nodes or a set of nodes, as well as wireless channel variations. In this way, natural failures are physical (hardware) faults caused by natural phenomena and without human intervention to produce node defects or physical deterioration. Moreover, the network is composed of mobile nodes with limited energy resources, which causes topology changes when a node \( v_i \) runs out of energy resources. The topology may also change due to node movement,
Table 1

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>$v_i$</td>
<td>A given node with an individual node identity $i$, where $1 &lt; i &lt; n$</td>
</tr>
<tr>
<td>$N(v_i)$</td>
<td>A set of neighbour nodes within the radio range of a given node $v_i$</td>
</tr>
<tr>
<td>SN</td>
<td>Source Node</td>
</tr>
<tr>
<td>RN$_i$</td>
<td>A subset of neighbour nodes considered as possible relay node</td>
</tr>
<tr>
<td>F</td>
<td>Forwarding node</td>
</tr>
<tr>
<td>DN</td>
<td>Destination node</td>
</tr>
<tr>
<td>$P_{SN,DN}$</td>
<td>A path connecting any pair of SN and DN via multiple $F$</td>
</tr>
<tr>
<td>$P(RN, SN)$</td>
<td>Geographical advance of a given RN, towards DN, where</td>
</tr>
<tr>
<td>$D(RN, SN)$</td>
<td>Euclidean distance between a given RN, and DN, where</td>
</tr>
<tr>
<td>LQE</td>
<td>Link quality estimation, where $0 &lt; LQE &lt;= LQE_{max}$</td>
</tr>
<tr>
<td>$P_0$</td>
<td>Initial energy power</td>
</tr>
<tr>
<td>$P_x$</td>
<td>Energy required to transmit each packet</td>
</tr>
<tr>
<td>$P_v$</td>
<td>Energy required to move with a certain speed $s$</td>
</tr>
<tr>
<td>DFD</td>
<td>Dynamic forwarding delay before transmitting the received packet, where $0 &lt; DFD &lt;= DFD_{max}$</td>
</tr>
</tbody>
</table>

i.e., a node $v_i$ moves out of the transmission range of its neighbour $v_{i+1}$.

Wireless channel variations also cause topology changes, since wireless transmissions often experience link error periods and the nodes may stop to overhear the transmission of each other. This is because several factors affect the propagation of wireless signals, which contribute to channel impairments. Moreover, wireless transmission might suffer from interference by concurrent transmissions, coexisting wireless networks, and other electromagnetic sources. The hardware transceivers may also distort the received/sent signals because of their internal noise [24].

The persistence of node failures might be classified into permanent and transient, depending on the duration of node failures. Transient failures occur when a node resumes its operations after a failure, otherwise it is a permanent failure. For example, transient failures occur when the nodes move out of each other's transmission range or use up their energy resources with a following battery replacement, and in case of channel variability. On the other hand, permanent failures could be caused when nodes stop to work permanently due to natural faults or run out of energy resources without battery replacement [5].

3.3. Problem statement

Given a pair $(SN, DN) \in V$, the goal of a beaconless OR is to find a subset of reliable forwarders $F$ to create a path $P_{SN,DN} = \{SN, F_1, F_2, \ldots, F_k, DN\} \subset V$ to connect any pair of $SN$ and $DN$. In particular, the forwarding selection mechanism must find a subset of optimal $F$ to provide packet delivery guarantees. The optimal $F$ must provide greater progress towards $DN$ with reliable links and enough energy to forward the video packets with a low packet loss rate.

We assume that a compressed video is composed of I-, P- and B-frames with different priorities, such as proposed in MPEG codec. Hence, from a human visual system’s standpoint, the loss of high priority frames causes severe video distortions [25]. More specifically, the loss of an I-frame causes error propagation through the other frames within a Group of Picture (GoP), since the decoder uses the I-frame as a reference point for reconstruction of all the other frames within the same GoP. Thus, the video quality only recovers when the decoder receives an unimpaired I-frame. For the loss of a P-frame, the impairments extend to the remaining frames within a GoP. In addition, the loss of P-frames at the beginning of a GoP causes higher video distortion than loss at the end of a GoP. The loss of a B-frame only affects the video quality of that particular frame.

4. A beaconless Opportunistic Routing based on a cross-layer approach

In this section we describe our cross-layer approach. LinGo includes forwarding and MAC functionalities. In this way, it assumes a CSMA/CA mechanism, and relies on beaconless OR method, which has two operational modes to establish a reliable virtual backbone, namely contention-based forwarding and backbone-based forwarding modes. In addition, we integrate the beaconless OR with a QoE/video-aware redundancy mechanism to add redundant packets based on the frame importance, enabling robust and efficient multimedia transmissions with reduced overhead.

4.1. QoE/video-aware redundancy mechanism

LinGo takes into account the video characteristics from the user’s perspective, to enable multimedia transmissions with a good quality level. Moreover, the constraints of the mobile nodes increase the effects of wireless channel errors, and application-level packet redundancy mechanisms can be employed as an error-control scheme for handling losses in mobile multimedia IoT communications. Packet redundancy mechanisms acts completely different compared to link-layer mechanisms. Such mechanism has been employed due to its suitability for video communications and the nature of error coding at the application layer [21].

The proposed redundancy mechanism adds $r$ redundant packets to a set of $k$ original video packets. Indeed, it encodes $h$ original video packets into a set of $k$ coded packets by generating $(r = k - h)$ additional packets. The $DN$ reconstructs $k$ original video packets by receiving any $h$ out of the $k$ packets $(k > h)$. Thus, as soon as the $DN$ receives $k$ video packets correctly, it may decode the frame immediately and drop the subsequent redundant packets.

The QoE/video-aware redundancy scheme [23] achieves robust video transmission over a bandwidth-limited unreliable networking environment, as experienced in mobile multimedia IoT environments, since it considers Reed–Solomon coding to create redundant packets. It adds redundant packets only for priority frames based on the impact on their human visual system, i.e., not in a black-box manner as happen in many non-QoE approaches, such as [18–20]. Thus, it protects the priority frames in congestion/link error periods, and supports QoE-aware multimedia transmissions together with reduced packet overhead compared to existing redundancy mechanisms.

4.2. Contention-based forwarding mode

Whenever a $SN$ wants to send a video sequence, it triggers the contention-based forwarding mode by broadcasting the video packet to its neighbours $N(SN)$. However, before $SN$ transmits a video packet, it must determine its own location $(x_{SN}, y_{SN})$ and include it in the packet header, which contains the following information: $<x_{SN}, y_{SN}, pktid, SN_{id}, DN_{id}>$. After broadcasting the packets, $SN$ may wait during a maximum DFD value $(DFD_{max})$ for its neighbours $N(SN)$ to decide about the transmission of the received packets.

Hence, neighbours within the radio range of $SN$ $(N(SN))$, i.e., $RN_1, RN_2, RN_3, RN_4$, and $RN_5$ depicted in Fig. 2, compete for forwarding the received packet in a completely distributed manner. In particular, upon receiving a packet, each $N(SN)$ knows the SN location.
by analysing the packet header. In addition, each N(SN) is aware of itself location and also the DN location. Thus, based on their own positions, as well as the geographical location of SN and DN, N(SN) can determine their forwarding area. LinGO divides the surrounding area of SN into Positive Progress Area (PPA) and Negative Progress Area (NPA), as shown in Fig. 2. PPA comprises the forwarding area, where each N(SN) is closer to DN than SN. Otherwise, each N(SN) is inside NPA.

Each N(SN) located within NPA drops the received packet, since it is further away from DN than SN, i.e., nodes RN_1 and RN_2 depicted in Fig. 2. On the other hand, each N(SN) within the PPA is considered as possible relay nodes (RN_s), i.e., nodes RN_s, RN_a, and RN_b, depicted in Fig. 2. Instead of forwarding the packet immediately, each RN computes a DFD value in the interval [0, DFD_max]. starts a timer according to the DFD value, and waits for the conclusion of this timer to transmit the received packet. More specifically, LinGO adopts the DFD calculation to add short delay timer before forwarding the received packet, which helps to pick up the best RN, in a completely distributed manner in order to unicast the subsequent packets without additional delay. In this way, the RN, that generates the smallest DFD value replaces the SN location with its own location in the packet header, and thus it forwards the packet first. This node is considered as a forwarding node (F).

Each RN, cancels the running timer and also deletes the buffered packet when overhearing a retransmission coming from F for the same pkt_a buffered. At the same time, LinGO uses the transmitted packet as passive acknowledgement, i.e., SN senses a retransmission for the same pkt_a by F, and concludes that the packet was successfully received by F. Thus, the SN must forward subsequent video packets explicitly addressed to F and without including additional delay. The algorithm continues until the packet reaches DN, which sends an explicit acknowledgement. In this way, LinGO builds a reliable virtual backbone between SN and DN via multiple F.

Nevertheless, the virtual backbone creation may fail when there is no RN, inside the PPA, i.e., an empty PPA, or due to node mobility. In addition, the hidden terminal problem might appear, and SN is unable to overhear the packet relaying from F. Hence, as soon as SN does not detect the relaying of a previously broadcasted packet from any RN, after the DFD_max, it must repeat the contention-based forwarding mode until it establishes the virtual backbone to unicast the subsequent packets. Fig. 3 depicts the general overview of the contention-based forwarding mode. In this example, RN_2 forward the pkt first, but SN does not overhear this transmission, and thus SN stays in contention mode and broadcasted the pkt_{t+1} after DFD_max. RN_1 forwarded the pkt_{t+1} first and SN overhears this transmission, and thus SN unicasts subsequent packets to RN_1, i.e., it switches to backbone-based forwarding mode.

### 4.3. Metrics for forwarding selection mechanism

As mentioned before, LinGO postpones the forwarding decision to the receiver side based on the DFD function. Moreover, LinGO takes into account multiple metrics to compute the DFD, including link quality, geographical information, and remaining energy. The use of multiple metrics increases reliability, robustness, and video quality level from the user’s experience. More specifically, each RN computes the DFD as follows:

\[
\text{DFD} = DFD_{max} \times (\alpha \times \text{LinkQuality} + \beta \times \text{progress} + \gamma \times \text{energy})
\]

The DFD includes coefficients (α, β, and γ) to give priority to each metric depending on the application requirements. The sum of the coefficients (α + β + γ) is equal to 1. In the following, we explain how each RN computes LinkQuality, progress, and energy.

#### 4.3.1. Metric definition 1 – LinkQuality

Through metric 1, we attempt to provide reliable transmission, i.e., high packet delivery ratio. Existing beaconless OR protocols consider the transmission range as a circle, and thus they assume successful transmissions as long as two nodes are within the transmission range of each other. However, this is not a realistic assumption, considering the dynamic and asymmetric nature of wireless links, as shown in [24]. In this context, we consider the link quality between two nodes as part of DFD, and this is computed by Eq. (2) in the interval [0, 1].

Link Quality Estimation (LQE) denotes a single value for the link quality communication for a wireless link between two nodes in the presence of wireless links, as shown in [24]. In this context, we consider the link quality between two nodes as part of DFD, and this is computed by Eq. (2) in the interval [0, 1].

\[
\text{LinkQuality} = \begin{cases} 
0 & \text{if } \text{LQE} < \text{LQE}_{\text{Bad}} \\
\text{LQE}_{\text{Min}} - \text{LQE} & \text{if } \text{LQE}_{\text{Bad}} < \text{LQE} < \text{LQE}_{\text{Good}} \\
1 & \text{if } \text{LQE} \geq \text{LQE}_{\text{Good}} 
\end{cases}
\]

Baccour et al. classified the links according to the values of Packet Reception Ratio (PRR) into three regions of connectivity, namely connected (PRR higher than 90%), transitional (PRR between 10% and 90%), and disconnected (PRR lower than 10%) [24]. Based on that, we defined the bounds of disconnected and connected regions by means of two LQE thresholds: LQE_{bad} and LQE_{good}. Both should be defined according to experiments. In this way, we can classify a link as disconnected, as soon as a given RN received a packet with LQE lower than LQE_{bad}; or as connected when LQE is higher than LQE_{good}; or as transitional for LQE, ranging between LQE_{bad} and LQE_{good}.

According to Eq. (2), a given RN, with connected link to SN has higher probability to forward the packet faster (i.e., LinkQuality = 0), since this link can provide higher reliability to transmit the packets. For disconnected links, the LinkQuality returns 1, which makes a given RN, less likely to forward the packet faster, due to the lower PRR provided by such link. A transitional link generates a LinkQuality ranging from 0 to 1, and low LQE, gives higher value to Eq. (2). This is because such link cannot provide reliable transmission. In this way, LinGO supports reliable multimedia transmissions with QoE support in dynamic and mobile environments.
4.3.2. Metric definition 2 – progress

We define progress as the geographical advance of a given RN, towards DN with respect to SN, i.e., a given RN, with high progress means a node closer to DN. We compute progress $P$ in Eq. (3).

$$
\text{Progress} = \begin{cases} 
\frac{2R - P(RN, SN)}{2R} & \text{if } D(RN_i, DN) > R \\
0 & \text{if } D(RN_i, DN) < R 
\end{cases}
$$

We denote $D(RN, DN) \in [0, R]$ as the Euclidian distance between a given RN, and DN. $R$ as the radio range, and $2R$ as the maximum progress. The sum of two segments $(P_1(RN_1) + P_2(RN_2))$ composes the geographical advance $P(RN, SN) \in [0, 2R]$ of a given RN, towards the DN, as shown in Fig. 4. We define $P_1(RN_1) \in [0, R]$ as the projection of the distance travelled from SN to any RN, onto the line from SN to DN. On the other hand, the projection of line $RN_i - RN_j$ on line $SN - DN$ defines $P_2(RN_i) \in [0, R]$. Moreover, in terms of practical implementation, we assume a fixed $R$ for all nodes. However, this assumption might not be valid in realistic scenarios, since $R$ can dynamically change due to shadowing effects, attenuation from buildings, etc. Thus, an on-line algorithm to compute $R$ can be used to deal with this problem, such as proposed by Palazzi et al. [26].

The existing work [14] has defined progress function as $P_1(RN_1)$, which may cause collisions, because multiple RN, can forward packets at the same time when they have the same progress, i.e., $P_1(RN_1) = P_1(RN_2)$, as shown in Fig. 5. However, $RN_2$ is closer to the line SN – DN, increasing the progress in our definition, and also SN can transmit the video packets to DN via RN, with only one hop, which cannot be achieved, by increasing the progress function given higher priority to any RN. As soon as it is able to transmit packets directly to DN. Relaying packets by intermediate nodes is often not more energy-efficient than direct transmission [16]. Otherwise, RN, with higher progress generate lower input to DFD, increasing the probability to forward the packet faster.

4.3.3. Metric definition 3 – energy

Battery-powered mobile nodes, such as mobile robots or UAVs, should consider energy for the forwarder selection to provide energy-efficiency support. Thus, we propose to compute the energy $E$ in $[0, 1]$ according to Eq. (4).

$$
E = \begin{cases} 
P_{transmit} R_E > E_{min} \\
1 & \text{if } R_E < E_{min}
\end{cases}
$$

$E_{min}$ means the energy required to transmit packets ($E_{transmit}$) and move ($E_{movement}$). For instance, RN, need $E_{transmit} = K \times P_{tx}$ to transmit a given number of $k$ multimedia packets. Moreover, RN, require $E_{movement} = s \times P_{s}$ to move at a certain speed $s$. We need to compute $E_{transmit}$, since we consider battery replacement. Thus, a given RN, has priority to forward the packet faster, when it has enough remaining energy ($R_E$) to forward subsequent video packets, and if needed move back to the control centre for battery replacement.

4.4. Backbone-based forwarding mode

Transmitting all video packets in contention-based forwarding mode causes additional delays and interferences. In addition, DN receives more duplicated packets if packets are broadcast over multiple forwards F. For instance, packet duplication occurs when two RN, within the same PPA do not overhear the transmission of each other. Those issues reduce the video quality level, being undesirable for mobile multimedia IoT applications. Hence, LinGO avoids the drawbacks of broadcast transmissions by introducing a backbone-based forwarding mode, where LinGO builds a reliable virtual backbone between SN and DN via multiple $F$ by means of contention-based forwarding mode. More specifically, as soon as SN overhears the transmission for the same pkt$_{id}$, it must switch to the backbone mode, where nodes must transmit the subsequent video packets explicitly addressed to $F$ and without additional delay.

Moreover, the video content might be delivered in presence of a node failure or mobility and as well as channel variations. For instance, the network conditions of $F$ may change, $F$ may move out of the SN radio range, or $F$ might use up its energy resources. Alternatively, another RN, with better network conditions may enter into the SN radio range. In this context, LinGO enhances robustness by reconstructing the virtual backbone in order to detect topology changes in time intervals called Link Validity time Estimation (LIVE). During the LIVE interval, instead of the nodes broadcasting the packets, they must transmit video packets in a unicast fashion, and thus LinGO avoids the problems of broadcast transmissions. The LIVE value should be adjusted according to the desired degree of fault tolerance and energy consumption. From the energy consumption point-of-view, the reconstruction of the virtual backbone must occur with low frequency, i.e., high LIVE value. On the other hand, high frequency of virtual backbone reconstruction, i.e., low LIVE value, provides better fault tolerance system.

5. Evaluation

In this section, we describe the methodology and metrics to evaluate the quality level of transmitted videos under dynamic topologies caused by node failure, mobility, and channel variation. We assess the performance of the QoE-aware redundancy mechanism, as well as the impact of number of nodes on the video quality and on the signalling overhead. We present the impact of temporary or permanent node failures on the video quality. Finally, we introduce the video quality for different nodes speed, and video characteristics, i.e., video motion and complexity levels.
5.1. Simulation description and evaluation metrics

We used the Mobile MultiMedia Wireless Sensor Network (M3WSN) OMNeT++ framework [27] for our simulations, which supports wireless channel temporal variations, node mobility, and node failures. The simulations last for 200 s and run with the lognormal shadowing path loss model. SN sends the first video sequence of 10s at the 4th second of the simulation time, and transmits a new video every 20s. We have obtained a total number of 10 video transmissions per simulation. The results are averaged over 33 simulation runs with different randomly generated seeds to provide a confidence interval of 95%. We deployed \( n \) nodes over a 40 \( \times \) 40 m flat terrain with one SN located at (5,5), one DN located at (38,38), and \((n - 2)\) RN, deployed uniformly. They are equipped with CC2420 transceiver, using transmission power of –15 dBm, and relying on the traditional CSMA/CA MAC protocol without RTS/CTS messages and retransmissions. We encoded the video sequences with typical parameters for a natural disaster recovery application, i.e., H.264 codec at 200 kbps, 30 frames per second, and in a quarter common intermediate format (176 \( \times \) 144). The decoder uses Frame-Copy [25] as the error concealment method to replace each lost frame with the last received one, which is expected to make less severe impact of frame losses on the video quality.

We measured the quality level of each transmitted video by means of well-known objective and subjective QoE metrics, namely Structural Similarity (SSIM) and Mean Opinion Score (MOS) [25], respectively. This is due to QoE metrics overcome the limitations of QoS schemes or metrics regarding human’s perception and subjectivity to evaluate the video quality. In this way, SSIM is based on a frame-to-frame assessment of three video components, i.e., luminance, contrast, and structural similarity, which ranges from 0 to 1, and higher value means better video quality. We used the MSU Video Quality Measurement Tool (VQMT) to measure the SSIM value for each transmitted video.

Subjective evaluation captures all details that might affect user’s experience. In this context, MOS is one of the most frequently used metric for subjective evaluation, and it requires human observers rating the overall video quality. For MOS evaluation, we used the Single Stimulus (SS) method of ITU-R BT.500-11 recommendations. The human observers watch only once the video sequence and then give a score using the following scale: Bad; Poor; Fair; Good; and Excellent. The choice of a SS paradigm fits well to a large number of emerging multimedia applications [25].

5.2. Evaluation of LinGO parameters and overall video quality level

The coefficient values \((\alpha, \beta, \text{and } \gamma)\) of the DFD function (Eq. (1)) affect the LinGO performance. Based on results showed in [22], we optimised them and concluded that \(\alpha = 0.5, \beta = 0.4, \text{and } \gamma = 0.1\) gives the LinGO best results. This is because LinGO achieved the best trade-off between high progress towards DN together with reliable links and enough energy to forward the packets with an acceptable video quality level from the user’s perspective.

5.2.1. Impact of packet-level video/QoE-aware redundancy mechanism

Fig. 6 shows the impact of the QoE/video-aware redundancy mechanism for a network composed of 30 static nodes deployed in the simulation area. The mechanism improves the video quality by 20% compared to multimedia transmissions without packet redundancy. This is because it adds redundant packets based on the frame importance, enabling the decoder to recover losses of priority frames. Thus, it protects priority frames in congestion and link error periods. It also achieves robust video transmission over a bandwidth-limited and unreliable networking environment with reduced overhead, as to be expected in many mobile multimedia IoT applications.

Moreover, LinGO increases the video quality by 18% and 55% compared to BLR and MRR, respectively. This occurs because MRR gives priority to a given node becoming a forwarder, when it receives a packet with a weak signal. In addition, in contrast to BLR, LinGO takes into account multiple metrics for the forwarder selection mechanism, including geographical information, link quality, and energy, which enable LinGO to find reliable forwarders.

5.2.2. Impact of number of nodes on the video quality level and signalling overhead

Fig. 7 shows the video quality for networks containing 20, 30, and 40 static nodes deployed in the simulation area. These scenarios take into account only changes in the wireless channel environment, i.e., without the presence of node failure or mobility. For those scenarios, LinGO increases the video quality level by 15% and 30% compared to BLR and MRR, respectively. In addition, the video quality level is reduced when the node density decreases, since the number of neighbours decreases and consequently minimizes the likelihood to establish a reliable backbone. For instance, networks composed of 20, 30, and 40 nodes have around 3, 6, and 8 neighbours per node, respectively.

Regarding the signalling overhead, BLR adds 6 control packets per node for networks composed of 20, 30 and, 40 nodes. This is because the backbone creation may fail as explained in Section 4.2, and BLR defines a recovery strategy to deal with this situation, where the SN broadcasts a control packet and all of its neighbours...
reply with a control packet indicating their positions. Then, SN chooses the RN, closer to the DN. On the other hand, LinGO and MRR do not include any control packet, since they define a simple recovery strategy, where the SN must repeat the contention-based forwarding mode, as described in Section 4.2. Moreover, it is important to highlight that MRR includes an extra overhead and delay for a location update mechanism, because the nodes need to transmit control packets to find DN location. However, we implemented only the routing algorithm, because we consider a static DN.

BLR decreases the number of duplicated packets received by DN, and consequently reduces the number of acknowledgments transmitted by DN, since it considers a reduced forwarding area. For instance, in a network with 20 nodes, the DN received 7, 1, and 2 duplicated packets per transmitted video via LinGO, BLR, and MRR, respectively. In addition, the number of duplicated packets is two or three times for networks with 30 and 40 nodes, respectively.

5.3. Reliability and robustness

We evaluate the reliability and robustness of LinGO compared to BLR and MRR by deploying static nodes, and the topology changes are caused by individual node failures, as well as wireless channel variations. We defined two scenarios, where one has temporary node failures and another one has permanent node failures. For both scenarios, we created the worst-case scenario for topology changes, where the SN established the virtual backbone and 10% of 1-hop neighbours of SN/DN have individual node failures. We also performed simulations by failing 10% of 1-hop neighbours of SN or DN. Those results are not shown, but they also confirm the robustness of LinGO.

5.3.1. Impact of transient node failures

Fig. 8 shows the SSIM values for all frames of video 6 in a scenario with 30 nodes, with and without transient node failures, and LIVE values of 2 and 4. We can see a poor video quality for the first second of the video (Frames 0–29), regardless of the OR. This is because the first P-frames were lost and the decoder cannot reconstruct the first second of the video with a reasonable quality. The video quality level decreases again around frames 120 and 240. During the transmission of these frames, the SN re-established the backbone by means of contention-based forwarding mode in order to detect topology changes causing frame losses due to interferences by broadcast transmissions.

For a LIVE value of 4, LinGO and BLR transmitting video frames in scenarios with node failures (i.e., LinGO-Fail and BLR-Fail) provide bad video quality up to frame 120, because the DN received only the first frame, and thus the decoder replaces each lost frame with the last received one. For frames 121–300, LinGO transmits video frames with higher reliability even in presence of node failures (i.e., LinGO-Fail), since the decoder can reconstruct the video frames with similar quality compared to BLR transmitting the video without node failures. Moreover, LinGO in presence of node failures reduces the video quality by 3% compared to LinGO without node failures. This is because in presence of node failures, LinGO is still able to re-establish a reliable virtual backbone. The videos transmitted via MRR with and without node failures (i.e., MRR and MRR-Fail) have the worst quality, because MRR gives priority to a node becoming a forwarder, when it receives a packet with weaker signals, decreasing the video quality level.

For a LIVE value of 4, the video quality degrades for a long period of time compared to a LIVE value of 2, because nodes need more time to detect node failures, as well as to adapt to topology changes, as shown in Fig. 8. This is because the evaluated beaconless OR protocols rely on backbone reconstruction to recover from node failures, which affects the degree of fault tolerance. Thus, we decided to use a LIVE value of 2 for the next simulations, since it enables the protocols to recover the video quality quickly in case of topology changes.

Fig. 9 shows the video quality for 10 videos transmitted with and without transient node failures, where the transient node failures happened during the transmissions of videos 6 and 7. In contrast to BLR and MRR, LinGO without node failures keeps the video quality high and constant, i.e., SSIM around 0.87 for videos 1–10. LinGO also has smaller confidence intervals than MRR and BLR, i.e., a small variation in the video quality for different random-generated seeds. This is explained because LinGO builds a reliable backbone, which protects frames during link error periods. For instance, LinGO reduces the loss of I- and P-frames by up to 50% compared to BLR and MRR, which are the priority frames and their loss increase the video distortion. Hence, LinGO enables video dissemination with QoE support in scenarios with topology changes caused by channel quality variations.

For scenarios with transient node failures, videos 1–5 and 8–10 are transmitted without any node failures, which explain the similar video quality level compared to scenarios without any node failures regardless the OR, as shown in Fig. 9. On the other hand, during the transmission of video 6, nodes create the backbone and 10% of network nodes have individual transient failures lasting until the end of video 7. Besides the topology changes caused by node failure, a burst of packets might be lost until the SN recreates the virtual backbone, since one of the nodes from the virtual backbone might be not available anymore to forward the packets. In the
worst case, there will be a burst of lost packets during the **LIVE** interval, because this is the time interval for backbone reconstruction.

Fig. 9(a) shows that video 6 transmitted via LinGO with node failures decreases its video quality by 5%, compared to LinGO without node failures. It is important to notice that the video quality is still better than BLR and MRR without any node failure, since LinGO adapted better to topology changes caused by transient node failures. Video 6 transmitted using BLR and MRR with transient node failures has decreased the video quality up to 10%, compared to video 6 transmitted via BLR and MRR without any node failures, because those protocols are not able to re-establish a reliable backbone in case of topology changes.

We can compare the results of Fig. 9(a) with Fig. 9(b) to analyse the impact of node density. By doing that, we can see that when the number of nodes increases, the impact of node failures on the video quality level decreases, regardless of the protocols. This is because the nodes have more neighbours, which increase their likely to reconstruct a reliable virtual backbone, and thus enable the nodes to adapt better to topology changes.

### 5.3.2. Impact of permanent node failures

Fig. 10 shows the video quality for networks with 30 and 40 nodes, with and without the presence of permanent node failures, where permanent node failures happened during the transmissions of videos 6–10. LinGO transmits video 6 with similar quality level compared to BLR without any node failures for a network with 30 nodes. Moreover, LinGO in presence of permanent node failures recovered the video quality for videos 7–10, since LinGO adapted better to topology changes. On the other hand, BLR and MRR under failures reduce the video quality compared to LinGO.

In addition, BLR and MRR do not recover the video quality as LinGO does for transmitting videos 7–10. Finally, the impact of node failures decreases as soon as the node density increases.

### 5.4. Impact of node mobility

We deployed 30 mobile nodes moving according to the Random Waypoint mobility model. We defined \( s_{\text{min}} = 0 \) and three different \( s_{\text{max}} \) (1, 5, and 10 m/s). Thus, we can analyse the impact of the moving speed on the final video quality level. As soon as \( s_{\text{max}} \) increases, the video quality decreases. This is because the forwarder node moves faster out of the transmission range of the **SN**, which breaks quickly the virtual backbone. These issues cause higher packet loss rate, and consequently decrease the video quality level from the user’s perspective.

LinGO outperforms BLR and MRR for these three maximum moving speeds. This is because in contrast to BLR, LinGO considers multiple metrics for forwarding decisions, enabling the nodes to transmit video packets with reduced loss rate. For instance, LinGO reduces losses of I- and P-frames by 30% compared to BLR and MRR. Hence, LinGO protects priority frames during link error periods, and consequently increases the video quality level.

### 5.5. Subjective video quality evaluation

The Highway video [28] has similar motion and complexity levels compared to the case of a mobile node capturing video flows while it is moving. In addition, Hall video sequence [28] has similar characteristics to a mobile node stopped in a certain area to capture a video. These video characteristics are expected in a typical natural disaster recovery application with mobile robots or UAVs.
For these reasons, we selected these two video sequences to our subjective evaluation. The set of transmitted videos via LinGO, BLR, and MRR is publicly available at [29].

In our subjective evaluation, 25 observers evaluated the videos, including undergraduate and postgraduate students as well as university staff. They had normal vision, and their age ranged from 18 to 45 years old. We implemented a software to play the videos in a random order at the centre of the monitor against a neutral grey background, as recommended by ITU. The developed software runs on a Desktop PC Intel Core i5, 4 GB RAM, and a 21” LCD monitor to display the video sequences for the observer to score them.

Fig. 12 shows the subjective video quality evaluation by means of the MOS metric. Those results indicate that LinGO provides higher video quality compared to BLR and MRR in scenarios involving videos with similar motion and complexity. This is explained by the fact that BLR and MRR have a higher frame loss rate than LinGO. For instance, LinGO reduces the losses of I- and P-frames for Hall and Highway video sequences by up to 30%, since it relies on multiple metrics to establish a reliable virtual backbone protecting the frames of link error periods. Those issues increase the video quality, as required in many mobile multimedia IoT applications with QoE support.

We randomly selected frames from the Hall and Highway video sequences, with the aim of analysing the frames from a user point-of-view, as displayed in Fig. 13. Frame 193 of the Highway video sequence is the moment when a car moves across the scene. On the other hand, frame 238 of the Hall video sequence is the moment when a man was walking a hall for entering in a door. The moment or frame with a moving region of interest on a static background is useful to analyse the monitored area, such as required for environmental monitoring and natural disaster recovery applications. For instance, the end-users (or end-systems) could visually determine the real impact of an event, and be aware of what is happening in the environment by means of visual information.

The Highway and Hall frames transmitted using LinGO have low distortion compared to the same frames sent using BLR and MRR. This is because LinGO establishes a reliable backbone, which protects the frames during link error periods. This is assured even though the topology is continuously changing or for videos with different motion and complexity levels, which is required in many

![Fig. 11. Impact of moving speed.](image)

![Fig. 12. Subjective evaluation.](image)

![Fig. 13. Frame 289 of hall and frame 193 of highway video sequences for different beaconless OR protocols.](image)
mobile multimedia IoT applications. Apart from the distortions on the Hall and Highway frames transmitted via BLR and MRR, the vehicle does not appear in the same position compared to the original Highway frame transmitted via BLR and MRR. This is due to the frame was lost, and the decoder reconstructed the frame based on the previously received frames. Thus, we can conclude that LinGO provides robust multimedia transmissions with QoE assurance in scenarios with dynamic topologies.

From our performance evaluation analysis, we identified that BLR and MRR perform poorly compared to LinGO in a scenario composed of mobile nodes, nodes failures, and videos with different motion and complexity levels. The results achieved in this article are summarised in Table 2.

6. Conclusions

This article introduced LinGO to enable efficient, robust, and reliable video dissemination with QoE support in dynamic multimedia mobile scenarios. It supports the transmission of video flows, which can be delivered to multimedia platforms for further processing and analysis. Examples are applications to guide rescue operations allowing appropriate actions to be taken based on visual information. LinGO relies on a beaconless OR method with two operational modes, where the backbone mode reduces delays and maximises system performance. It takes multiple metrics into account, i.e., link quality, geographical information, and remaining energy, for forwarding decisions. Moreover, LinGO relies on a QoE-aware redundancy mechanism to add redundant packets based on the frame importance to optimise video transmissions over wireless and dynamic routes. The simulation results highlighted LinGO’s reliability, robustness, and QoE support by measuring the video quality in presence of topology changes. These topology changes are caused by individual node failures, mobility, and wireless channel changes. We measured the video quality level of each transmitted video by means of well-known objective and subjective metrics for QoE, namely SSIM and MOS. The evaluation showed that LinGO reached a SSIM gain of around 30% compared to BLR and MRR, for scenarios composed of mobile nodes with different moving speeds, and videos with different motion and complexity levels. (see Fig. 11).

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